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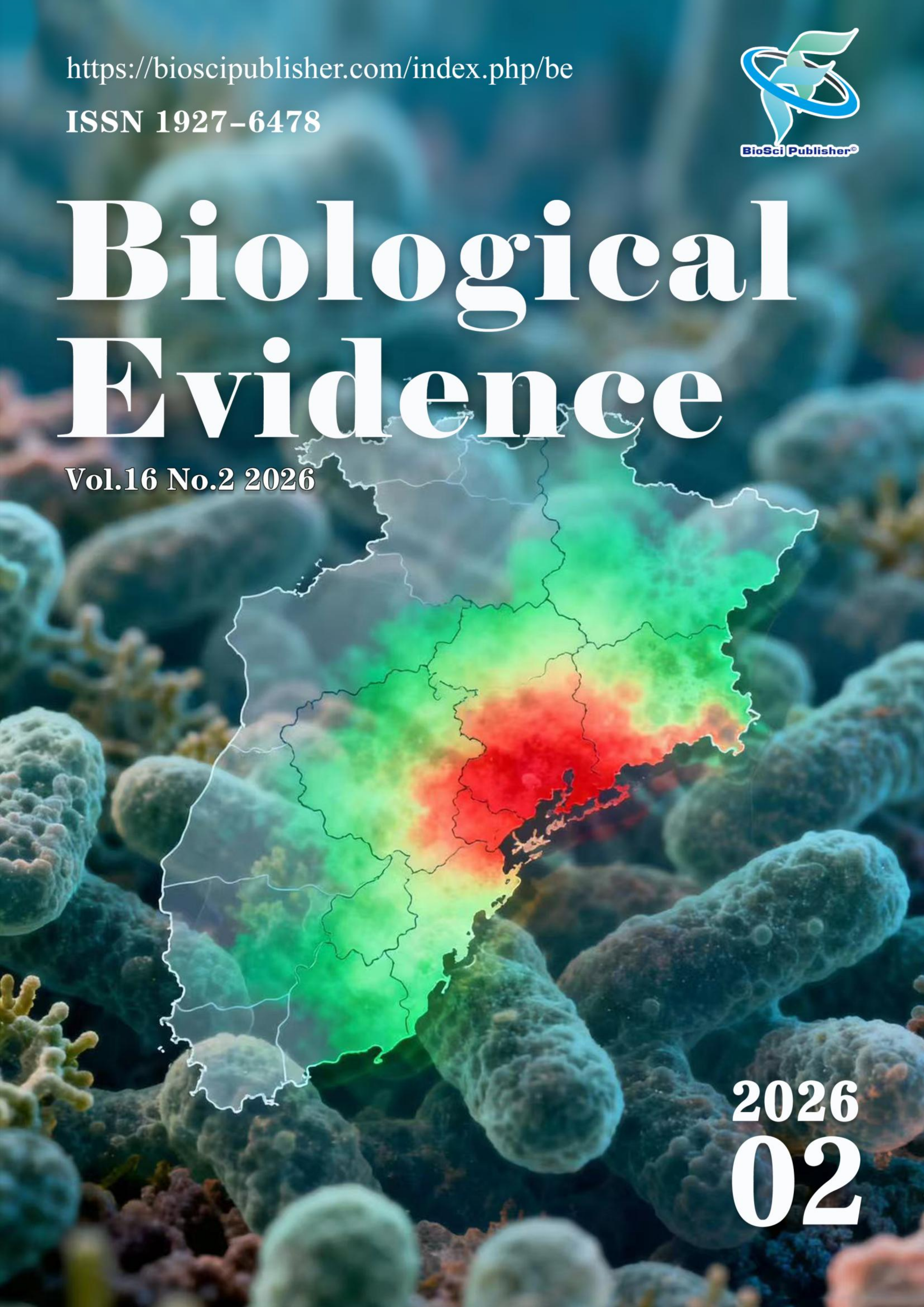

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Latest Content

Review Article Open Access

Evaluation of Fig Varieties for Dual-Purpose Fresh and Dried Use

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Abstract This study takes fig (*Ficus carica* L.) as the research object and conducts a systematic analysis of the overall quality performance of different varieties from the perspective of dual use for fresh consumption and drying. Under a unified evaluation framework, multidimensional comparison and evaluation of germplasm resources were carried out focusing on key indicators for fresh consumption, including fruit appearance traits, pulp quality, flavor characteristics, nutritional composition, and postharvest storage performance, as well as processing suitability indicators such as dry matter content, sugar accumulation, peel characteristics, drying efficiency, and dried product quality. Significant differences were observed among fig varieties in terms of morphology, physiological and biochemical traits, and sensory quality. Some superior genotypes showed synergistic advantages in both fresh quality and drying performance, such as higher soluble solids content, better peel structure, and stronger antioxidant capacity. Combined with optimized cultivation management practices and harvesting strategies, the comprehensive utilization value of dual-purpose varieties can be further improved. This study provides a theoretical basis and practical reference for fig variety selection, resource development, and the integrated development of fresh and dried fig industries.

Keywords Fig (*Ficus carica* L.); Dual-purpose evaluation; Fresh quality; Drying suitability; Variety selection

1 Introduction

Fig (*Ficus carica* L.) is one of the oldest domesticated fruit trees. It is widely grown in Mediterranean and semi-arid regions and is increasingly regarded as a functional food crop. It is easy to propagate vegetatively, can adapt to a wide range of soils and climates, and has long been closely linked with traditional dietary systems. These factors have allowed fig cultivation to continue for thousands of years. Fresh figs contain about 80% water and spoil very easily. Their postharvest storage life is usually only a few days, which limits market circulation and leads to significant losses in areas without adequate cold-chain conditions (Pandidurai et al., 2021). In contrast, drying can significantly concentrate sugars, dietary fiber, minerals, and various phytochemicals, resulting in a stable product with high energy density, longer shelf life, and wider uses. New drying methods, such as slice drying or osmotic dehydration, can improve year-round supply while maintaining or even enhancing phenolic compounds and mineral content (Manjunath et al., 2019).

In terms of nutrition, both fresh and dried figs are rich in carbohydrates, dietary fiber, minerals (especially potassium and calcium), vitamin C, and polyphenolic compounds with antioxidant activity (Sandhu et al., 2023). The drying process significantly increases the concentration of sugars and dietary fiber, and it usually also raises total phenolic content and antioxidant capacity, especially in dark-skinned cultivars and in peel tissues (Yang et al., 2023).

This study evaluates fig cultivars from a dual-purpose perspective. Under uniform conditions, it systematically assesses both fresh consumption and drying performance, focusing on key fruit traits related to fresh use and important indicators related to drying. By comparing different cultivars and selecting those that meet quality requirements for both uses, this study provides a scientific basis for cultivar selection in new and existing orchards. It also promotes the use of locally adapted but underutilized germplasm resources and supports the development of an integrated fresh–dried fig industry chain in Mediterranean-type environments.

2 Germplasm Resources and Variety Selection

2.1 Overview of global fig germplasm diversity

Fig germplasm resources are very rich and widely distributed in the Mediterranean Basin, West Asia, and newly developed cultivation regions. A large pool composed of local varieties, wild types, and introduced cultivars has been characterized using morphological, pomological, biochemical, and molecular tools. The results consistently show high phenotypic and genetic diversity (Sclavounos et al., 2023).

Studies from Tunisia, Morocco, Algeria, Azerbaijan, Greece, and Iran indicate wide variation in tree structure, leaf traits, and especially in fruit size, shape, color, and ripening time. Although most germplasm can be grouped into a few basic fruit shape and skin color categories, the variation within these groups is still significant (Abdelsalam et al., 2019).

Analyses based on molecular markers such as SSR and ISSR show that fig germplasm has abundant alleles, high polymorphism, and relatively weak genetic structure. Most of the variation exists within populations rather than among populations or regions (Ali-Shtayeh et al., 2014; Ahmad and Noori, 2023).

2.2 Selection criteria for candidate varieties

In dual-purpose evaluation, the selection of candidate varieties aims to cover different fruit traits, quality characteristics, and genetic backgrounds. Key focus is placed on fruit-related traits, such as single fruit weight, fruit size, shape, skin color, flesh thickness, and dried fruit weight. These traits show wide variation ranges and high coefficients of variation, and they are important discriminant indicators in multivariate analysis (Khadivi and Mirheidari, 2022).

Morphological and agronomic traits (such as tree vigor, yield, and maturity time) are combined with physicochemical and biochemical indicators (such as soluble solids, acidity, phenolic compounds, flavonoids, and antioxidant capacity). These indicators are closely related to consumer preference and processing suitability (Almeida et al., 2022).

2.3 Description of selected fig varieties

Local varieties from traditional fig-growing regions perform well in fruit size, dried fruit weight, and sensory quality, and they are important genetic resources for breeding. Among North African germplasm, some local varieties have large, nearly spherical fruits, attractive skin color, and high sugar content, making them suitable for both fresh consumption and drying (Hssaini et al., 2019). Germplasm from the Eastern Mediterranean region includes types with relatively large fruits, diverse skin colors, and good overall quality, showing a wide range of phenotypic variation.

Introduced varieties such as “Brown Turkey” have been more systematically studied in terms of growth characteristics, yield, fruit traits, and nutritional quality. Some of these varieties show strong performance in combined morphological and biochemical evaluations (Almeida et al., 2022). The combination of local and introduced varieties reflects both the long-term diversification of figs and their current commercial value.

3 Fresh Consumption Evaluation Indicators

3.1 Fruit appearance traits (size, shape, peel color)

In the fresh market, figs must first meet consumers’ visual expectations. Fruit size and weight are key commercial evaluation criteria because they directly affect grading and market attractiveness. There are large differences in average fruit weight among varieties; for example, genotypes such as ‘Banane’, ‘Brown Turkey’, and ‘San Martino’ usually produce significantly larger fruits (Mahmoudi et al., 2018) (Figure 1). Fruit shape (length-to-width ratio) and ostiole characteristics are also included in standardized description systems, as they influence visual appeal, handling convenience, and safety (e.g., susceptibility to insect or pathogen entry) (Tikent et al., 2025).

Peel color is the most direct indicator reflecting varietal characteristics and maturity. Light- and dark-colored varieties can be clearly distinguished, and their color parameters (L*, C*, h°) show strong varietal dependence.

Dark-colored varieties usually have lower hue angle (h°) and higher contents of anthocyanins and phenolic compounds, while light-colored varieties show higher brightness (L*) and chroma (C*) (Hssaini et al., 2020). Changes in peel and pulp color are also among the most sensitive indicators of ripeness and are often used together with firmness to determine the optimal harvest time.

Figure 1 Photographs of the studied fig cultivars (Original, 2015) (Adopted from Mahmoudi et al., 2018)

3.2 Flesh quality (texture, juiciness, seed content)

The acceptance of fresh figs largely depends on their texture, especially flesh firmness and juiciness. Firmness is commonly used as an important indicator of harvest timing and maturity. Fruits harvested at a higher maturity stage (i.e., "tree-ripe") are usually softer, but when firmness is still sufficient to withstand transport, they are more preferred by consumers.

Professional sensory evaluation usually includes firmness, juiciness, graininess, stickiness, and smoothness. These characteristics vary with cultivar and maturity level. Fruits that are not fully ripe usually show higher compression force and thicker skin, giving a firmer perception, sometimes accompanied by bitterness or astringency. In contrast, fruits at higher maturity are juicier and softer.

Seed content and the perception of achenes are also important factors. Sensory evaluation often scores seed presence and adhesion, as excessive seed content may negatively affect mouthfeel. Differences among varieties in pulp thickness and cavity size influence the pulp proportion and juiciness (Mahmoudi et al., 2018).

3.3 Flavor characteristics (sugar–acid ratio, aroma components)

Fig flavor results from the combined effects of sugars, organic acids, phenolic compounds, and volatile substances. Soluble solid content (SSC) and titratable acidity (TA) are commonly used indicators. The SSC:TA ratio (maturity index, MI) is closely related to perceived sweetness and overall acceptance (Pereira et al., 2020). Tree-ripe fruits usually have higher SSC and lower TA, and SSC is often more strongly correlated with consumer preference than TA.

Descriptive sensory studies show that different varieties have unique aroma profiles, which can be described by attributes such as "fruity," "melon-like," "berry-like," "citrus-like," and "honey-like" (King et al., 2012). Fruits with lower maturity often show “green” and astringent notes, while those at higher maturity present stronger sweetness and flavor intensity.

Instrumental analysis (SPME–GC–MS) shows that fig aroma consists of a complex mixture of volatile compounds, including alcohols, aldehydes, esters, and terpenes. Key compounds such as hexanal, (E)-2-hexenal, and limonene contribute significantly to the aroma of fresh figs (Gündeşli et al., 2024). Principal component analysis often indicates that the maturity index (MI) and pulp color parameters are important predictors of sensory quality.

3.4 Nutritional composition (sugars, vitamins, phenolic compounds)

Fresh figs are characterized by relatively high carbohydrate content, especially glucose and fructose, which dominate in both peel and pulp and vary among cultivars. SSC reflects both sugar accumulation and water content and is a core indicator of fresh quality.

In addition, figs are rich in vitamin C, minerals (especially potassium and calcium), dietary fiber, and small amounts of protein, with significant differences among varieties and tissues (Maatallah et al., 2024).

In recent years, phenolic content and antioxidant activity have gradually been included in quality evaluation systems. This is particularly important for dark-skinned varieties, whose peels usually contain higher levels of phenolic compounds and show stronger antioxidant capacity.

3.5 Shelf life and postharvest performance

For fresh consumption, shelf life is a key evaluation indicator because figs have high moisture content and soften easily, making them highly perishable fruits. Postharvest performance mainly includes weight loss rate, firmness retention, color stability, decay incidence, and the maintenance of SSC and bioactive compounds during storage (Byeon and Lee, 2020).

There are differences among varieties in maintaining firmness and external quality. Varieties with higher initial firmness can be harvested at higher maturity while still maintaining good transport tolerance.

Postharvest treatments such as modified atmosphere packaging (MAP) and UV-C treatment can significantly extend shelf life. For example, under low-temperature conditions, combining UV-C with MAP can effectively maintain fruit firmness, reduce decay rate, and preserve good appearance (Souza et al., 2022). Cold storage can also alter metabolite composition, indicating that different varieties respond differently to storage conditions.

4 Evaluation Indicators of Drying Suitability

4.1 Dry matter content and moisture characteristics

The initial dry matter content determines how much water needs to be removed and has a clear effect on drying time, energy consumption, and final texture. The target moisture content of safe dried fig products is usually around 18%~24% (wet basis), which corresponds to a relatively low water activity and helps long-term storage (Pandidurai et al., 2021). Varieties or treatments with higher solid content can reach this target moisture faster and usually show a lower dehydration ratio.

Moisture loss generally follows thin-layer drying kinetics and is mainly in the falling-rate period. Effective moisture diffusivity and equilibrium moisture content are often used to compare drying behavior among different varieties and product forms. Osmotic pre-dehydration and sugar solution treatments can remove part of the water before drying and make the initial moisture more consistent, which improves process control and helps retain nutrients.

4.2 Sugar accumulation and caramelization potential

High total soluble solids (TSS) and sugar contents (glucose, fructose, sucrose) are important for achieving proper sweetness, water activity, and texture in dried figs. During drying, sugars become concentrated, and TSS can increase to about 30~35 °Brix or even higher (Villalobos et al., 2016).

Pre-treatments that maintain or increase sugar content can improve flavor and consumer acceptance. High sugar levels also promote Maillard reactions and caramelization, which can help form desirable flavors if controlled properly. However, excessive browning and sugar crystallization may reduce product quality.

4.3 Peel thickness and crack resistance

Peel properties affect mechanical strength and surface quality during dehydration. A peel with good elasticity and integrity helps maintain fruit structure, reduces cracking, and lowers contamination risk during drying (Lachtar et al., 2022). In contrast, fragile peels are more likely to crack or show excessive browning, which reduces market value.

Color stability (L*, a*, b*, ΔE) is commonly used to evaluate peel quality. Compared with natural sun drying, controlled drying systems are better at maintaining brightness and color uniformity (Zare and Jalili, 2020). Pre-treatments such as sulfite treatment or osmotic treatment can further reduce browning, but their effectiveness depends on the variety and processing conditions.

4.4 Drying efficiency and dehydration rate

Drying efficiency depends not only on the drying method but also on variety characteristics, such as fruit size and composition. Artificial and assisted drying systems can usually shorten drying time to 1-3 days, while traditional sun drying takes much longer (Nagaraja et al., 2016).

Pre-treatments like osmotic dehydration or soaking can increase effective moisture diffusivity and speed up water removal. Indicators such as effective moisture diffusivity, activation energy, dehydration ratio, and energy consumption are widely used to evaluate drying performance.

4.5 Quality of dried products (texture, color, flavor, and storage stability)

The final product quality reflects a combination of physical, chemical, and sensory properties. The texture should remain soft and chewy, and proper pre-treatment and drying methods can improve hardness and rehydration capacity (Gençdağ et al., 2021).

Color is an important commercial attribute, and products with lighter and more uniform color are usually preferred. Controlled drying systems are better than natural sun drying in maintaining color. Appearance, aroma, and taste are the main factors affecting consumer acceptance.

Storage stability depends on maintaining low moisture content and low water activity while limiting oxidation and microbial growth. Properly processed figs can be stored for several months, although quality gradually declines over time (Dumitru, 2018). Advanced preservation methods, such as coating treatments and optimized drying–storage combinations, can further extend shelf life and maintain product quality.

5 Comparative Evaluation of Dual-Purpose Performance of Fig Varieties for Fresh Consumption and Processing

5.1 Comprehensive evaluation model and scoring system

For fresh figs, a weighted evaluation system is usually applied to rank eating quality, including fruit size, shape, color, SSC (soluble solid content), acidity, and sensory attributes (Prgomet et al., 2021). For dried or processed products (such as dried fig slices and osmo-dehydrated figs), indicators like TSS (total soluble solids), acidity, peelability, absence of defects, color stability, and sensory preference are combined into an overall score (Shishkina et al., 2022). Multivariate statistical methods, such as principal component analysis (PCA), canonical correlation analysis (CCA), and cluster analysis, are often used to integrate morphological, agronomic, and biochemical traits. These methods help classify genotypes into groups and identify materials with superior overall performance.

5.2 Correlation between fresh quality traits and drying traits

Fresh quality traits (such as fruit size, SSC, and peel characteristics) are generally positively correlated with dry matter content, sugars, and phenolic compounds. This suggests that genotypes with good fresh-eating quality may also show stronger flavor and higher functional value after drying (Arvaniti et al., 2019). In Smyrna-type figs, dry fruit weight is significantly correlated with leaf density, fruit length, and fruit width, indicating that vigorous growth and larger fruit size often lead to higher dry yield (Khadivi et al., 2018). Fruit geometry, peel characteristics, sugar content, and phenolic compounds tend to change together, and can be used as key combined indicators to predict dual-purpose potential.

5.3 Screening and identification of high-performance dual-purpose varieties

Dark-skinned varieties from Algeria and Morocco show good fruit traits, high consumer acceptance, and relatively high levels of phenolic compounds and antioxidant capacity. These varieties are suitable both for fresh consumption and for producing dried products with high nutritional value (Tikent et al., 2022). Some underutilized Italian varieties, such as 'Processotto Nero', 'Natalese Nera', and 'Verde di Natale', perform well in fruit weight, TSS, peelability, and maturity time. After processing into dried fig slices, they also receive high sensory scores, indicating good processing adaptability as well as good fresh-eating quality (Ferrara et al., 2023) (Figure 2). Varieties ranked highly in comprehensive evaluations (such as 'Bursa Siyahı', 'Yediveren', elite local genotypes from Turkey and Bangladesh, and 'Mlouki' and 'Assal') are also considered important dual-purpose candidates when drying conditions are available (Maatallah et al., 2024).

Figure 2 Drying process and product transformation of underutilized local fig cultivars into fig disks (Adapted from Ferrara et al., 2023)

5.4 Trade-off between fresh quality and drying adaptability

Traits preferred in the fresh market (such as easy peeling and obvious skin cracking) may increase the risk of damage during sun drying or storage, while crack-free skin is more favorable for dried product quality. Highly mature fruits with high SSC and soft texture have advantages for fresh consumption, but their low mechanical strength makes them more prone to damage during handling and may affect drying uniformity. In contrast, fruits with slightly firmer texture and higher dry matter content are more suitable for dehydration processing (Shishkina et al., 2022). Although higher phenolic content and dark skin color can improve nutritional value, improper control during drying may intensify browning (Uslu et al., 2024).

6 Case Study of Dual-Purpose Fig Varieties

6.1 Evaluation of representative fig varieties

'Brown Turkey' is generally regarded as an early-bearing and high-yielding variety, showing medium to relatively high productivity along with desirable fresh fruit quality. Its fruits are of moderate size, have relatively high soluble solids content, and perform well in consumer evaluations in terms of flavor and texture (Koly et al., 2024).

Similar integrated morpho-pomological and biochemical assessments have also been applied to local varieties in the Apulia region, such as ‘Processotto Nero’, ‘Natalese Nera’, and ‘Verde di Natale’. Key indicators, including fruit weight, peel color, ease of peeling, total soluble solids (TSS), and ripening time, were systematically recorded prior to processing (Ferrara et al., 2023).

6.2 Performance under fresh consumption conditions

For fresh consumption, ‘Brown Turkey’ demonstrates good fruit traits and nutritional quality, ranking relatively high in multivariate comprehensive evaluations. This is mainly attributed to its favorable flavor, texture, juiciness, as well as its vitamin C content and antioxidant-related properties (Koly et al., 2024). These findings suggest that this variety is more suitable as a stable and reliable option for the fresh fruit market rather than a premium cultivar aimed at extreme sensory quality.

6.3 Drying processing performance and product quality

Studies on the drying of ‘Brown Turkey’ figs indicate that, with appropriate pretreatments—such as soaking in fructose or sucrose solutions and sulfiting-combined with controlled tray drying or oven drying processes, it is possible to obtain dried fig products with a moisture content of about 24% (wet basis). These products can maintain good sugar retention, moderate acidity, mineral content, and relatively high sensory scores, including color, texture, and flavor (Singh and Kaur, 2025). Varieties with better initial fruit characteristics, such as higher fruit weight, better coloration, higher TSS, and easier peeling, tend to perform better in consumer preference evaluations, where appearance and pleasant flavor are the main factors driving acceptance.

7 Cultivation and Management Practices

7.1 Agronomic measures affecting fruit quality

Moderate deficit irrigation can improve the quality and storage life of fresh figs, but excessive water stress reduces gas exchange, promotes leaf drop, and shortens the production cycle (Ammar et al., 2020). Under semi-arid conditions, controlling irrigation at about 85%~95% of crop evapotranspiration (ETc) can optimize yield, water use efficiency, and fruit quality. At the same time, potassium fertilization can partly alleviate water stress (Moura et al., 2023). Integrated water-fertilizer management and balanced application of N-P-K fertilizers can significantly increase yield, fruit size, total soluble solids (TSS), sugar content, and ascorbic acid compared with rainfed or low-input systems (Ali et al., 2025). Pruning intensity and timing (closely related to phenological stages) are also important, helping balance vegetative growth and fruiting, and improving marketable yield and fruit size (Pereira et al., 2017).

7.2 Harvest timing for dual-use optimization

Fig is a climacteric fruit and is highly perishable, so harvest maturity strongly affects quality. Fruits harvested at higher maturity (“tree-ripe”) have higher single fruit weight, soluble solids content (SSC), and SSC:TA ratio, but lower acidity and firmness, and are more acceptable to consumers than those harvested at “commercial maturity” (Crisosto et al., 2010). Under dry conditions in India, the best eating quality usually occurs 7~8 weeks after syconium development. Early harvesting can cause cell structure disorder, while overripe fruits have high water content, poor texture, and are more prone to cracking and decay (Singh et al., 2023). For dual purposes (fresh consumption and processing), fruits for long-distance fresh markets should be harvested at slightly lower maturity, while fully ripe fruits are more suitable for local consumption or drying.

7.3 Regional adaptability and environmental effects

Fig cultivars show strong genotype × environment interaction. Different cultivars vary greatly in yield, earliness, and TSS, so selection should be based on local climate conditions and market timing. Differences also exist among cultivars in photosynthetic efficiency, oxidative stress indicators, and drought tolerance, highlighting the need to match cultivars with irrigation regimes according to local water availability (Ammar et al., 2020). Climate change, including rising temperatures and reduced rainfall, together with pest and disease pressure, has already led to yield decline in some Mediterranean regions (Mellal et al., 2023).

7.4 Pest and disease factors affecting fruit quality

Pests and diseases directly affect fruit marketability and suitability for drying. In tropical field trials, mealybug infestation and ostiole-end cracking significantly reduced fruit quality, and different cultivars showed different levels of susceptibility (Moniruzzaman et al., 2020). Fungal pathogens such as *Diaporthe* spp. can cause leaf blight, branch dieback, and fruit spot, weakening tree vigor and affecting fruit appearance (Nur-Shakirah and Mohd, 2025). In southern Italy, fig decline has been identified as a disease complex caused by multiple factors, including Botryosphaeriaceae, Fusarium species, and bark beetles, characterized by cankers, vascular discoloration, wilting, and significant yield loss (Habib et al., 2025).

8 Challenges and Future Research Directions

8.1 Limitations of current evaluation methods

At present, most evaluations mainly focus on morphological traits and fruit characteristics (such as fruit size, color, weight, and soluble solids content, SSC), as well as simple multivariate ranking. These studies are often limited to a single region or specific climatic conditions. Drying properties, postharvest performance, and storage responses are rarely integrated with field data, although cold storage studies have shown that different cultivars exhibit significant quality differences during storage (Byeon and Lee, 2020). Molecular diversity studies (such as ISSR, SSR, and iPBS) are usually not well connected with detailed fruit quality phenotyping, which limits their direct application in breeding selection (Uçer et al., 2025).

8.2 Breeding needs for dual-purpose trait improvement

Many screening studies have identified superior genotypes with large fruit size, high SSC, rich bioactive compounds, or strong drought resistance. However, these traits are rarely integrated into systematic breeding programs. Wild species, local varieties, and underutilized germplasm resources show wide phenotypic and genetic variation, and they have the potential to develop ideal dual-purpose types (for both fresh consumption and processing). However, they are mainly used for resource characterization rather than systematic hybrid utilization (Elmeknassia et al., 2025). Future breeding should not only improve fresh fruit quality but also focus on key traits such as high dry matter content, peel characteristics, ostiole size, and stress resistance (Aljane et al., 2018).

8.3 Role of genomics and phenotyping technologies

The availability of chromosome-level fig genome assemblies and the development of high-density molecular markers make it possible to link SNPs and candidate genes with traits such as fruit size, sugar content, acidity, bioactive compounds, and drought response regulatory networks (e.g., NAC transcription factor FcJA2) (Ren et al., 2025). Studies based on SSR, ISSR, and iPBS have shown high genetic diversity within populations and weak geographic differentiation, providing a strong foundation for marker-assisted selection (Qurbanova et al., 2025). Future research should combine these molecular markers with standardized and high-throughput evaluations of fruit quality, stress physiology indicators, and drying suitability.

Author Contributions

The author conducted this study, including literature review, data analysis, and the drafting and revision of the manuscript. The author has read and approved the final version of the manuscript.

Conflict of Interest Disclosure

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

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Research Insight Open Access

Nitrogen Management for High-Yield and High-Capsaicin Chili Production

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Abstract Chili pepper (*Capsicum* spp.) is an important economic crop, and its yield and capsaicin content are directly related to product quality and industrial value. Nitrogen is a key nutrient affecting chili growth, development, and secondary metabolism. Its application rate and form not only determine yield level, but also play a crucial role in regulating capsaicin synthesis. This paper systematically reviews the dynamics of nitrogen in chili cultivation systems, its uptake mechanisms, and its effects on plant growth, yield formation, and nitrogen use efficiency. It focuses on the metabolic pathways, key enzyme activities, and gene expression mechanisms involved in nitrogen-regulated capsaicin biosynthesis. Studies show that an appropriate nitrogen supply and a reasonable NH_4^+:NO_3^- ratio can promote plant growth and increase yield while enhancing the accumulation of capsaicin and related metabolites. In contrast, both excessive and insufficient nitrogen disrupt the balance between yield and quality. In addition, practices such as integrated water–fertilizer management, controlled-release fertilizers, split application, and multi-nutrient coordinated management can improve nitrogen use efficiency and reduce environmental risks. In the future, combining precision agriculture technologies with genetic improvement strategies will help achieve coordinated development of high yield, high quality, and ecological sustainability in chili production.
Keywords Chili pepper; Nitrogen management; Capsaicin; Yield; Nitrogen use efficiency

1 Introduction

Chili pepper (*Capsicum* spp.) is an important vegetable and spice crop widely cultivated around the world. Its main characteristics include pungency, color, flavor, and health-promoting functions (Duranova et al., 2022). In addition to its traditional food value, chili has become a key raw material in multiple industries such as food, nutraceuticals, pharmaceuticals, and cosmetics. The demand for high yield and stable pungency is increasing.

Chili fruits are rich in various vitamins (A, C, E, B6, and K), minerals, carotenoids, flavonoids, polyphenols, and capsaicinoids, which give them high nutritional value and functional properties (Bal et al., 2022; Ali et al., 2025). Capsaicin, as the main capsaicinoid compound, is the primary source of pungency in chili and has a wide range of biological activities, including antioxidant, anti-inflammatory, analgesic, anti-obesity, antimicrobial, and anticancer effects. It also has positive effects on cardiovascular and metabolic health (Hernández-Pérez et al., 2020; Faisal and Mustafa, 2025).

In chili production, nitrogen supply level and its form affect leaf chlorophyll content, photosynthetic capacity, biomass accumulation, and fruit yield. However, excessive nitrogen may delay maturity, reduce pungency, lower quality, and increase the risk of environmental pollution. Optimizing nitrogen application has been shown to improve nitrogen use efficiency while maintaining or increasing yield and reducing resource waste (Zamljen et al., 2023). In addition to its effects on primary growth, nitrogen also regulates secondary metabolism. Nitrogen application rate and nitrogen form (ratio of ammonium to nitrate) can influence the content of capsaicin and dihydrocapsaicin, the activity of related enzymes (such as PAL and capsaicin synthase), and the expression of genes involved in capsaicinoid biosynthesis.

This study evaluates nitrogen management strategies for achieving both high yield and high capsaicin content in chili production. It focuses on the effects of nitrogen rate and nitrogen form on plant growth, yield, and capsaicinoid accumulation. The study explores how different nitrogen supply levels and nitrogen sources affect plant performance, capsaicin and related compounds, and key metabolic indicators. The objective is to provide practical agronomic recommendations to improve fertilizer use efficiency, support environmental sustainability, and meet the quality requirements of the chili food and pharmaceutical industries.

2 Nitrogen Dynamics in Chili Cultivation Systems

2.1 Forms of plant-available nitrogen (NH_4^+ and NO_3^-)

In chili cultivation, plant-available nitrogen mainly exists in the forms of ammonium nitrogen (NH_4^+) and nitrate nitrogen (NO_3^-). Both forms can support plant growth, but NO_3^- is usually the main form absorbed by chili roots, especially in drip irrigation or fertigation systems where nitrification is active. Under these conditions, nitrate nitrogen has high mobility in the soil solution. In contrast, ammonium nitrogen has lower mobility and a shorter residence time; it can act as a direct nitrogen source and also as a substrate for nitrification (Ferrón-Carrillo et al., 2021).

The relative proportion of NH_4^+ and NO_3^- in the rhizosphere is strongly influenced by several factors, including fertilizer type (such as urea, nitrate fertilizers, and ammonium fertilizers), application rate, soil adsorption properties, and irrigation method (Bharati et al., 2023). Compared with supplying nitrate alone, an appropriate NH_4^+:NO_3^- ratio can promote root development, nitrogen accumulation, and improvement in fruit quality, including increased capsaicin content (Zhang et al., 2019).

2.2 Soil nitrogen transformation processes (mineralization, nitrification, denitrification)

Nitrogen transformation processes in soil determine the supply of NH_4^+ and NO_3^- over time. Organic nitrogen from organic fertilizers, crop residues, and soil organic matter is converted into NH_4^+ through mineralization, which enriches the pool of plant-available nitrogen and supports a stable nitrogen supply under organic or integrated nutrient management systems (Horel et al., 2019; Mancinelli et al., 2019).

After that, NH_4^+ is oxidized into NO_3^- through nitrification. This process is mediated by microorganisms and is most active under good aeration, suitable moisture, and near-neutral pH conditions. In chili systems, this explains why NO_3^--N is dominant in the root zone and closely related to yield.

Under waterlogged or anaerobic conditions, NO_3^- can be reduced to gaseous nitrogen forms (N_2O and N_2) through denitrification, leading to nitrogen loss and reduced fertilizer efficiency (Das et al., 2024). Excessive nitrogen application and poor irrigation management can result in high accumulation of mineral nitrogen in soil, low plant uptake efficiency (about 10% of applied nitrogen), serious nitrate leaching, and large nitrogen losses from the soil–plant system.

2.3 Nitrogen uptake mechanisms in *Capsicum* species

Nitrogen uptake in *Capsicum* species depends on the coordination between root physiological functions and transport systems. Roots absorb NH_4^+ and NO_3^- from the rhizosphere and redistribute nitrogen to aboveground parts and fruits. Root systems adjust their length, surface area, and branching according to nitrogen availability. Aerated drip irrigation can significantly increase root length and activity, thereby enhancing nitrogen uptake capacity, and this is positively correlated with chili yield.

Chili plants show clear patterns of nitrogen distribution, with total nitrogen mainly allocated to leaves, seeds, and reproductive organs. This provides a basis for capsaicin biosynthesis, which relies on amino acid precursors. Nitrogen uptake efficiency and internal utilization efficiency vary among cultivars and under different water–fertilizer combinations.

Studies using ^{15}N isotopes show that, with suitable cultivar and management matching, nitrogen use efficiency can remain relatively high even under low nitrogen or deficit irrigation conditions (Zamljen et al., 2022). Appropriate nitrogen levels and balanced NH_4^+:NO_3^- ratios can increase total nitrogen accumulation in roots, stems, leaves, and fruits. They also enhance the activity of key enzymes such as glutamine synthetase (GS) and glutamate synthase (GOGAT), as well as the expression of nitrogen metabolism-related genes, which together promote yield formation and the synthesis of secondary metabolites.

2.4 Environmental factors affecting nitrogen availability

Environmental conditions and management practices play an important role in regulating nitrogen availability in chili fields. Soil pH, temperature, moisture, and electrical conductivity (EC) all influence microbial mineralization and nitrification processes, as well as the balance between NH_4^+ and NO_3^- and nitrogen loss pathways (Abd-Hamid et al., 2023).

In organic curly chili production systems, mulching methods and weather factors significantly affect soil nitrogen content. Non-mulched and organic bamboo mulch treatments can maintain higher soil nitrogen levels, while plastic mulch tends to result in lower levels. At the same time, EC is a strong positive predictor of soil nitrogen, while lower pH and higher temperatures tend to reduce nitrogen availability (Wulan et al., 2025).

Irrigation methods influence nitrogen use by affecting soil aeration and nitrogen distribution. For example, aerated drip irrigation can improve the spatial uniformity of NO_3^--N, enhance root activity, and increase nitrogen uptake. Compared with conventional drip irrigation, it significantly improves yield and fruit quality (Lei et al., 2024).

There is also an interaction between salinity and nitrogen application. A moderate increase in nitrogen can partly reduce the effects of salt stress, but excessive nitrogen application can increase soil salinity, which suppresses early plant growth and reduces yield (Yasuor et al., 2017).

3 Effects of Nitrogen on Chili Growth and Yield Formation

3.1 Effects on vegetative growth and biomass accumulation

Nitrogen significantly promotes the vegetative growth and dry matter accumulation of chili (*Capsicum*). With increasing nitrogen application, plant height, leaf number, branch number, leaf area, and aboveground biomass generally increase until reaching an optimal level. Beyond this level, excessive nitrogen may inhibit growth or cause toxicity symptoms (Da Silva et al., 2020; Mahmud et al., 2020; Nisa et al., 2024). Chili biomass assimilation is sensitive to nitrogen fertilization, and nitrogen supply affects total dry matter of shoots and fruits by regulating leaf area development. Integrated nutrient management and the use of organic fertilizers (such as farmyard manure, vermicompost, and poultry manure) combined with mineral nitrogen can further enhance vigorous vegetative growth. In contrast, insufficient or deficient nitrogen supply limits chlorophyll formation and canopy expansion (Biratu et al., 2021).

3.2 Effects on flowering, fruit set, and fruit development

Nitrogen supply plays an important role in reproductive development by regulating flowering intensity, fruit set, and fruit growth. Adequate nitrogen promotes early flower bud differentiation and increases the number of flowers, leading to higher fruit number per plant, greater fruit length, higher single fruit weight, and increased total yield. In chili and 'Anaheim' sweet pepper, higher nitrogen levels can promote early flower bud formation, but excessive or frequent nitrogen application reduces mature fruit yield and may even lead to early termination of the fruiting period (Payero et al., 1990). Excess nitrogen often stimulates excessive vegetative growth, suppresses assimilate allocation to reproductive growth, and results in lower fruit set and reduced yield, although plants appear vigorous. Appropriate nitrogen levels (e.g., 100~225 $kg{\cdot}N{\cdot}ha^{-1}$, depending on the cultivation system) improve fruit length, fruit number, and marketable yield, whereas nitrogen deficiency reduces flower number and fruit size (Timilsina and Khanal, 2024).

3.3 Nitrogen Use Efficiency (NUE) in chili production systems

Under conventional high nitrogen fertilization or fertigation conditions, nitrogen use efficiency (NUE) in chili is usually low. A large amount of nitrate nitrogen remains in the soil or substrate, while only a limited proportion is absorbed by plants and converted into biomass and fruits. In substrate cultivation and drip irrigation systems for sweet pepper, yield increases within a certain range as nitrogen application increases. However, when nitrogen input exceeds crop demand, NUE declines continuously and nitrate accumulation increases (Chemweno et al., 2025). Moderate nitrogen application combined with slight water deficit can improve NUE and water use efficiency without significantly reducing yield. Field experiments on processing chili and studies based on critical nitrogen dilution curves show that when the initial soil nitrogen level is high, a relatively low nitrogen rate (about

120 kg N ha^{-1}) is sufficient to maintain yield. This indicates that fertilizer input and nitrate leaching can be reduced while maintaining productivity (Tang et al., 2023) (Figure 1).

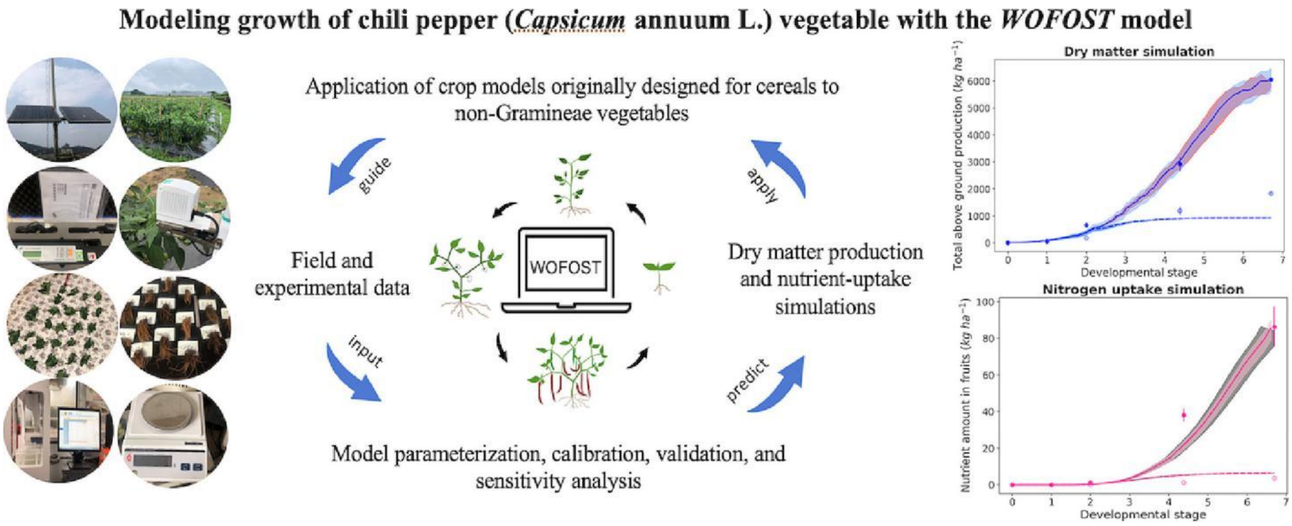

Figure 1 Growth simulation of chili pepper (*Capsicum annuum* L.) based on the WOFOST model and dynamic analysis of dry matter accumulation and nitrogen uptake (Adapted from Tang et al., 2023)

3.4 Yield response under different nitrogen application levels

The yield response of chili and sweet pepper to nitrogen typically follows a curvilinear pattern. As nitrogen application increases from zero to an optimal range, yield gradually increases; beyond this range, yield stabilizes or even declines. Field and pot experiments show that maximum or near-maximum yields can be achieved at 100~230 kg•N•ha^{-1} for chili, 150~225 kg•N•ha^{-1} for greenhouse sweet pepper, and about 120 kg•N•ha^{-1} for open-field processing chili. Further increases in nitrogen application do not result in additional yield gains (Han et al., 2021; Subedi et al., 2023). Excessive nitrogen application (>230~300 kg•N•ha^{-1} or high-concentration nutrient solutions) can reduce yield, shorten the fruiting period, or cause leaf toxicity, indicating that excess nitrogen is not only agronomically inefficient but also environmentally harmful. Results based on the WOFOST-Chili model and multi-objective optimization of water and nitrogen show that extremely high nitrogen levels cannot simultaneously achieve maximum yield, highest NUE, and optimal environmental benefits. Instead, moderate nitrogen application represents the best compromise for high-yield chili production (Vadillo et al., 2024).

4 Regulation of Capsaicin Biosynthesis by Nitrogen

4.1 Overview of capsaicin biosynthetic pathways

Capsaicin biosynthesis originates from the convergence of two metabolic pathways. One is the phenylpropanoid pathway, which provides the aromatic structural unit vanillylamine derived from phenylalanine. The other is the branched-chain fatty acid pathway, which supplies the C9 acyl group from valine or leucine.

In the phenylpropanoid pathway, phenylalanine is first deaminated to form cinnamic acid, which is further converted into ferulic acid derivatives, and then into vanillin and vanillylamine. At the same time, branched-chain amino acids are converted into fatty acid CoA thioesters. The final step is an acylation reaction, in which an acyltransferase links vanillylamine with fatty acyl-CoA to form capsaicin and related capsaicinoids. This process mainly occurs in the placenta tissue of the fruit.

4.2 Key enzymes and genes involved in capsaicin synthesis

During capsaicin biosynthesis, the key enzymes include phenylalanine ammonia-lyase (PAL), cinnamate 4-hydroxylase (C4H), 4-coumarate CoA ligase (4CL), hydroxycinnamoyl transferase (HCT), and caffeoyl-CoA O-methyltransferase (COMT) in the phenylpropanoid branch, as well as branched-chain amino acid aminotransferase (BCAT), ketoacyl synthase (KAS), and acyl-CoA ligase (ACL) in the fatty acid branch (Kabita et al., 2019).

The BAHD family acyltransferase encoded by Pun1/AT3 catalyzes the final condensation reaction and is a key factor in pungency formation. Loss-of-function alleles of this gene result in the absence of capsaicin production (Egan et al., 2019). The putative aminotransferase pAMT is responsible for providing vanillylamine and shows strong developmental stage and tissue-specific regulation.

In extremely pungent cultivars, genes such as Pun1, pAMT, KAS, and BCAT are upregulated in both placenta and pericarp tissues, significantly increasing capsaicin content in the whole fruit. The transcription factor MYB31 (Cap1/Pun3) acts as a master regulator that activates genes involved in capsaicin biosynthesis and is an important genetic basis for extreme pungency in C. chinense (Zhu et al., 2019).

4.3 Effects of nitrogen levels on capsaicin accumulation

Nitrogen supply influences the capsaicin biosynthetic pathway by regulating precursor availability, enzyme activity, and gene expression. Moderate nitrogen application can increase total phenolic compounds (precursors), enhance the activity of PAL and capsaicin synthase, and upregulate the expression of genes such as PAL, AT3 (Pun1), 4CL, C4H, COMT, pAMT, and HCT, thereby achieving the highest capsaicin content.

In contrast, both low and excessive nitrogen levels reduce PAL activity, precursor content, and related gene expression, while increasing the activity of competing phenolic pathways and degradation enzymes such as peroxidase (POD) and polyphenol oxidase (PPO).

Similar results have been observed in hydroponically grown C. frutescens. As the nutrient solution (nitrogen) concentration increases, capsaicin content first rises to an optimal range but decreases beyond this point, indicating that excessive nitrogen may cause toxicity or shift metabolism toward basic growth processes (Rahim et al., 2024).

In habanero pepper, capsaicin content is highest under nitrogen stress, decreases significantly after a small nitrogen supply, and increases again at higher nitrogen levels, suggesting a complex nonlinear response to nitrogen (Medina-Lara et al., 2008). Proper NPK or organic nitrogen management can simultaneously improve yield and capsaicin/dihydrocapsaicin content, although the effects depend on cultivar differences (Hammam et al., 2020; Stan et al., 2021) (Table 1).

4.4 Trade-off between yield and capsaicin content

Nitrogen creates a trade-off relationship among vegetative growth, yield, and capsaicin accumulation, rather than a simple opposition. Moderate nitrogen application usually promotes fruit size, placenta development, and yield, while maintaining relatively high capsaicin levels. For example, applying 562.5 kg/ha urea or using a moderate EC level of AB fertilizer can achieve this balance (Rahim et al., 2024).

Excessive nitrogen tends to stimulate vegetative growth and fruit development, but may reduce capsaicin content due to dilution effects, decreased PAL and capsaicin synthase activity, or increased allocation of metabolites to competing phenolic and lignin pathways.

On the other hand, severe nitrogen limitation can induce higher capsaicin accumulation in some genotypes, but this is usually accompanied by reduced yield. By optimizing nitrogen application rates and maintaining balanced nutrient management (including moderate deficit fertilization in some highly pungent cultivars), it is possible to maintain or even increase capsaicin content without significant yield loss.

5 Nitrogen Management Strategies for Optimizing Yield and Quality

5.1 Optimal nitrogen application rate and timing

Chili yield and capsaicinoid content show a curvilinear response to nitrogen (N) application, with the optimal level clearly lower than the excessive rates commonly used in practice. In open-field sweet pepper production, the highest yield was obtained at 153~230 kg•N•ha^{-1}. In coastal regions of Bangladesh, 116 kg•N•ha^{-1} was identified as the optimal rate, and no further yield increase was observed at 145 kg•N•ha^{-1} (Nahida et al., 2024).

Table 1 Interaction between cultivar and fertilization on capsaicinoid content and Scoville scale (Adopted from Stan et al., 2021)

Treatment	Capsaicin (C) (mg·g^{-1} d.w.)	Dyhidrocapsaicin (DhC) (mg·g^{-1} d.w.)	Ratio C/DhC	Capsaicinoids (mg·g^{-1} d.w.)	Scoville Heat Units (SHU)
De Cayenne×Ch	0.69 ± 0.04 b	0.37 ± 0.01 bc	1.86 ± 0.06 cdefgh	1.06 ± 0.06 c	17066 ± 886.72 c
De Cayenne × O + Ch	0.39 ± 0.02 fghi	0.28 ± 0.02 def	1.40 ± 0.11 hi	0.67 ± 0.02 hi	10787 ± 245.93 hi
De Cayenne × O	0.47 ± 0.03 def	0.23 ± 0.01 fgh	2.05 ± 0.16 cde	0.70 ± 0.03 ghi	11270 ± 491.86 ghi
De Cayenne × Ct	0.52 ± 0.02 cd	0.33 ± 0.01 cd	1.58 ± 0.05 efghi	0.85 ± 0.03 ef	13685 ± 483.00 ef
Traian 2 × Ch	0.56 ± 0.02 c	0.41 ± 0.01 b	1.37 ± 0.03 i	0.97 ± 0.03 cd	15617 ± 464.77 cd
Traian 2 × O + Ch	0.34 ± 0.01 ghij	0.16 ± 0.01 ijk	2.13 ± 0.07 bc	0.50 ± 0.02 jk	8050 ± 245.93 jk
Traian 2 × O	0.35 ± 0.01 ghij	0.26 ± 0.01 efg	1.35 ± 0.04 i	0.61 ± 0.02 ij	9821 ± 278.86 ij
Traian 2 × Ct	0.41 ± 0.02 efgh	0.29 ± 0.01 def	1.42 ± 0.07 ghi	0.7 ± 0.02 ghi	11270 ± 245.93 ghi
Turkish × Ch	0.33 ± 0.01 hij	0.13 ± 0.01 jk	2.55 ± 0.16 ab	0.46 ± 0 k	7406 ± 0.00 k
Turkish × O + Ch	0.27 ± 0.01 j	0.13 ± 0.01 jk	2.09 ± 0.12 bcd	0.40 ± 0.01 k	6440 ± 92.95 k
Turkish × O	0.29 ± 0.01 j	0.11 ± 0.01 k	2.65 ± 0.12 a	0.40 ± 0.01 k	6440 ± 161.00 k
Turkish × Ct	0.32 ± 0.01 ij	0.19 ± 0.01 hij	1.69 ± 0.07 cdefghi	0.51 ± 0.02 jk	8211 ± 245.93 jk
Sigaretta × Ch	0.31 ± 0.01 ij	0.19 ± 0.02 hij	1.66 ± 0.17 cdefghi	0.50 ± 0.01 jk	8050 ± 185.91 jk
Sigaretta × O + Ch	0.42 ± 0.02 efg	0.21 ± 0.02 ghi	2.02 ± 0.12 cdef	0.63 ± 0.04 i	10143 ± 580.49 i
Sigaretta × O	0.39 ± 0.01 fghi	0.24 ± 0.01 fgh	1.63 ± 0.07 defghi	0.63 ± 0.02 i	10143 ± 245.93 i
Sigaretta × Ct	0.49 ± 0.01 cde	0.26 ± 0.01 efg	1.89 ± 0.08 cdefg	0.75 ± 0.02 fgh	12075 ± 245.93 fgh
Jovial × Ch	0.83 ± 0.01 a	0.53 ± 0.02 a	1.57 ± 0.06 efghi	1.36 ± 0.02 a	21896 ± 371.81 a
Jovial × O + Ch	0.76 ± 0.01 ab	0.48 ± 0.02 a	1.59 ± 0.05 efghi	1.24 ± 0.02 b	19964 ± 278.86 b
Jovial × O	0.45 ± 0.02 def	0.32 ± 0.01 cde	1.41 ± 0.04 hi	0.77 ± 0.02 fgh	12397 ± 371.81 fgh
Jovial × Ct	0.57 ± 0.01 c	0.37 ± 0.01 bc	1.54 ± 0.01 ghi	0.94 ± 0.01 de	15134 ± 185.91 de
Chorbadjiiski × Ch	0.52 ± 0.01 cd	0.33 ± 0.01 cd	1.58 ± 0.02 efghi	0.85 ± 0.02 ef	13685 ± 245.93 ef
Chorbadjiiski × O + Ch	0.42 ± 0.01 efg	0.27 ± 0.01 defg	1.56 ± 0.02 fghi	0.69 ± 0.02 ghi	11109 ± 245.93 ghi
Chorbadjiiski × O	0.44 ± 0.01 def	0.24 ± 0.02 fgh	1.85 ± 0.1 cdefgh	0.68 ± 0.02 hi	10948 ± 322.00 hi
Chorbadjiiski × Ct	0.49 ± 0.01 cde	0.31 ± 0.01 cde	1.58 ± 0.01 efghi	0.80 ± 0.01 fg	12880 ± 185.91 fg

Note: Ch—Chemical; O + Ch—Organic + Chemical; O—Organic; Ct—Control. Along each line, values followed by different letters are significantly different according to the Tukey's test at $p \leq 0.05$; d.w.—dry matter

Greenhouse experiments showed that moderately reducing nutrient solution supply by 20%~40% during the 6 days before harvest could improve nitrogen recovery efficiency and increase capsaicinoid and flavor compound content, while maintaining yield (Wang et al., 2022).

5.2 Split application versus basal application

Split nitrogen application helps synchronize fertilizer supply with crop uptake, reduces leaching losses, and often maintains or even increases yield at equal or lower nitrogen levels. Under saline-alkaline conditions, applying 150 kg•N•ha^{-1} (N150) as ammonium nitrate through multiple fertigation events at key stages (vegetative growth, flowering, and harvesting) significantly improved plant growth, fruit number, and capsaicin content, especially when combined with effective microorganisms (Abdelkhalik et al., 2023).

In chili cultivation with polyethylene mulching in Indonesia, both split soil fertilization and drip fertigation performed better than single basal application, resulting in higher total and marketable yields (Susila and Oktavia, 2020).

Field studies comparing different fertilizer ratios (basal:topdressing = 100:0, 50:50, 30:70) showed that the 50:50 treatment, combined with livestock manure and chemical fertilizers, improved nitrogen use efficiency (NUE) while maintaining yield. In contrast, excessive basal nitrogen (100:0) increased early soil nitrate levels but did not improve yield (Lee et al., 2022).

5.3 Controlled-release fertilizers and fertigation technology

In systems without drip irrigation, controlled-release nitrogen fertilizers can partly replace the effect of split applications. In mulched sweet pepper production, pre-plant application of sulfur-coated urea and polymer-coated urea (90~180 kg•N•ha^{-1}) produced yields comparable to or higher than those achieved with 12 weekly fertigation events, with higher NUE at lower nitrogen rates, especially in coarse sandy soils (Reyes et al., 2008).

In fertigation-based chili production, appropriate fertilization intervals and frequency (e.g., every 3 days, 1~3 times per day) can promote plant growth and increase fruit number, although the effect on individual fruit weight is relatively small (Padmini et al., 2023).

Open-field studies indicate that optimizing the ratio between basal fertilizer and fertigation—by combining slow-release fertilizers or organic-inorganic compound fertilizers with partial fertigation—can maintain yield while reducing soil nitrate accumulation. In addition, short-term reduction of water and fertilizer supply before harvest can improve fruit quality and nutrient harvest index without reducing yield.

5.4 Synergistic management with other nutrients (P, K, and micronutrients)

Proper nitrogen management needs to be coordinated with phosphorus (P), potassium (K), and micronutrients to fully realize yield potential and capsaicinoid accumulation. Application of 75%~100% recommended NPK fertilizer significantly enhanced vegetative growth, yield components, and capsaicin content. The best performance was observed with 100% NPK combined with nano-micronutrients (Fe, Zn, B, Mn, Cu, Mo), which produced significantly higher yield and capsaicin content than the unfertilized control (Ahmed and Abdelkader, 2020).

In semi-arid sandy soils, combining soil fertilization with foliar application (e.g., 50% soil + 50% foliar) significantly increased leaf area, fruit number, fruit weight, and plant NPK nutritional status compared to soil fertilization alone (Hemida et al., 2023).

Compared with unfertilized treatments, integrated use of chemical and organic fertilizers in an NPK system significantly improved yield and capsaicin content, although responses varied among cultivars. Under low phosphorus conditions, mycorrhizal inoculation enhanced N, P, K, and capsaicin content in chili fruits, indicating that proper phosphorus supply and microbial symbiosis can work together with nitrogen to improve pungency and nutritional quality.

Furthermore, an appropriate NH_4^+:NO_3^- ratio (25:75) increased N, P, and K accumulation and capsaicin content by upregulating the GS/GOGAT pathway and genes related to capsaicin biosynthesis (Zhang et al., 2020).

6 Case Studies

6.1 High-yield chili production systems under optimized nitrogen input

Studies in both greenhouse and open-field chili production systems show that high yield does not depend on excessive fertilization, but on moderate and well-matched nitrogen application. In northwest China, sweet pepper grown under drip fertigation achieved the highest or near-highest yield when nitrogen was applied at 150~190 kg•N•ha^{-1} combined with 75%~80% ETc. At the same time, fruit quality remained good, and water and nitrogen use efficiency were significantly improved compared with higher nitrogen and irrigation levels (Xiang et al., 2018).

In subtropical monsoon regions, when soil moisture is maintained at 65%~80% of field capacity and nitrogen is applied at 6 g/plant, green pepper yield can reach about 580~620 g/plant. A slightly lower nitrogen level (3 g/plant) results in the highest water use efficiency (WUE) and nitrogen use efficiency (NUE) (Dai et al., 2022).

By optimizing nitrogen rates and combining them with controlled-release fertilizers or nitrification inhibitors, integrated nitrogen management can further increase yield and nitrogen recovery in open-field chili production. At the same time, nitrogen input can be reduced by about 38% compared with conventional farmer practices (Ma et al., 2022).

6.2 Strategies to improve capsaicin content in specialty chili cultivars

For high-pungency dried chili, a medium urea rate (562.5 kg/ha) can produce the highest capsaicinoid content and yield. This is mainly due to increased placenta biomass, higher total phenol content, enhanced activity of PAL and capsaicin synthase, and upregulation of genes related to capsaicinoid biosynthesis, while the activity of degradation enzymes is reduced (Zhang et al., 2024).

In the cultivar “Longjiao No. 5”, adjusting the NH_4^+:NO_3^- ratio to 25:75 increases capsaicin and dihydrocapsaicin content in the placenta. It also enhances GS/GOGAT enzyme activity and related gene expression, and promotes fruit weight gain (Zhang et al., 2020).

Under low-phosphorus soil conditions, inoculation with mycorrhizal fungi improves the uptake of nitrogen, phosphorus, and potassium, and increases capsaicin content in chili fruits. This provides an effective way to achieve high pungency and high mineral nutrition with lower input (Pereira et al., 2024).

Comparisons between greenhouse and open-field cultivation show that the local piquín variety has significantly higher pungency under greenhouse conditions, indicating that controlled environments play an important role in enhancing capsaicin potential (Díaz-Sánchez et al., 2021).

6.3 Comparative analysis of conventional and precision nitrogen management

Precision water and nitrogen management performs better than traditional high-input and fixed nitrogen application systems in terms of resource use efficiency and environmental outcomes, while maintaining yield.

In greenhouse sweet pepper, long-term drip fertigation experiments show that moderate water and nitrogen combinations (such as 75%~90% ETc and 150~225 kg•N•ha^{-1}) significantly improve yield, water use efficiency (WUE), and nitrogen partial factor productivity compared with the conventional treatment of 105% ETc and 300 kg•N•ha^{-1} (Wang et al., 2022).

A “prescription-adjustment” fertilization system based on crop evapotranspiration (ETc), nitrogen uptake models, and soil NO_3^- monitoring can reduce irrigation by 17% and nitrogen input by 35% without reducing yield. At the same time, nitrate leaching is reduced by about 58% compared with conventional management (Granados et al., 2013).

7 Challenges and Future Perspectives

7.1 Environmental issues (nitrogen leaching and greenhouse gas emissions)

In intensive chili production systems, nitrogen fertilizer is often applied far beyond the actual crop demand, which leads to increased nitrate leaching and N_2O emissions. Evaluations in Southwest China show that chili production has higher global warming potential, eutrophication potential, and acidification potential compared with other vegetable systems. This is mainly related to excessive nitrogen application and low nitrogen use efficiency (NUE). In subtropical chili systems, N_2O emissions increase exponentially with nitrogen input. An application rate of 150 kg•N•ha^{-1} can significantly increase yield, while emissions per unit yield are much lower than at 450 kg•N•ha^{-1} (Zhao et al., 2020). In addition, the use of controlled-release fertilizers and high-efficiency fertilizers can reduce N_2O emissions by 30%~50% while maintaining or even increasing yield (Zhang et al., 2023; Baek et al., 2024).

7.2 Balancing yield and quality in intensive systems

One key challenge is to avoid the trade-off between high yield and high capsaicin content. Moderate nitrogen levels (e.g., about 562.5 kg•urea•ha^{-1} for dry chili, and 153~230 kg•N•ha^{-1} for fresh chili) can maximize both yield and capsaicin content. Both nitrogen deficiency and excess can reduce pungency or limit plant growth. A slight reduction in nutrient supply before harvest can maintain stable yield while increasing capsaicin and flavor compounds, and also improve fertilizer use efficiency. The "high yield-high NUE" model, with slightly lower nitrogen and phosphorus inputs but higher potassium input, achieved a 35% yield increase and significantly reduced environmental impacts (Wang et al., 2018).

7.3 Advances in precision agriculture and smart fertilization technologies

Sensor-based irrigation–fertilization integrated systems and decision support tools are gradually being applied in chili production to achieve precise nitrogen management. Automated water and fertilizer management driven by soil moisture, using 75% of field capacity combined with 125% of the recommended nitrogen rate, significantly improved yield and nutrient use efficiency compared with conventional management (Ningoji et al., 2024). In addition, region-specific recommendation tools (such as Ferads), combined with automated fertilization systems, can produce near-quadratic yield responses. In some cultivars, fertilizer recommendations can be reduced to about 70%~79% without affecting yield (Susila and Suketi, 2023).

7.4 Genetic improvement of nitrogen use efficiency and capsaicin synthesis

Genotypic variation provides a long-term solution for maintaining pungency under reduced nitrogen input. Transcriptome analysis under low-nitrogen conditions shows clear differences between tolerant and sensitive chili genotypes in nitrogen-responsive genes. These genes are involved in photosynthesis, protein metabolism, secondary metabolism, and stress responses, and they are important targets for improving NUE (Wang et al., 2021). In terms of quality, key genes regulating capsaicin biosynthesis and their metabolic pathways (such as AT3/Pun1 and GS/GOGAT-related pathways) respond to nitrogen form and application level. This creates the possibility of breeding or engineering varieties that maintain high capsaicin synthesis under moderate nitrogen conditions. More broadly, biotechnological approaches even consider transferring the capsaicin biosynthesis pathway into other species, highlighting the potential of metabolic engineering to stabilize pungency under different environmental conditions.

Author Contributions

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Conflict of Interest Disclosure

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

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Disease-Resistant Tomato Cultivars for High-Quality Production

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Abstract Tomato (*Solanum lycopersicum* L.) is an important economic and nutritional crop worldwide, but its production has long been heavily constrained by various diseases. This study reviews the major types of diseases affecting tomato cultivation, with a focus on the genetic basis of disease resistance in tomato. It summarizes the main strategies currently used in resistance breeding. Through case analysis of typical resistant varieties and multi-resistant hybrids, it further shows that disease resistance, yield stability, and fruit quality can be improved together. The study also highlights the key role of resistant varieties in integrated disease management systems, as well as their potential value in improving postharvest quality and extending shelf life. Finally, in response to challenges such as pathogen evolution, climate change, and emerging diseases, it is suggested that future research should strengthen the integration of multi-omics, intelligent breeding, and high-throughput phenotyping technologies, so as to promote the coordinated development of disease resistance and high-quality tomato production and achieve sustainable agricultural goals.

Keywords Tomato (*Solanum lycopersicum* L.); Disease resistance breeding; Gene pyramiding; Molecular mechanisms; Quality traits

1 Introduction

Tomato (*Solanum lycopersicum* L.) is one of the most widely cultivated and economically important horticultural crops in the world. In recent years, the global planting area has been about 5 million hectares, with total production close to or exceeding 180–190 million tons. As a high-value crop, tomato not only supports the livelihoods of smallholder farmers but also drives large-scale commercial agriculture. It also contributes to a broad processing industry, including sauces, juices, ketchup, and canned products (Akotowanou et al., 2022).

From a nutritional perspective, tomato is widely recognized as an important component of a healthy diet. It is rich in vitamins (especially vitamin C and provitamin A), minerals, dietary fiber, and various bioactive compounds, including carotenoids (particularly lycopene and β-carotene), tocopherols, and phenolic metabolites. Regular consumption of tomatoes and their products can significantly increase dietary levels of carotenoids, lycopene, vitamin C, and polyphenols, which are closely associated with a reduced risk of cardiovascular diseases, certain cancers, and other chronic conditions (Egea et al., 2022).

Despite its importance, tomato production is severely constrained by a wide range of diseases. These diseases are caused by fungi, oomycetes, bacteria, viruses, viroids, and nematodes, and can infect plants at all stages from seedling to postharvest, often leading to serious yield and quality losses. Major diseases include soil-borne diseases such as Fusarium wilt, Verticillium wilt, bacterial wilt, and root-knot nematodes; foliar and fruit diseases such as early blight, late blight, Septoria leaf spot, and gray mold; as well as viral diseases such as tomato yellow leaf curl virus, tomato spotted wilt virus, and tomato brown rugose fruit virus (Adhikari et al., 2017). These pathogens not only reduce yield but also lower market and processing quality by affecting fruit size, color, firmness, and storage ability, while increasing the risk of postharvest decay.

Traditional disease management mainly relies on chemical pesticides and intensive plant protection inputs. However, this approach brings environmental and health risks, increases production costs, and accelerates the development of pathogen resistance to pesticides. At the same time, climate change, soil degradation, and the expansion of global trade have further intensified and redistributed disease pressure, promoting the spread of new or more aggressive pathogen strains. Under these conditions, the use of host resistance has become one of the key strategies for sustainable tomato production. With the help of molecular markers, genomics, and CRISPR/Cas gene editing technologies, breeding programs are now focusing on developing new varieties that combine durable resistance to major diseases with high yield, early maturity, and good fruit quality (Rane et al., 2024).

This study explores how to integrate genetic disease resistance with strict quality requirements to support stable, efficient, and nutritious tomato production. It clarifies the global economic and nutritional importance of tomato and the scale of yield and quality losses caused by diseases in major production systems. It also systematically summarizes current research progress on major and emerging tomato diseases and reviews breeding and biotechnological strategies for developing resistant varieties. By linking disease resistance with yield stability, market standards, and nutritional value, this study outlines the pathways and prospects for achieving sustainable tomato production under multiple stress conditions.

2 Major Diseases Affecting Tomato Cultivation

2.1 Fungal diseases

Early blight is mainly caused by Alternaria solani and is one of the most destructive leaf diseases in tomato. It forms brown necrotic spots with typical concentric rings on leaves. In severe cases, it leads to heavy defoliation, reduced photosynthetic area, and can cause yield losses of up to 80% under favorable conditions (Ivanović et al., 2022). All aboveground parts of the plant can be affected. The disease becomes serious under conditions of high temperature, heavy dew, and high humidity.

Late blight is caused by Phytophthora infestans, a highly infectious oomycete disease that attacks leaves and fruits. It can destroy an entire crop within a few days. Cool and humid conditions favor its outbreaks, and historically it has caused total crop failure in Solanaceae crops (Oladokun et al., 2019).

Fusarium wilt is caused by *Fusarium oxysporum* f. sp. lycopersici. It is a soil-borne vascular disease that blocks the xylem vessels, leading to unilateral yellowing, wilting, and eventually plant death. The pathogen can survive in soil for a long time, and yield losses in susceptible varieties can reach 10%~80% (Li et al., 2024).

2.2 Bacterial diseases

Among bacterial diseases, bacterial wilt caused by *Ralstonia solanacearum* is one of the most destructive soil-borne diseases. It infects the vascular system, causing rapid and often irreversible wilting, stunting, and even death of plants, especially under warm and humid conditions. Contaminated soil, irrigation water, and plant residues allow the pathogen to survive for long periods, making it difficult to continue tomato cultivation in affected fields.

Bacterial spot is mainly caused by bacteria of the genus Xanthomonas. It is an important disease of leaves and fruits in both open-field and greenhouse production. The disease forms small water-soaked spots that later turn dark and scab-like, leading to leaf drop, reduced photosynthesis, and visible lesions on fruit surfaces, which lower market quality (Panno et al., 2021).

Because bactericides are often less effective against bacterial diseases and the pathogens can spread through seeds or water, control of these diseases is relatively difficult. Therefore, breeding resistant varieties and maintaining strict sanitation measures are particularly important.

2.3 Viral diseases

Tomato yellow leaf curl virus (TYLCV) is a whitefly-transmitted begomovirus and one of the most damaging tomato viruses worldwide. Infected plants show severe leaf curling, shortened internodes, chlorosis, and stunted growth, resulting in a sharp decline in fruit set and yield. Yield loss in susceptible varieties can approach 100% (Mugao, 2023).

Tomato mosaic virus (ToMV) is a highly stable virus belonging to the genus Tobamovirus. It can spread through mechanical contact, contaminated tools, seeds, and workers. The disease causes mosaic patterns, mottling, and deformation of leaves, as well as fruit deformation, size reduction, and internal browning. These symptoms greatly reduce market value and processing quality, especially under greenhouse conditions (Ding et al., 2019).

Tomato hosts a very large range of viruses, with more than 300 viruses or viroids reported so far. Therefore, TYLCV and ToMV are only representative examples among many viral threats. In breeding for disease resistance, multiple viral factors need to be considered together.

3 Genetic Basis of Tomato Disease Resistance

3.1 Types of resistance

Tomato shows two main types of resistance: vertical resistance (species- or race-specific) and horizontal resistance (quantitative resistance). Vertical resistance is usually controlled by one or a few major R genes. These genes can recognize specific pathogen effectors and trigger strong defense responses. Typical examples include Ve genes for resistance to Verticillium wilt, I genes for Fusarium wilt, Mi genes for resistance to root-knot nematodes, and Ty genes for resistance to tomato yellow leaf curl disease. These genes often provide near-complete resistance, but they are easily broken by newly emerging pathogen races.

In contrast, horizontal resistance is usually controlled by multiple genes, with several QTL acting together. Each locus contributes a small effect, and this type of resistance often works against a wide range of pathogen strains. For example, resistance QTL for early blight, bacterial wilt, anthracnose, and tomato chlorosis virus (ToCV) have been widely reported (Khojasteh et al., 2024). This quantitative resistance is generally more durable, but it is relatively difficult to select and fix in breeding populations.

3.2 Resistance genes and QTL

Many key resistance genes in tomato have been cloned or mapped. The Ve locus contains Ve1 and Ve2, among which Ve1 encodes a receptor-like protein that provides resistance to race 1 of Verticillium dahliae and V. albo-atrum. The I gene family (such as I-2), located on chromosome 11, confers resistance to specific races of *Fusarium oxysporum* f. sp. lycopersici and has been widely used in commercial varieties (Orchard et al., 2023). The Mi gene provides resistance to root-knot nematodes and, in some genetic backgrounds, is also associated with resistance to other pests (Ercolano et al., 2012).

For virus resistance, several Ty genes (Ty-1 to Ty-6) derived from wild species can provide resistance or tolerance to tomato yellow leaf curl virus. Among them, Ty-2 encodes an NLR protein, and its locus has been widely used in breeding through gene pyramiding (Dhaliwal et al., 2020).

Besides major genes, meta-analysis of large-scale mapping studies has identified dozens of meta-QTL (MQTL) related to bacterial and fungal diseases. These MQTL significantly narrow down the genomic intervals and reveal candidate defense genes such as NDR1, PR proteins, and WRKY transcription factors. Individual studies have identified multiple QTL associated with resistance to early blight, bacterial wilt, anthracnose, and ToCV. These QTL usually explain moderate but significant phenotypic variation, indicating that quantitative resistance is widely present (Adhikari et al., 2023; Gebhardt, 2023).

3.3 Molecular mechanisms

At the molecular level, tomato disease resistance depends on a layered immune system. Pattern-triggered immunity (PTI) is activated when pattern recognition receptors on the cell surface detect pathogen-associated molecular patterns, leading to basic defense responses such as reactive oxygen species burst, cell wall reinforcement, and defense gene expression (Abbasi et al., 2021). Effector-triggered immunity (ETI) is mainly mediated by intracellular NLR-type R proteins, which recognize specific pathogen effectors and trigger faster and stronger responses, often accompanied by localized cell death (hypersensitive response). Genome-wide studies show that tomato contains hundreds of NLR genes, and their expression is induced during pathogen infection, highlighting their key role in ETI (Bashir et al., 2022).

These immune layers are tightly regulated by signaling pathways centered on salicylic acid (SA), jasmonic acid (JA), and ethylene (ET). In the interaction between Alternaria and tomato, JA and ET signaling pathways work together under the regulation of transcription factors to control defense responses against necrotrophic fungi (Tominello-Ramirez et al., 2024). SA-related genes, such as EDS1, NDR1, and NPR1-like regulators, are involved in Ve1-mediated signaling pathways and broader defense responses. Many resistance-related QTL and candidate genes encode components of these pathways, including WRKY transcription factors, PR proteins, and receptor-like kinases.

4 Breeding Strategies for Disease-Resistant Varieties

4.1 Conventional breeding methods

Traditional breeding for disease resistance in tomato mainly relies on selection and hybridization, often using wild relatives as sources of resistance genes. Under natural or artificial disease pressure, repeated cycles of backcrossing and phenotypic selection have produced lines resistant to begomoviruses, late blight, bacterial wilt, Fusarium wilt, and tomato mosaic virus. Among them, multi-resistant F7 lines can show relatively high yield under suitable conditions (Hanson et al., 2016).

Backcross breeding is widely used to introduce specific resistance genes into elite but susceptible genetic backgrounds while recovering the genome of the recurrent parent. This approach provides a foundation for further improvement of multi-resistant lines using molecular techniques.

However, relying only on conventional breeding usually takes a long time, and when using distant wild donors, it is often affected by linkage drag.

4.2 Marker-assisted selection (MAS)

Marker-assisted selection (MAS) tracks molecular markers tightly linked to resistance genes and QTLs, allowing early and accurate selection in segregating generations, which greatly speeds up the breeding process (Borrelli et al., 2018).

MAS has been widely used to introduce and combine Ty genes related to tomato yellow leaf curl disease, Ph genes related to late blight, the root-knot nematode resistance gene Mi, and many other resistance loci.

Marker-assisted backcrossing and gene-specific marker techniques make the pyramiding of multiple resistance traits more efficient. Lines carrying combinations such as Ty-1/Ty-2/Ty-3 with Ph-2/Ph-3 or Sw-5 and Tm-2^2 can be developed. These lines show strong overall resistance and good horticultural traits (Kaushal et al., 2024). Compared with relying only on phenotypic selection, MAS significantly improves the accuracy, efficiency, and reliability of disease-resistance breeding.

4.3 Genomic and biotechnological approaches

Genomic selection (GS) uses whole-genome markers and prediction models to select superior genotypes for complex quantitative resistance traits without phenotyping every generation. With the increasing availability of high-density genomic resources, this method is showing good application potential in tomato breeding (Anand et al., 2025).

Biotechnological approaches provide more options for disease-resistance breeding. CRISPR/Cas genome editing can precisely modify resistance (R) genes and susceptibility (S) genes, allowing rapid development of resistant materials without extensive crossing.

In tomato, CRISPR/Cas9 has been used to knock out susceptibility genes such as Pelo and Mlo1 to obtain resistance to TYLCV and powdery mildew. Knocking out DMR6-1 and MYBS2 can enhance broad-spectrum resistance to bacterial, oomycete, and late blight pathogens. Editing XSP10 and SlSAMT improves tolerance to Fusarium wilt. Edited plants usually show enhanced resistance with minimal effects on growth (Pramanik et al., 2021; Debbarma et al., 2023) (Figure 1).

Deletion of the PMR4 genomic region led to the development of the non-transgenic powdery mildew-resistant variety "Tomelo" in less than 10 months, showing the high efficiency and precision of this technology. In addition, CRISPR can be used for rapid domestication of stress-resistant wild materials, keeping their resistance while introducing good agronomic traits.

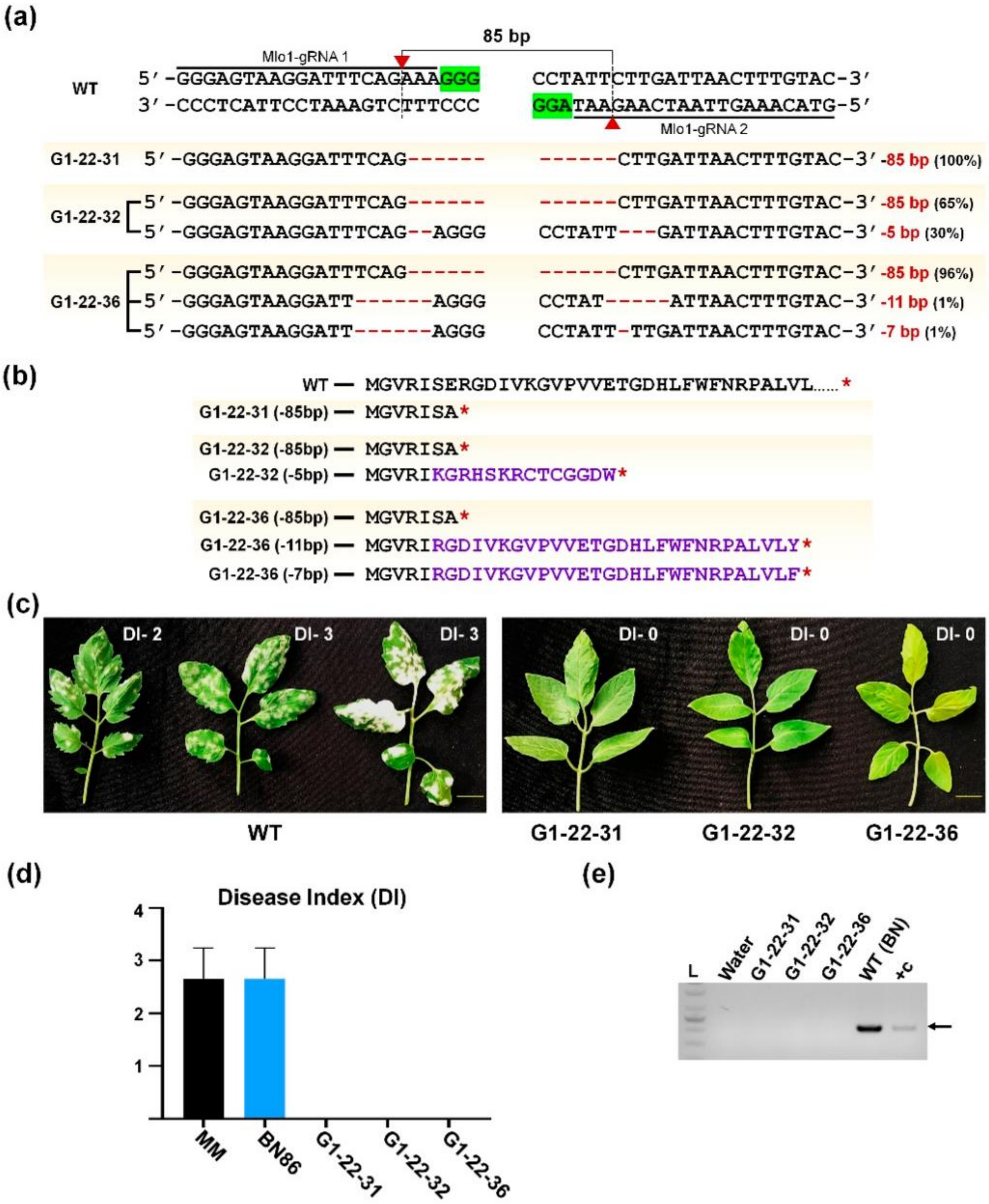

Figure 1 Characterization of CRISPR/Cas9-mediated *SlMlo1* genome-edited tomato lines for powdery mildew resistance. (a) Indel patterns of three *SlMlo1*-knockout plants showing the homozygous (G1-22-31), biallelic (G1-22-32), and chimeric (G1-22-36) genotype. The knockout efficiency (%) of individual lines evaluated using the ICE tool. Red dash indicates the deleted nucleotides; (b) Comparison of amino acid sequence between wild-type (WT) MLO1 protein and truncated region resulting from knockout alleles. Stop codon in red star symbol and altered amino acids in blue was indicated; (c) Analysis of *SlMlo1*-knockout mutant lines tested for resistance against powdery mildew-causing fungus Oidium neolycopersici. The phenotype of the mutant plants evaluated at 21 days post-infection (DPI). Referring to visual fungal growth symptoms, we calculated the disease index; (d) Powdery mildew disease index was calculated with WT (BN-86 and Moneymaker (MM)) and G1 *SlMlo1* mutant lines (G1-22-31, G1-22-32, G1-22-36). Error bars represent SE (three biological replicates); (e) Detection of O. neolycopersici by PCR method using strain-specific 16S ribosomal RNA (rRNA) primers. Non-infected plants used as mock control; fungal DNA used for PCR as a positive control (Adopted from Pramanik et al., 2021)

4.4 Resistance gene pyramiding

Resistance gene pyramiding combines multiple resistance genes and/or QTLs into a single variety to achieve broader and more durable resistance. Through marker-assisted pyramiding, genes such as Ty-1, Ty-2, and Ty-3 for tomato yellow leaf curl disease, Ph-2 and Ph-3 for late blight, and the Mi gene for root-knot nematode resistance have been integrated into the same genetic background. This has resulted in lines and hybrids with high overall resistance and stable yield under disease pressure (Prabhandakavi et al., 2021).

Double PCR and linked marker techniques allow efficient stacking of resistance genes for viruses and soil-borne diseases through backcrossing, enabling predictable recovery of elite genetic backgrounds with fewer plants.

Gene editing further expands the ability of gene pyramiding. Using multiplex CRISPR/Cas systems, multiple S or R genes can be edited at the same time, producing broad-spectrum resistance in a single generation and avoiding linkage drag (Tiwari et al., 2023). Combining resistance genes with different mechanisms and integrating good agronomic management practices is key to achieving long-term stable resistance in high-quality tomato varieties.

5 Disease-Resistant Varieties and Their Performance

5.1 Commercialized disease-resistant varieties

Widely used cultivars and hybrids usually carry resistance to key diseases such as Fusarium wilt, Tomato yellow leaf curl disease (TYLCD), Tomato spotted wilt virus (TSWV), and bacterial wilt. These resistances may exist individually or be combined through gene pyramiding. In Mexico, commercial Saladette-type hybrids carrying resistance genes to Fol races 1-3, TYLCV, and TSWV not only meet strict quality standards in both the United States and domestic markets, but also show early maturity (Lafrance et al., 2024). In India and other regions, F1 hybrids with resistance to multiple diseases (such as early blight, bacterial wilt, and leaf curl disease) have been widely used for both fresh consumption and processing purposes (Kaushal et al., 2020).

5.2 Yield stability and adaptability

The performance of disease-resistant varieties is influenced by season, production system, and disease pressure. In Mali, AVTO1710 can still maintain a relatively high yield (40.9 t/ha) during the rainy season, when many local varieties perform poorly, while VIO43614 performs best under drier conditions with high TYLCD incidence, showing good adaptability to different environments (Bihon et al., 2022). In Honduras, the line AVTO1903 shows high marketable yield under both open-field (101.3 t/ha) and greenhouse conditions (62.1 t/ha), indicating stable performance across cultivation systems (Flores et al., 2024). Late blight-resistant varieties such as “Mountain Gem” also show yield differences across regions, with clear yield improvement under grafting conditions, highlighting the importance of multi-location trials for resistant materials (Reeves et al., 2023).

5.3 Quality traits of disease-resistant varieties

Studies show that disease resistance can be combined with good fruit quality. In the Sinaloa region, hybrids resistant to Fol, TYLCV, and TSWV usually meet international standards in fruit firmness, color, pH, total soluble solids (TSS), acidity, and TSS/acid ratio, and some of them also have early maturity and good market quality (Lafrance et al., 2024). Differences exist among resistant materials in traits such as firmness, TSS, pH, dry matter content, and fruit shape index, allowing breeders to select lines that match local consumer preferences. Research on late blight-resistant families shows that strongly resistant genotypes can also approach the ideal type (ideotype), with good performance in fruit size, color, firmness, acidity, and soluble solids content (Copati et al., 2024). In addition, phenotypic analysis of diverse germplasm indicates that some resistant lines are not only high-yielding, but also have higher vitamin C content, antioxidant activity, and polyphenol levels, suggesting good potential for breeding varieties with both disease resistance and enhanced nutritional quality (Grozeva et al., 2020).

6 Integration of Disease Resistance and High-Quality Production

6.1 Balance between resistance and fruit quality

Breeding studies show that disease resistance and quality can be improved together, but there is still a certain trade-off between them. Materials carrying multiple Ty genes to enhance resistance to TYLCV usually show strong resistance. However, when selecting for low disease index and high yield, they are often accompanied by a decrease in vitamin C content and locule number, while fruit firmness, Brix value, and β-carotene content tend to increase (Mahmoud et al., 2025).

Dual resistance to ToLCV and bacterial wilt can be combined with good processing traits, but it is necessary to maintain a balance of lycopene, total soluble solids (TSS), and acidity during parent selection (Acharya et al., 2018). In addition, hybrids with multiple resistance to Fol, TYLCV, and TSWV can meet market standards in terms of fruit firmness, TSS/acid ratio, and color. This indicates that if quality traits are included simultaneously in breeding selection, disease resistance does not significantly reduce fresh fruit quality.

Evaluation of diverse germplasm resources also found that some materials possess both ToMV resistance, high soluble solids content, and strong antioxidant activity. These can be used as important parental resources for simultaneous improvement of resistance and quality.

6.2 Agronomic measures supporting resistant varieties

Resistant varieties perform best under integrated disease management (IDM) systems. The IDM model that combines resistant or grafted plants with biological agents, pheromone traps, and need-based pesticide application not only increases yield but also significantly reduces pesticide use.

In areas with high incidence of bacterial wilt, integrated measures such as soil improvement, application of Bacillus subtilis, and intercropping systems can effectively reduce disease occurrence and improve input-output efficiency (Sheneka et al., 2025). In addition, studies on Fusarium wilt and late blight indicate that a single control method is not enough for long-term management. Instead, soil health management, crop rotation, and biological control should work together with resistant varieties to achieve sustainable control (Jehani et al., 2025).

6.3 Postharvest quality and shelf life

Disease resistance can also indirectly improve postharvest quality by reducing disease incidence, since healthy plants and fruits are less prone to decay. Breeding strategies that combine ToLCV resistance with delayed ripening traits have successfully developed hybrids with extended shelf life and stable yield (Manjunath et al., 2025).

Studies show that genotypes with higher fruit firmness have lower disease incidence during storage and can maintain a longer shelf life, thereby reducing market losses (Imali et al., 2025) (Figure 2). In addition, molecular improvement of gene loci related to fruit firmness and shelf life can delay fruit softening and enhance resistance to pathogens during transportation and storage.

7 Case Studies of Disease-Resistant Tomato Varieties

7.1 Breeding progress of TYLCV-resistant tomato varieties

Resistance to TYLCV (Tomato yellow leaf curl virus) is mainly achieved by introgressing Ty genes from wild relatives and combining gene-specific markers with linked markers for gene pyramiding. For example, commercial F1 hybrids such as ‘Brivio’, ‘Dania’, ‘SV8320’, and ‘Tyrmes’ commonly contain combinations of multiple resistance genes, including Ty-1/Ty-3, Ty-2, Ty-4, and ty-5. Under field TYLCV pressure, these varieties may show moderate or mild symptoms, but they can still maintain relatively good yield and fruit quality (Mahmoud et al., 2023). Studies have shown that pyramiding Ty-1/Ty-3 with Ty-2 using marker-assisted selection can significantly enhance resistance, confirming the synergistic effect of stacking multiple loci (Lee et al., 2020). In variety trials under natural TYLCV pressure in Georgia, USA, cultivars carrying Ty-1 or Ty-3/Ty-6 showed lower disease incidence and higher yield compared with susceptible controls, indicating good field resistance (Acharya et al., 2025). However, resistance based on Ty-1 may break down under high-temperature conditions, suggesting limitations in environmental adaptability of the current resistance system (Koeda and Kitawaki, 2024).

7.2 Fusarium wilt-resistant tomato hybrids

Resistance to tomato Fusarium wilt mainly comes from the I gene family introgressed from wild species (Chitwood-Brown et al., 2021). By crossing lines carrying the I-3 gene with commercial cultivars containing I-1 and I-2, the FOX hybrid series has been developed. Some of these materials show resistance to different physiological races of *Fusarium oxysporum* f. sp. lycopersici (Fol), but their agronomic traits still need improvement. When used as rootstocks, FOX4 can effectively suppress wilt occurrence while maintaining yield and fruit quality, whereas FOX1 may have some negative effects on certain quality traits (Fernandes et al., 2022). In addition, germplasm screening in different regions has identified various resistant or moderately resistant materials. These can be used as resistance donors or directly promoted varieties to reduce yield losses. Meanwhile, new resistance loci identified in the wild species Solanum pennellii further expand the genetic base for commercial hybrid breeding (Li et al., 2022).

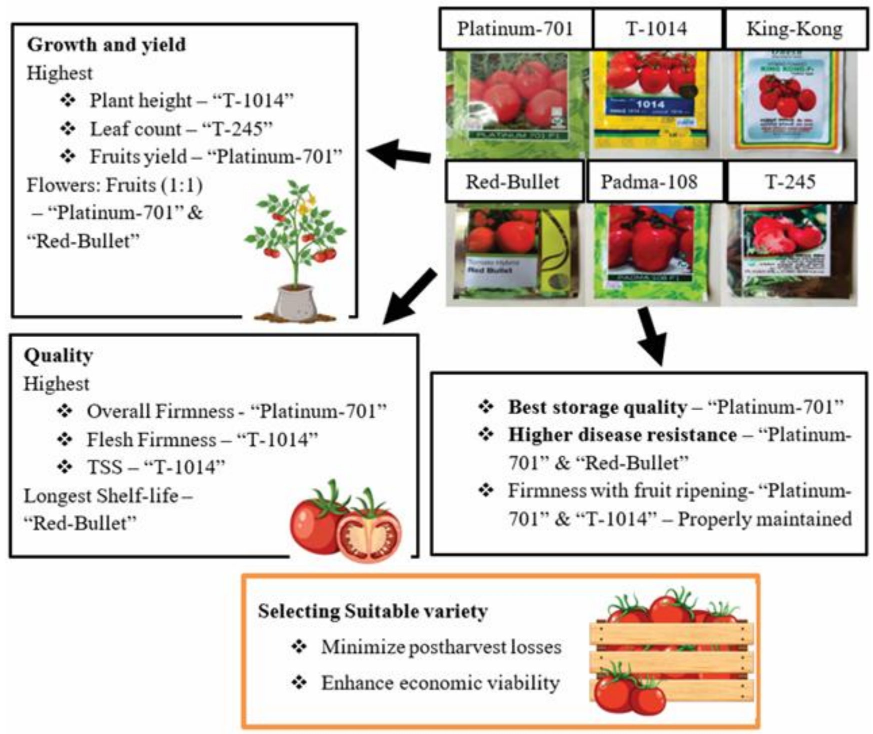

Figure 2 Comparative evaluation of tomato varieties based on growth, yield, quality, and postharvest performance (Adapted from Imali et al., 2025)

7.3 Multi-resistant varieties under protected cultivation conditions

In protected cultivation systems, tomatoes are often exposed to combined pressure from soil-borne pathogens and viruses. Grafting susceptible scions onto Fusarium wilt-resistant rootstocks can effectively reduce disease occurrence under naturally infested soil conditions, while maintaining plant growth and yield (Kawicha et al., 2025). For viral diseases such as TYLCV, efficient inoculation systems allow rapid screening of breeding materials, which speeds up the development of multi-resistant varieties (Bian et al., 2024). At present, F1 hybrids combining TYLCV resistance with resistance to other diseases are widely used in greenhouse production systems. These resistant varieties not only help stabilize yield but also reduce reliance on chemical pesticides.

8 Challenges and Future Prospects

8.1 Evolution of pathogen virulence

Many tomato pathogens evolve rapidly and can easily weaken resistance based on single major-effect genes. The loss or mutation of avirulence genes and effectors, as observed in Cladosporium fulvum and its Avr genes, allows pathogens to evade Cf gene-mediated resistance (De La Rosa et al., 2024; Zaccaron and Stergiopoulos, 2024). Experimental evolution studies of Ralstonia solanacearum on quantitatively resistant tomato lines show that the pathogen adapts through convergent rewiring of virulence regulatory networks, rather than completely overcoming resistance. This highlights its strong adaptive potential even under quantitative resistance (Gopalan-Nair et al., 2021). For viruses such as ToBRFV and similar threats, new strains have already broken traditional ToMV/TMV resistance genes, creating an urgent need for new resistance resources and gene-editing strategies (Panno et al., 2021).

8.2 Climate change and disease dynamics

Climate change is expected to increase disease pressure by altering temperature, humidity, and rainfall patterns, thereby shifting pathogen distributions and promoting outbreaks. Studies predict that many plant pathogens will expand their geographic ranges and occur more frequently, which could significantly impact tomato production and food security (de Almeida et al., 2020). Field evidence from Nepal shows that changes in temperature and precipitation are closely associated with increased incidence of late blight, leaf curl disease, and black spot in tomato, forcing farmers to use more pesticides to maintain yields (Bhandari et al., 2021). In addition, emerging viruses such as ToBRFV are spreading into new regions, a process partly driven by both climate change and global trade.

8.3 Future breeding directions

Future breeding will increasingly rely on multi-omics integration and advanced analytical approaches. The combined application of transcriptomics, ionomics, and other omics technologies in tomato has identified candidate genes and SNPs associated with resistance to late blight and ToBRFV, providing a basis for developing more precise molecular markers and functional targets (Deb et al., 2023). Further studies emphasize the need to integrate genomics, transcriptomics, metabolomics, and effectoromics to better understand resistance mechanisms and guide the design of durable resistance (Adhikari et al., 2020).

Artificial intelligence-assisted breeding and phenotyping are becoming key tools. Image-based high-throughput phenotyping in tomato bacterial wilt research can detect subtle quantitative differences and identify new QTLs earlier than manual scoring. In addition, integrating multi-omics data with machine learning to predict resistance phenotypes is considered an important future direction, highlighting the potential of intelligent breeding platforms to accelerate the development of disease-resistant crops (Cembrowska-Lech et al., 2023).

Author Contributions

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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.

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Feature Review Open Access

Effects of Rain Shelter Cultivation on Cherry Fruit Cracking and Quality

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Abstract Sweet cherry (*Prunus avium* L.), as a high-value fruit crop, has long been constrained by rain-induced fruit cracking, while fruit quality is highly dependent on canopy microenvironment and cultivation practices. This study focuses on rain-shelter cultivation systems and systematically analyzes the integrated mechanisms by which canopy structure, rainfall exposure, water relations, and light distribution influence fruit cracking and quality formation. Fruit cracking is mainly driven by factors such as skin structural properties, water absorption processes on the fruit surface, and the duration of surface wetness. Meanwhile, canopy structure significantly affects cracking risk by regulating rainfall interception, ventilation conditions, and fruit spatial distribution. Planar and well-ventilated canopy architectures help reduce fruit wetting duration and lower the incidence of cracking. Although rain-shelter facilities can effectively block precipitation, they also alter microenvironmental conditions such as light, temperature, and humidity. By properly configuring canopy architecture, optimizing pruning and fruiting zone management, and integrating scientific water and nutrient regulation, it is possible to reduce cracking risk while maintaining or improving fruit market quality. This study provides a systematic theoretical basis and integrated management strategies for efficient sweet cherry production in rainy regions.
Keywords Sweet cherry; Fruit cracking; Rain-shelter cultivation; Canopy structure; Fruit quality

1 Introduction

Sweet cherry (*Prunus avium* L.) is one of the most economically valuable temperate fruit crops. It is widely favored for its bright appearance, unique flavor, and rich content of bioactive compounds such as anthocyanins, vitamins, and minerals (Correia et al., 2018). The market price of sweet cherries largely depends on fruit appearance and firmness, so it is considered a high-value crop, and even slight quality deterioration can lead to significant economic losses for growers (Toivonen and Manganaris, 2020).

Commercial cherry production is seriously limited by rain-induced fruit cracking, which is widely regarded as one of the most important agronomic problems in sweet cherry production (Knoche and Winkler, 2017). Cracking usually occurs from the early coloring stage to full maturity, and it becomes more severe when rainfall or prolonged surface wetness coincides with fruit ripening. Under unfavorable conditions, losses can exceed 80% (Quero-García et al., 2021). Cracked fruits not only quickly lose market value due to damaged appearance, but are also more susceptible to fungal decay, and their storability and shelf life are significantly reduced (Xu et al., 2025). This phenomenon is highly complex, involving multiple factors such as cultivar differences, skin characteristics, fruit size, water relations, and surface wetness (Knoche, 2019).

Fruit quality traits of sweet cherry-including color, firmness, sugar and acid content, and bioactive compounds-are highly sensitive to canopy microclimate and cultivation practices (Mineață et al., 2024). Rain protection facilities, such as plastic covers, high tunnels, and rain shelters, can effectively reduce direct contact between rainwater and fruit, thereby significantly lowering cracking incidence in most cases (Suran et al., 2019). However, these facilities also change light, temperature, and humidity conditions within the canopy, typically reducing solar radiation by 40%~60% and altering air temperature and relative humidity (Blanco et al., 2021). These changes may negatively affect fruit coloration, firmness, soluble solids content, and pigment accumulation (Muñoz-Alarcón et al., 2025). In contrast, some complementary measures, such as reflective ground mulches or the application of biostimulants, have been shown to improve or make fruit color, firmness, and sugar content more uniform under covered conditions (Afonso et al., 2024).

Given the important role of rain shelters in reducing cracking risk, while also potentially affecting fruit quality, it is necessary to systematically evaluate their overall effects in cherry production. In this study, rain-protected cultivation is analyzed as an integrated system to assess its effects under field conditions on: (i) the incidence and severity of rain-induced fruit cracking, and (ii) key quality traits such as skin color, fruit firmness, and sugar accumulation. By linking cracking responses with fruit quality variations across different canopy positions and seasonal conditions, this study aims to clarify the trade-offs of rain-protected cultivation and identify conditions that can both reduce cracking risk and maintain or improve commercial quality, thus providing a theoretical basis and practical guidance for more sustainable and profitable sweet cherry production in rainy regions.

2 Biological Characteristics of Cherries Related to Cracking and Quality

2.1 Fruit skin structure and cracking sensitivity

The cherry fruit skin (composed of cuticle + epidermis + hypodermis) is the primary load-bearing structure. It experiences high mechanical tension and has limited elastic extensibility, so additional expansion can easily lead to tissue rupture (Winkler et al., 2016). A thinner cuticle and more severe microcracks increase the fruit's sensitivity to rain-induced cracking because these factors weaken the barrier function of the skin, allowing water to enter more easily into localized areas. Local rupture of flesh cells beneath the epidermis, followed by crack propagation in a "zipper-like" manner, further indicates that fruit skin with low mechanical strength and insufficient elasticity plays a key role in cracking sensitivity (Knoche et al., 2025). When the skin barrier is damaged, water can rapidly enter through the fruit surface and the pedicel region, increasing local mechanical stress in the skin.

2.2 Water uptake pathways in cherry fruit

Under rainfall or prolonged surface wetness, water can be directly absorbed through the fruit skin, especially in the presence of microcracks or water-accumulating areas (such as the pedicel cavity and stylar end), where surface wetness duration is extended (Santos et al., 2023). This surface water uptake pathway is a major driving factor of fruit cracking, and its extent is closely related to the duration of surface wetness and the wetted area.

At the whole-plant level, when soil moisture is high, water is transported upward through the xylem and phloem, affecting the water status of the fruit and potentially interacting with surface water uptake. However, recent studies emphasize the importance of local processes in the fruit skin rather than only the role of overall turgor pressure (Aydın et al., 2025).

2.3 Characteristics of quality formation

The color formation of sweet cherries is mainly driven by the accumulation of anthocyanins, and anthocyanin synthesis is strongly regulated by light. Insufficient light (such as shading or low-light stress) reduces anthocyanin content, thereby affecting the development of red coloration in the fruit (Tang et al., 2023). Soluble sugars (such as fructose, sucrose, and related sugars) accumulate rapidly during ripening, and their levels are closely related to leaf photosynthesis and carbon assimilation. Shading reduces the photosynthetic capacity of leaves, thereby decreasing sugar accumulation in the fruit and affecting overall quality.

3 Cherry Canopy Training Systems and Their Structural Characteristics

3.1 Common cherry training systems

Modern cherry orchards are increasingly relying on high-density training systems to regulate tree vigor, improve light distribution and fruit quality, and facilitate labor-intensive operations such as pruning, harvesting, and the installation of rain covers or protective nets. Among these systems, Kym Green Bush (KGB), Upright Fruiting Offshoots (UFO), central leader and tall spindle systems, and the Spanish bush system represent different canopy structure types, which significantly affect fruit distribution and the microclimate within the fruiting zone (Long et al., 2015).

The KGB system is a multi-leader, bush-like structure composed of several upright and relatively short leaders emerging from low on the trunk, forming a compact canopy suitable for ground-based operations (Lang et al., 2019). Due to higher planting density and multiple leaders, KGB orchards usually have larger canopy volume and leaf area per unit land, which helps improve light interception. However, if branches are not renewed regularly, internal shading can easily occur (Yuri et al., 2021). The KGB system generally shows high yield per unit area and good harvesting efficiency, as most fruits are distributed within easy reach from the ground (Soysal et al., 2025).

The UFO system trains a trunk-like structure horizontally along a trellis, with multiple vertical fruiting shoots evenly distributed along it, forming a planar “fruiting wall” (Law and Lang, 2016). This narrow two-dimensional canopy captures light efficiently, simplifies pruning and renewal of fruiting shoots, and concentrates fruit along vertical axes that are easy to manage. Individual trees in the UFO system are relatively small, but the density of fruiting shoots per unit area is high, which helps achieve early fruiting, stable yield, and high harvesting efficiency, especially when most fruits can be picked from the ground (Ampatzidis and Whiting, 2013).

Central leader and tall spindle systems (including forms such as Vogel Central Leader and Tall Spindle Axe) are conical three-dimensional canopy structures characterized by a single trunk with multiple lateral fruiting branches distributed along it (Lang et al., 2019; Stone et al., 2022). These systems can develop larger trees with greater canopy volume and can produce fruits with good size and firmness, especially when lateral branches are properly spaced to avoid shading (Karakaya et al., 2022). Tall spindle variants are more slender and allow higher planting density, but the fruiting zone often extends beyond ground operation height, requiring ladders for management, and light distribution within the lower canopy is often less uniform (Rabcewicz et al., 2017).

The Spanish bush system is a multi-leader, low-trunk structure, where several main scaffold branches originate near the ground, distributing fruiting shoots within a relatively open canopy of moderate height (Long et al., 2015). When canopy density is properly controlled, this system can produce large fruits with high firmness and good coloration. Compared with tall central leader trees, its bush-like structure improves operational accessibility, although fruits may still be distributed deeper within the canopy (Karakaya et al., 2022).

3.2 Structural characteristics affecting cherry fruit environment

Among the different training systems mentioned above, fruit distribution, canopy permeability, and fruiting zone height are key structural traits that determine the fruit microenvironment, thereby influencing cracking risk and fruit quality. Structures dominated by vertical leaders (such as UFO upright shoots, KGB small leaders, and tall spindle trunks) tend to concentrate fruits along vertical axes, while systems dominated by lateral branches (such as central leader systems with long scaffold branches and Spanish bush systems) distribute fruits more on horizontal or inclined branches away from the trunk (Lang et al., 2019). Planar structures like UFO concentrate fruits within a narrow band close to the trellis, which is beneficial for uniform light exposure and rain cover installation; in contrast, multi-leader bush systems (such as KGB and Spanish bush) create a more three-dimensional fruiting space, which can easily lead to differences in light, temperature, and humidity within the canopy (Ampatzidis and Whiting, 2013).

Canopy openness and compactness also have important effects on the fruit environment. Open or planar canopies, with less leaf overlap, allow better light penetration, improve photosynthetic uniformity, and thus enhance fruit coloration and soluble solids content; in contrast, dense and compact canopies tend to cause shading, reduce internal light levels, and suppress fruit quality and dry matter accumulation (Gonçalves et al., 2008). Large, dense, and vertically structured trees usually have greater shaded leaf area, which can result in poor fruit coloration and lower soluble solids content (SSC) and acidity. On the other hand, smaller or structurally optimized canopies reduce ineffective shading and improve fruit quality throughout the canopy (Zhang et al., 2025).

In addition, the height and accessibility of the fruiting zone not only affect management operations but also alter the microclimate around the fruit. “Ground-operated” systems such as KGB and UFO place most fruits within reach from the ground, which improves harvesting efficiency and allows more uniform coverage of rain shelters and protective nets over the fruiting area (Law and Lang, 2016). In contrast, in central leader and tall spindle systems, many fruits are located higher in the canopy, where different heights experience variations in wind, radiation, and rainfall exposure, and where the installation and management of protective structures become more complex (Rabcewicz et al., 2017). Therefore, the interaction between training structure and rain protection design plays a key role in determining fruit wetness duration, microclimate conditions, and ultimately the occurrence of cherry cracking and overall fruit quality.

4 Effects of Canopy on Rain Exposure and Cherry Fruit Cracking

4.1 Rainfall interception characteristics under different canopy structures

In open and sparse canopies, more rainfall can pass directly through the leaf layer, so exposed fruit clusters receive stronger direct impact from raindrops, and a larger proportion of the fruit surface becomes wetted. In dense canopies, the upper leaves intercept a considerable amount of rainfall. This water then drips or flows along branches and pedicels, forming localized high-frequency dripping zones around the lower fruits, and even small areas of water accumulation at the pedicel cavity and stylar end. In both situations, when fruit clusters extend beyond the leaf layer or hang below drip points, their effective wetted area increases, making them high-risk sites for fruit cracking (Balbontín et al., 2013).

4.2 Duration of surface wetness on cherry fruit

Besides the amount of intercepted water, the duration of surface wetness is a key factor determining fruit cracking: the longer the wetness lasts and the larger the wetted area, the higher the cracking frequency (Ranjan et al., 2022). Canopy ventilation (driven by wind penetration and airflow within the canopy) directly affects the evaporation rate of free water on the fruit surface or in the pedicel cavity. Dense canopies with poor ventilation tend to maintain high humidity and slow down the drying process, which can even promote dew formation and extend wetness duration under no-rain conditions. In contrast, more open or well-ventilated canopies usually allow faster drying and shorter wetness duration, reducing the risk of cracking. However, if fruits are directly exposed to rainfall, this advantage may be offset.

4.3 Fruit position within the canopy and cracking sensitivity

The spatial position of fruits within the canopy creates different microclimates and rain exposure patterns. Fruits located in the outer and upper parts of the canopy are more likely to be affected by direct rainfall and wind-driven raindrops. They tend to have a larger wetted area and, even though they dry faster, may still show higher cracking rates (Winkler et al., 2020). In contrast, fruits in the inner and lower canopy are more shaded and experience higher relative humidity. Dripping from upper leaves and weaker air movement prolong their wetness duration, and after rainfall, dew or condensed water may remain as a local water film around the pedicel cavity or stylar end. This spatial variation leads to clear heterogeneity in cracking distribution within the tree: in some cases, cracking is concentrated in outer regions directly exposed to rain, while in others it is more common in lower, high-humidity zones, depending on the balance among rainfall exposure, interception patterns, and drying conditions (Balbontín et al., 2013).

5 Effects of Canopy on Light Distribution and Cherry Fruit Quality

5.1 Light conditions and peel coloration formation

The synthesis of anthocyanins in cherry peel is highly dependent on light. Fruits exposed to good light conditions, or those with enhanced light through ground reflective films or supplemental lighting, show significantly higher red coloration intensity and anthocyanin content than shaded fruits (Muñoz-Alarcón et al., 2025) (Figure 1). Shading or low-light stress can significantly inhibit anthocyanin accumulation by downregulating key structural genes in the anthocyanin biosynthesis pathway, resulting in lighter fruit color and reduced market quality.

Within the same canopy, fruit coloration varies clearly at different positions. Cherries located in the lower or inner shaded areas usually have poorer coloration, while fruits in the upper canopy with sufficient light show better color. This difference becomes more obvious under plastic rain-shelter coverings where incident light is further reduced (Palacios-Peralta et al., 2022).

5.2 Effects on sugar accumulation

Light conditions not only affect leaf photosynthesis but are also directly related to carbon metabolism in the fruit. Low-light stress reduces photosynthetic capacity, carbon assimilation efficiency, and nutrient accumulation, leading to lower soluble sugar content and higher acidity at fruit maturity (Tang et al., 2023).

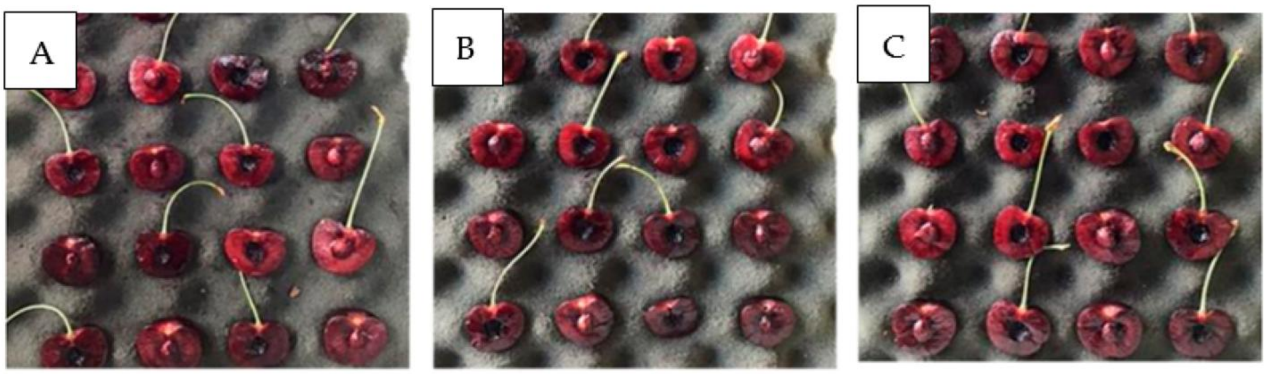

Figure 1 Fruit condition at post-harvest of sweet cherries (cv. Regina) subjected to one control (without reflective film) (A), one treatment with reflective film placed at 21 DBH (B), and a second treatment with reflective film placed at 34 DBH (C) (Adopted from Muñoz-Alarcón et al., 2025)

In contrast, fruits located in the upper canopy with sufficient light generally have higher soluble solids content (SSC) than shaded fruits in the lower canopy, and this difference is especially obvious in covered orchards (Pino et al., 2023).

A well-designed canopy structure can create an appropriate leaf-to-fruit ratio, providing more photosynthates for individual fruits and promoting SSC and dry matter accumulation. However, overly dense canopies, excessive fruit load, or long-term shading can inhibit sugar accumulation and delay fruit ripening.

5.3 Effects on fruit firmness and shelf life

Light conditions and the canopy microenvironment also affect fruit firmness and postharvest storage performance. Under plastic covering or shading conditions, cherry fruits usually show reduced firmness and changes in acidity, which may be related to insufficient light, altered calcium and dry matter distribution, and accelerated softening during storage (Xin et al., 2021).

In dense and heavily shaded canopy areas, poor air circulation and high humidity can lead to moisture retention on the fruit surface and increased metabolic activity. These conditions can increase the incidence of fruit cracking and reduce postharvest quality, such as higher risks of browning, decay, and tissue breakdown (Abdipour et al., 2020).

In contrast, optimizing canopy structure (such as open tree forms and good ventilation) or using reflective ground films to improve light distribution can enhance fruit firmness, promote uniform ripening, and extend shelf life. However, it should be noted that reflective films may increase soil moisture, which under certain conditions can raise the risk of fruit cracking (Correia et al., 2017).

6 Practical Strategies for Cherry Orchard Canopy Management

6.1 Cherry-specific pruning strategies

In high-density modern cherry production systems, pruning mainly focuses on renewing fruiting wood, avoiding excessive shading, and maintaining an open canopy structure with good light exposure (Long et al., 2020). Summer pruning is commonly used to remove overly vigorous shoots and shorten excessive vegetative growth, which helps improve light penetration inside the canopy and enhances fruit coloration, soluble solids content, and dry matter accumulation in shaded areas (Anthony and Minas, 2021).

Targeted removal of overlapping branches, crossing branches, and inward-growing shoots can reduce canopy complexity, improve air circulation, and prevent the formation of blind wood and dense outer “wall-like” structures. These structures tend to retain moisture and negatively affect spray coverage and the efficiency of protective systems (Macit et al., 2017; Hansen and Black, 2019).

Techniques that promote uniform bud break and branch distribution along the central leader (or main axis) help efficiently fill canopy space while avoiding excessive lateral branching, which can lead to overcropping and reduced fruit quality.

6.2 Optimization of tree training systems

Selecting an appropriate training system is essential for efficient use of light and labor, as well as for adapting to local climate conditions and protective structures. Planar training systems (such as UFO, super slender spindle, or tall spindle) form narrow fruiting walls that can intercept 60%-70% of incoming light and provide relatively uniform light distribution. This is especially beneficial in high-radiation areas or under rain shelters where photosynthetically active radiation (PAR) is reduced (Anthony and Minas, 2021; Stone et al., 2022).

Bush-type systems (such as KGB) develop multi-leader, compact canopies. Under conditions with sufficient light, low humidity, and lower risks of cracking and disease, these systems can achieve high yields and efficient harvesting (Lang et al., 2019; Soysal et al., 2019).

Training systems should match site conditions, tree vigor, climate characteristics, and the design of rain protection structures. Otherwise, problems such as excessive shading, increased blind wood, and stronger competition between trees may occur (Yan et al., 2025).

Tree height management is also important. Moderately taller trees that remain “pedestrian” or “semi-pedestrian” in height can improve light interception and make it easier to install rain covers and protective nets evenly. In contrast, overly tall trees increase shading in the lower canopy, complicate facility management, and create uneven fruit growing conditions.

6.3 Fruiting zone management

Active management of the fruiting zone can optimize fruit distribution within the canopy, improving light exposure and air movement. In high-density systems, proper branch structure and renewal pruning can promote fruiting on well-lit and accessible positions along the trunk and upright shoots, while avoiding fruiting in deeply shaded areas. This reduces the occurrence of poorly colored and low-quality fruit (Ayala and Lang, 2017; Yin et al., 2023).

In planar systems, maintaining proper spacing between upright shoots is critical for light penetration and uniform fruit quality. Excessively dense upright shoots increase shading and reduce soluble solids and dry matter content.

Crop load should be regulated not only at the whole-tree level but also in terms of spatial distribution within the canopy. Excessive crop load, especially when concentrated in shaded areas, is negatively correlated with fruit dry matter and soluble solids content. In contrast, a more balanced distribution of crop load helps improve overall fruit quality consistency (Yin et al., 2023).

Therefore, integrating pruning, training system management, and crop load regulation can create an open and evenly distributed fruiting wall or bush canopy. Such structures can operate efficiently under rain shelters, achieving better light use efficiency, faster drying, and reduced risks of fruit cracking and disease.

7 Comprehensive Measures to Reduce Fruit Cracking in Cherry Production

7.1 Rain-shelter systems

Plastic rain shelters, elevated tunnels, and net or tent systems form a physical barrier that prevents or reduces direct contact between rainfall and the fruit surface, making them one of the most effective measures to control fruit cracking. Multi-span elevated tunnels and pole-wire rain shelters can reduce natural cracking rates by more than 40% and are widely used in high-rainfall regions. However, their high cost and the alteration of the microclimate (such as increased temperature and humidity, and reduced light) are important limiting factors (Lang, 2014).

The interaction between canopy structure and rain-shelter systems is critical. Planar fruiting walls and pedestrian training systems facilitate uniform installation of rain covers and allow good ventilation. In contrast, under enclosed plastic covers, large and dense canopies tend to accumulate humidity, increase disease incidence, and may even lead to fruit cracking without obvious surface wetness (Blanco et al., 2021). In addition, net covering can also reduce cracking to some extent, while moderately regulating the microclimate and promoting fruit enlargement (Gonçalves et al., 2023) (Figure 2).

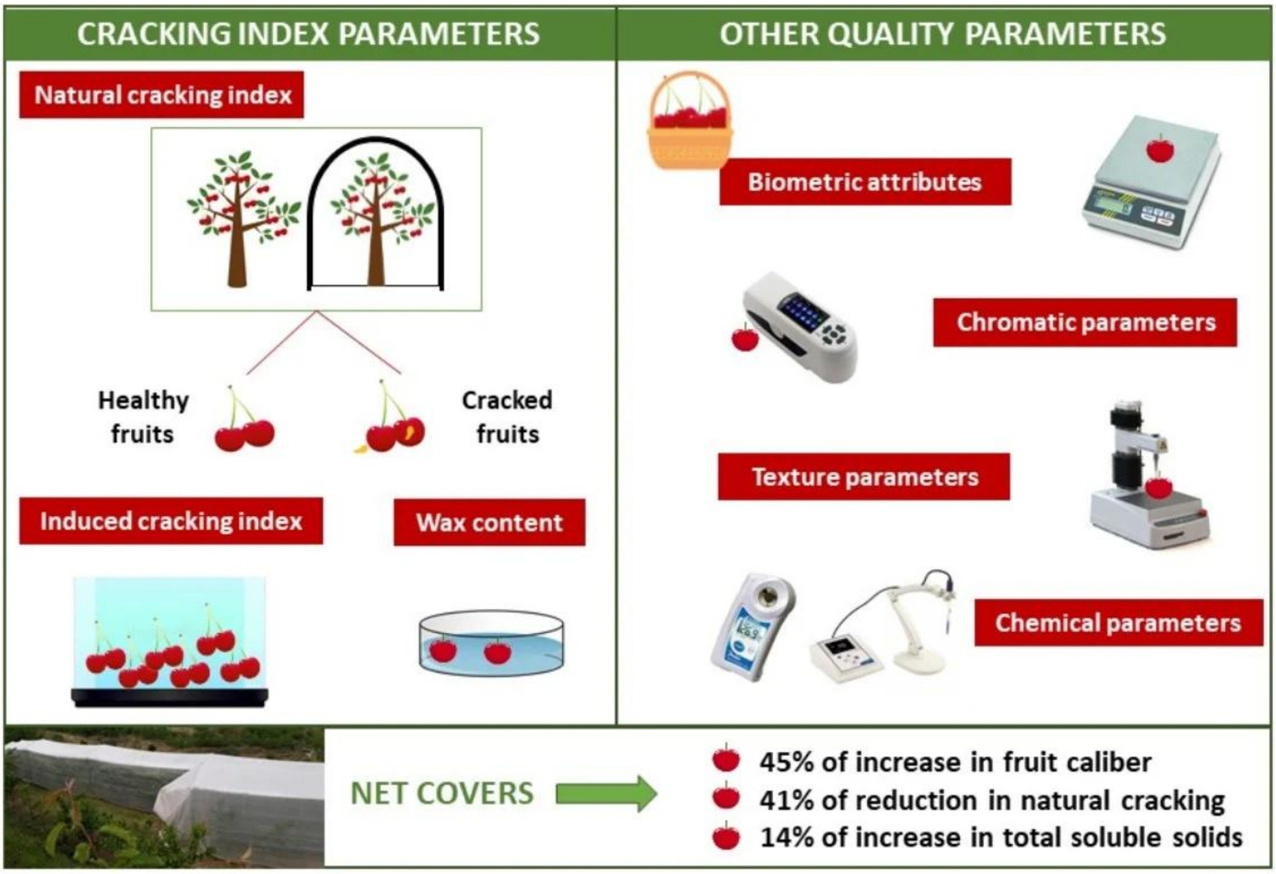

Figure 2 Comparison of fruit cracking and quality parameters of cherries under protective net covering systems (Adapted from Gonçalves et al., 2023)

7.2 Water and irrigation management

Soil moisture plays an important role in fruit cracking by influencing plant water relations. Excessive soil water or a sudden increase in soil moisture before harvest promotes root water uptake, thereby aggravating fruit cracking, even under rain-shelter conditions (Bustamante et al., 2021). In covered tunnels, poor soil moisture control may still result in severe cracking despite the absence of rainfall.

In contrast, deficit irrigation (for example, about 70% of crop evapotranspiration) can reduce cracking incidence from 27% to 8% and lower the cracking index, indicating that moderate control of water supply under precise management can effectively reduce cracking risk (Blanco et al., 2022).

7.3 Nutritional and chemical regulation measures

Pre-harvest calcium spraying is widely used to strengthen cell walls and improve the mechanical properties of the fruit skin. It generally reduces fruit cracking and increases fruit firmness. However, its effectiveness is inconsistent due to differences in product type, application timing, cultivar, and climatic conditions. Calcium chloride, calcium nitrate, and calcium hydroxide have all shown effectiveness in reducing the cracking index in both laboratory and field trials. However, because surface calcium can be washed off by rain, reapplication may be necessary after heavy rainfall (Kafle et al., 2016).

Foliar spraying of calcium and potassium can not only reduce fruit cracking but also improve the proportion of marketable fruit, as well as enhance fruit firmness and postharvest quality. These effects have been observed under both open-field and protected cultivation conditions (Varaldo et al., 2023). New anti-cracking agents include silicon applied to the canopy and hydrophobic biofilms (such as palm oil-cellulose coatings). Under suitable conditions, their effects can match or even exceed those of calcium treatments, while also increasing soluble solids content and improving the stability of fruit–pedicel attachment (Rombolà et al., 2023).

In addition, plant growth regulators and biostimulants (such as abscisic acid (ABA), methyl jasmonate, and seaweed extracts) show potential in improving cracking resistance and regulating fruit ripening. However, their effects are strongly influenced by cultivar and year, and standardized application protocols have not yet been established (Ruiz-Aracil et al., 2023).

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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.

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Effects of Pruning Systems on Fruit Yield and Quality in Loquat

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Abstract This study focuses on loquat (*Eriobotrya japonica* Lindl.) and systematically analyzes how different pruning systems affect yield and fruit quality. By examining the growth habits of loquat, its flowering and fruiting characteristics, and the relationship between canopy structure and yield, the effects of various pruning methods—including light, moderate, heavy, and seasonal pruning—were compared under practical production conditions. Pruning regulates canopy structure, improves ventilation and light penetration, and optimizes the source–sink relationship, thereby significantly influencing flower bud differentiation, fruit set, and fruit development. Moderate pruning can maintain relatively high yield while improving fruit size, soluble solids content, and appearance quality. In contrast, overly light pruning tends to produce smaller fruits, whereas excessive pruning reduces yield. Intensive pruning methods such as double heading help promote the formation of high-quality fruiting branches, improving individual fruit weight and the proportion of premium fruits. Pruning should be coordinated with practices such as flower and fruit thinning, fertilization, irrigation, and planting density management to achieve a balance between yield and quality. A well-designed pruning system is a key technical approach for improving orchard productivity and economic returns, and it plays an important role in the refined management of modern orchards.
Keywords Loquat (*Eriobotrya japonica* Lindl.); Pruning methods; Yield regulation; Fruit quality; Comparative analysis

1 Introduction

Loquat (*Eriobotrya japonica* Lindl.) is an evergreen subtropical fruit tree belonging to the Rosaceae family and has become an increasingly important component of diversified fruit production systems worldwide. Major producing countries include China, Brazil, Spain, Italy, as well as some regions in the Middle East and South Asia. Loquat fruits mature from late spring to early summer, usually during a market window when other fresh fruits are not yet widely available. This allows loquat to "fill the market gap" and obtain relatively high market prices due to its early maturity and unique sensory qualities (Hueso et al., 2021). Loquat fruit is favored for its juicy texture and pleasant flavor, and it is rich in sugars, organic acids, carotenoids, phenolic compounds, vitamins, and mineral nutrients, showing high nutritional value and pharmacological potential (Cai et al., 2019; Tinebra et al., 2022). High-quality loquat for fresh consumption generally has large fruit size, attractive peel color, high soluble solids content, a good balance between sweetness and acidity, and a low incidence of physiological disorders (Deng et al., 2023). In addition to fresh consumption, loquat can be processed into juice, jam, dried slices, fruit wine, and canned products. Its leaves and seeds can also be used as raw materials for health products and functional foods, further increasing its economic value (Dhiman et al., 2022). However, despite its strong development potential, the commercial expansion of the loquat industry in many regions is still limited by relatively low and unstable yields and the difficulty of consistently achieving high fruit quality compared with other pome fruits such as apple and pear (Jing et al., 2023).

Loquat trees are vigorous and tend to form large and dense canopies. Without effective canopy management, trees often become too tall, with poor ventilation and light penetration, outward movement of fruiting positions, and increased susceptibility of flowers and fruits to adverse conditions such as low-temperature injury and sunburn. Proper pruning practices (usually combined with training systems) can help control tree height, improve canopy structure, reduce the occurrence of pests and diseases, and promote the formation of high-quality fruiting branches. Traditional pruning and training methods are mostly based on growers' experience. Because tree structural responses are irreversible and slow to show results, and are also influenced by environmental conditions and labor constraints, optimization is difficult. In the absence of systematic pruning models tailored to the growth habits and phenological characteristics of loquat, many orchards commonly show problems such as overly tall canopies, crowded branches, and poor internal structure. These conditions lead to insufficient light inside the canopy, outward movement of fruiting zones, and reduced overall production efficiency. In high-density planting systems or aging orchards, these issues become more severe, increasing the difficulty of pruning and harvesting, raising labor costs, and potentially aggravating physiological disorders and postharvest losses. In addition, pruning needs to be coordinated with practices such as flower and fruit thinning, regulated deficit irrigation, nutrient management, and pollination management, which further increases management complexity (Ahmad et al., 2021).

Given the high economic importance of fruit size, earliness, and eating quality in the loquat market, it is necessary to conduct systematic research on pruning systems. Agronomic practices such as flower and fruit thinning, canopy optimization, and new pruning methods can significantly regulate fruit load, cell division, and the light microenvironment, thereby affecting fruit size, sweetness, appearance quality, and overall production efficiency. At present, systematic comparative studies on different pruning systems in terms of yield, key quality indicators (such as fruit weight, soluble solids, titratable acidity, and color), and operational feasibility are still limited. This study evaluates the effects of different pruning systems on canopy structure, fruiting characteristics, and physicochemical properties of fruits through field experiments, aiming to provide a theoretical basis for the optimized design and scientific management of loquat orchards.

2 Growth Characteristics of Loquat Related to Pruning

2.1 Growth habit and canopy structure of loquat trees

Loquat (*Eriobotrya japonica* Lindl.) is an evergreen fruit tree with strong vigor, and its growth habit and canopy structure largely determine how it responds to pruning. Under natural conditions, loquat trees tend to grow tall with vigorous vegetative growth. Without training and pruning, the canopy becomes too high, and the inner canopy is very dense, causing fruiting sites to shift toward the outer canopy. In this situation, flowers and fruits on the exposed outer layer are more likely to suffer from frost damage and sunburn, while the shaded inner canopy receives insufficient light, resulting in lower yield and poorer fruit quality. Loquat usually shows weak lateral branching ability, with long fruiting shoots and mainly terminal flower buds. This limits the number and uniform distribution of fruiting sites within a given canopy volume, making its productivity relatively lower compared with other pome fruit trees (Li et al., 2025). Differences among cultivars in shoot length, leaf–branch angle, and lateral branch number are closely related to hormone signaling pathways such as abscisic acid and strigolactones.

2.2 Flowering and fruiting characteristics

Loquat shows a unique flowering and fruiting pattern within the Rosaceae family. After a juvenile phase of about 4~6 years, the plant enters the adult reproductive stage, during which flower bud differentiation and flowering occur in autumn and winter, while fruit development continues throughout winter and fruits mature from early to mid-spring (Peng et al., 2022). The extended standardized BBCH scale divides its growth process into 7 main stages and 31 secondary stages, covering bud, leaf and shoot development, inflorescence formation, flowering, fruit development, and fruit ripening. There are significant differences among cultivars in phenological traits, including the onset and duration of flowering, the time from full bloom to maturity, and harvest time. Under Mediterranean or subtropical climates, some genotypes mature in early April, while others mature in late April or even later (Kaur, 2018; Kizil and Durgac, 2023). Loquat has large panicle inflorescences with many flowers and a naturally high fruit set rate. To obtain fruits that meet commercial size standards, thinning of flowers or fruits is usually required. Reducing the number of flower buds per inflorescence can increase fruit set, fruit size, and sweetness of the remaining fruits, mainly by reducing competition among sinks and improving the source–sink relationship of the tree. Flowering and fruit set are also affected by canopy orientation; under field conditions, the south side of the canopy usually shows higher flowering and final fruit set rates (Polat, 2015). Flowering time and floral initiation are regulated by at least two FT homologous genes (*EjFT1* and *EjFT2*), which respond to photoperiod and gibberellin signals; meanwhile, RAV transcription factors can delay flowering and extend the juvenile phase (Jiang et al., 2025).

2.3 Relationship between canopy structure and yield

Canopy structure determines the distribution of photosynthetically active radiation within the canopy, affects water transport and transpiration, and ultimately influences carbon acquisition and allocation. When trees are tall, unpruned, and have overly dense canopies, severe shading occurs inside the canopy, fruiting sites concentrate on the outer layer, and reproductive organs are more exposed to low temperature and sunburn, leading to reduced yield. In contrast, proper training and pruning that reduce tree height, open the canopy, and control branch number can improve light penetration and ventilation, and reduce the occurrence of pests and diseases. Vegetative growth parameters such as trunk cross-sectional area, shoot length, leaf area, and inflorescence size are significantly positively correlated with yield per tree and fruit size. This indicates that an optimal balance between vegetative growth and reproductive growth must be maintained by regulating canopy vigor and structure (Lin et al., 2025).

2.4 Sensitivity of loquat to pruning intensity and timing

In most production areas, loquat is usually pruned after harvest, generally from April to May. The summer shoots that emerge afterward complete flower bud differentiation and form flower buds by late summer or early autumn (Su et al., 2024). If pruning is too light, many weak shoots will participate in flowering, leading to excessive fruit set and smaller fruits. In contrast, overly heavy pruning may remove too many potential fruiting branches, reducing inflorescence number and overall yield. Removing about half of the vigorous summer shoots can effectively control inflorescence number, while promoting the remaining shoots to develop more leaves, thicker branches, and larger floral organs, ultimately improving fruit size. Regulation of vigorous shoots promotes cell division during floral organ development, and most fruit cell layers are formed before flowering. Therefore, any disturbance to shoot vigor or pruning timing before flowering can have a long-term effect on potential fruit size. Since loquat flowering and fruit development occur during cool or even cold seasons, any pruning or canopy-opening practice that changes the microclimate, light conditions, or temperature around the buds may affect the expression of key flowering regulatory genes such as *EjFT*s and *EjRAV*s, thereby influencing floral initiation, re-flowering ability, and fruit set (Peng et al., 2021).

3 Common Pruning Systems in Loquat Cultivation

3.1 Light pruning and its management characteristics

Loquat growers adopt various pruning systems, which differ in pruning intensity, timing, and objectives of canopy structure regulation, and these differences significantly affect subsequent fruit yield and quality. Light pruning is generally applied to mature trees whose canopy structure has already been established and whose production performance is stable. This method mainly involves removing dead branches, diseased branches, pest-damaged branches, crossing branches, and overly dense vegetative shoots, while retaining fruiting branch groups and the existing canopy framework as much as possible. By moderately opening up the canopy and improving internal light penetration and ventilation, light pruning helps maintain fruit quality and reduce disease occurrence without significantly reducing the number of inflorescences or overall yield (Li et al., 2005).

3.2 Moderate pruning and its application scenarios

Moderate pruning aims to more actively regulate shoot vigor, inflorescence density, and the balance between vegetative and reproductive growth, and thus has a more direct relationship with yield and quality optimization. In loquat production, a common moderate pruning practice is heading back fruiting shoots shortly after spring harvest. This heading treatment removes the terminal part of shoots that have just fruited, stimulating the emergence of strong summer shoots and limiting the total number of future inflorescences. These new shoots usually form flower buds in late summer or autumn and have a more appropriate leaf-to-fruit ratio, providing sufficient carbohydrate supply for fruit development. Moderate pruning is particularly suitable for trees with excessive flowering and small fruit size, or for orchards targeting high-end markets where large fruit size and high sugar content are prioritized over simply maximizing yield.

3.3 Heavy pruning and renewal strategies

Heavy pruning and renewal strategies are mainly applied when loquat trees become too tall, overly dense, or structurally aged. In unpruned or poorly managed orchards, the canopy is often large and crowded, with fruits concentrated on the outer parts, making them more susceptible to low-temperature damage and sunburn, while yield declines. Renewal pruning usually involves cutting back large upper branches or even main scaffold branches to reduce tree height and stimulate vigorous new shoot growth, thereby rebuilding the fruiting structure over several years. Although this relatively severe pruning reduces yield in the short term, it improves light distribution and canopy manageability. Once a new system of strong fruiting branches is established, it helps increase single fruit weight and enhances long-term yield stability.

3.4 Seasonal pruning methods (dormant period and growing season)

Due to the unique phenological characteristics of loquat (flowering in autumn–winter and maturing in late spring), the seasonal timing of pruning is critical. In many regions, the main pruning operations are carried out after harvest (April-May in subtropical East Asia), where fruiting shoots are headed back to promote summer shoot growth and induce flower bud formation later in the same year (Huang, 2025). This post-harvest pruning belongs to growing-season pruning and directly affects the number and vigor of flowering shoots. In contrast, pruning during the dormant period in late autumn or winter is usually lighter, mainly removing damaged or poorly positioned branches to optimize tree structure while avoiding disturbance to already differentiated inflorescences. In recent years, more intensive growing-season pruning systems have been developed, such as the annual "double heading" system: the first heading is performed after harvest on fruiting shoots, followed by a second heading in late summer or early autumn when small flower clusters just appear at the shoot tips. Although this seasonal pruning combination reduces the number of inflorescences, it promotes thicker shoots, more leaves, and larger inflorescences.

3.5 Structural pruning for canopy training

In the early stage of orchard establishment, structural training mainly involves key parameters such as planting density, trunk height, number and distribution of primary scaffold branches, and branch angles. Studies based on three-dimensional canopy models of loquat indicate that the angle between secondary scaffold branches and the trunk is about 15°, while the angle between adjacent secondary scaffold branches is 60°~90° (Tang et al., 2019) (Figure 1). In production practice, corresponding technical systems have been developed. A patented method in China specifies a trunk height of 60 cm and a planting spacing of 4 m × 4 m; in the first year, every fourth axillary bud is selected as a primary branch; in the second year, ropes are used to pull the primary branches outward; in the third year, the primary branches are fixed to bamboo poles to form an angle of about 77° with the trunk; in the fourth year, after flowering and fruit set, the central leader is removed, and excessive vegetative shoots are thinned at a certain ratio to form a low, open canopy with evenly distributed fruiting branches. Compared with untrained control trees, optimized structures such as the hierarchical central leader or low-canopy system not only advance the bearing period and increase fruit set rate by about 5%~6%, but also increase fruit weight by 35%-61% and improve soluble solid content (Li et al., 2005).

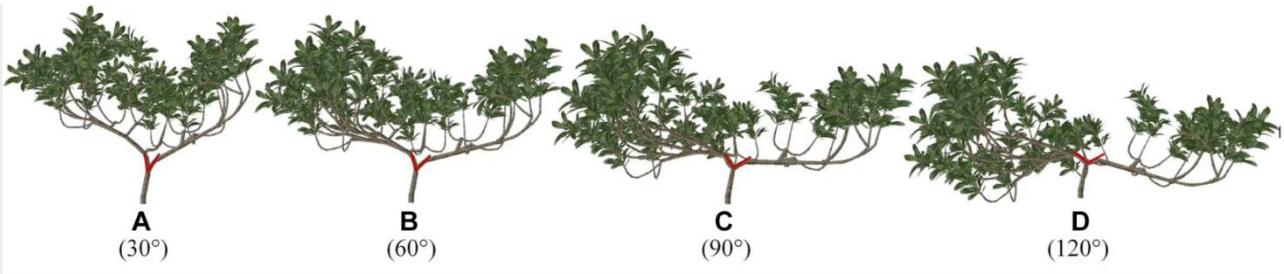

Figure 1 (A-D) Virtual representation of loquat morphology for different angles. The angle of the red line represents the angle below, that is, the angle of the level 2 scaffold branch in the three-dimensional space. The model was generated by the fast shaping and pruning function. The model information is the same for all scenarios, except for the angle (Adopted from Tang et al., 2019)

4 Effects of Pruning Methods on Vegetative Growth

4.1 Effects on shoot growth and branching

At the shoot level, post-harvest heading pruning can promote the sprouting of latent buds and the formation of new summer shoots, increasing the number of branches and leaf area on retained shoots. In recent years, a "double heading" pruning method has been developed. This involves one heading cut on fruiting shoots after harvest, followed by a second heading when small inflorescences form at the shoot tips in late summer. This approach can produce more vigorous new shoots. These shoots are usually thicker and have darker green leaves, indicating stronger photosynthetic capacity and higher vegetative vigor. Compared with the traditional single heading method, the effect is more obvious. The pruning intensity on a single shoot can regulate the total number of new shoots, shoot length, and leaf size. A moderate pruning level (removal of about 0.79~1.07 cm of woody tissue) is most favorable for new shoot formation and leaf development. Too light pruning cannot effectively stimulate renewal, while too heavy pruning may suppress inflorescence formation and reduce subsequent yield (Liu et al., 2008). For weakened or declining trees, heavy heading of large branches can reduce tree height and induce strong shoot regeneration. However, this vigorous vegetative growth may also divert nutrients in the short term and suppress reproductive growth.

4.2 Effects on canopy density and light distribution

Pruning also reshapes canopy density and internal light conditions by changing the number, length, and spatial distribution of branches. Branch angle and branch number are key factors determining light interception within the canopy. Without pruning, loquat trees often become too tall and overly dense, with leaves concentrated in the upper outer canopy. This leads to poor ventilation and insufficient light inside the canopy, resulting in low fruit set and higher disease risk. Through structural pruning and branch training (widening branch angles), a lower and more open canopy structure can be maintained. This reduces canopy volume and porosity gradients and improves light use efficiency both on the canopy surface and inside. Studies on other evergreen fruit trees support this pattern: although heavy pruning can quickly stimulate vegetative recovery, moderate pruning combined with proper pruning position is more beneficial for maintaining a compact canopy with good ventilation and light penetration in the long term (Jiménez-Brenes et al., 2017; Lodolini et al., 2023).

4.3 Regulation of the balance between vegetative and reproductive growth

Loquat fruit develops over a long period, from flowering in autumn–winter to harvest in late spring. The fruit clusters act as strong sinks and can suppress bud sprouting and limit shoot elongation. Comparisons between fruiting and defruited trees show that the presence of fruit significantly reduces bud sprouting in winter and early spring and shortens shoot length. In contrast, removing inflorescences or fruits promotes earlier bud sprouting and enhances vegetative growth across different seasons (Reig et al., 2014). This "sink effect" is partly mediated by hormonal changes. In fruiting trees, buds have higher levels of indole-3-acetic acid (IAA) and lower levels of zeatin, leading to a higher IAA/zeatin ratio, which is associated with suppressed bud growth. When the sink is removed, this ratio decreases, which favors the activation of vegetative buds. Excessive pruning may push the tree toward overly vigorous vegetative growth, delaying or reducing flower bud differentiation.

In loquat, genes such as *EjTFL1* and *EjRAV1/2* promote vegetative growth and branching while inhibiting flowering integrators (EjFTs and EjSOC1s). High expression of these genes can extend the juvenile phase or delay flowering transition (Jiang et al., 2020; Peng et al., 2021). By adjusting pruning intensity and timing (such as post-harvest heading and late-summer secondary heading), and by controlling shoot vigor and crop load, pruning systems can indirectly influence the expression window of these regulatory networks. This helps maintain a functional balance in the tree, ensuring both adequate vegetative renewal and stable reproductive capacity.

5 Effects of Pruning Systems on Fruit Yield

5.1 Effects on flower bud formation

The pruning system of loquat mainly regulates fruit production by controlling flower bud formation, fruit set and retention, and the final balance between fruit number and size. Heading-back pruning and its timing determine the vigor and leaf area of fruiting shoots (inflorescence-bearing shoots), thereby affecting the differentiation and development of flower buds. Strong shoots produced under an annual double-heading pruning system usually have thicker stems, more leaves, and significantly larger inflorescences compared with those under traditional single heading-back pruning. This indicates that enhanced cell division and floral organ growth during the flower bud stage are key driving factors for later fruit enlargement. Regulation of inflorescence "sink strength" also influences flowering dynamics at the whole-tree level: removing the main inflorescence can induce re-flowering, but the secondary inflorescences have fewer flower buds and branch axes, resulting in lower fruiting potential per inflorescence, while effectively extending the flowering and fruiting period by 2~4 months (Peng et al., 2022).

5.2 Fruit set and fruit retention performance

Experiments on manual thinning of loquat flower buds during the full bloom stage showed that retaining 4 flower buds per inflorescence, compared with retaining 12 buds, increased the fruit set rate per cluster by about 15%. This may be due to reduced competition for assimilates within the cluster and improved early source-sink relationships (Nordi et al., 2025). Studies combining flower and fruit thinning with bagging treatments indicate that reducing flower number can increase fruit set rate by up to 49%. Pruning strategies that create a moderate inflorescence load-either by reducing the number of fruiting shoots (such as double-heading) or by fine-scale thinning within inflorescences—can improve fruit set efficiency and reduce early fruit drop. In contrast, excessive flower density may suppress effective fruit set when the initial flower number is too high.

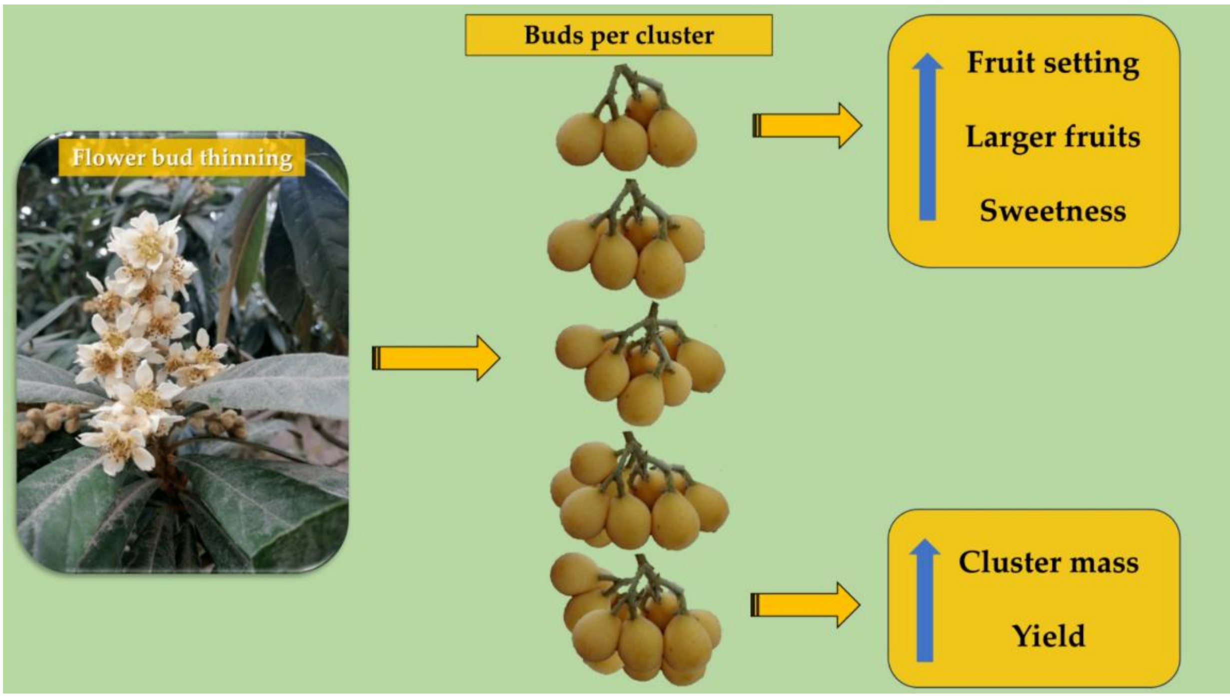

Figure 2 Effect of flower bud thinning on fruit set, fruit size, sweetness, and yield in clustered fruits (Adapted from Nordi et al., 2025)

5.3 Changes in fruit number and size

Loquat fruits show a single S-shaped growth curve under both heavy thinning and no-thinning conditions, but the growth curve under thinning is steeper, resulting in larger final fruit size, indicating stronger sink strength of individual fruits. Seed number and seed size are the main factors determining final fruit size, while leaf area per shoot shows only a weak correlation with fruit size. This highlights the importance of regulating fruit load based on the inherent sink capacity of fruits (Cuevas et al., 2003). At the shoot level, double-heading shows a similar pattern: this strong pruning method reduces the number of flowering shoots but produces larger flowers and significantly larger fruits. This is associated with enhanced cell division during early fruit development and downregulation of fruit weight-related genes (EjFWL1/2) (Su et al., 2024).

5.4 Overall yield performance under different pruning systems

At the cluster level, retaining more flowers can maximize yield per cluster, but this is often accompanied by smaller fruits and lower market value. At the whole-tree level, pruning methods that moderately reduce fruit number while significantly increasing average fruit weight and quality can improve the proportion of premium fruits and economic returns, even if total fruit number decreases. Double-heading can increase single fruit weight by about 35%, cluster weight by 32%, and the proportion of premium fruits (>65 g) to over 75%, resulting in more than a 60% increase in yield value per unit area compared with conventional pruning (Xu et al., 2013). For declining trees, heavy heading-back pruning can increase single fruit weight and gradually restore yield as the canopy is renewed. When these findings in loquat are combined with evidence from citrus (for example, increasing pruning intensity-removing up to 75% of main branches—can raise yield per tree by nearly 20% and improve fruit size and internal quality) (Al-Saif et al., 2023), a consistent pattern emerges: well-designed pruning systems regulate canopy vigor and fruit load, combined with flower and fruit thinning, shifting production from “many small fruits” to “fewer large, high-value fruits.” Even if the absolute number of fruits decreases, economic yield usually increases.

6 Effects of Pruning Systems on Fruit Quality

6.1 External fruit characteristics (size, uniformity, color)

Compared with retaining 10~12 flower buds per panicle, keeping only 4 buds can produce loquat fruits with greater single-fruit weight as well as larger longitudinal and transverse diameters, mainly because competition among “sinks” is reduced (Nordi et al., 2025). Consumers generally prefer fruits that are larger, have a higher flesh proportion, and contain smaller seeds, which confirms the commercial importance of pruning and thinning practices that reduce crop load to increase fruit size. Double-heading pruning promotes the formation of strong fruiting shoots with thicker branches and more leaves, which supports the development of larger floral organs and further increases fruit size, reflecting enhanced cell division during the early stages of fruit development. After thinning, fruit bagging can improve external quality by enhancing peel color and reducing surface defects. Aluminum-polyethylene composite bags increased fruit weight, length, and width to 1.37, 1.18, and 1.13 times those of the control, respectively, while also increasing peel thickness and edible rate, and significantly reducing sunburn, black spots, and damage from insects and birds (Zhi et al., 2021).

6.2 Internal quality (soluble solids, acidity, flavor balance)

Pruning, by regulating crop load and canopy microclimate, also affects internal fruit quality traits such as soluble solid content, titratable acidity, and their ratio, which together determine flavor balance. In flower bud thinning experiments, retaining 4 buds per panicle significantly increased soluble solids content and maturity index compared with higher crop load treatments, indicating sweeter fruits and a more balanced sugar-acid ratio at harvest. This improvement is mainly due to a more favorable source-sink relationship, allowing more carbohydrates to be allocated to each fruit. Although mineral nutrition is an important factor influencing internal quality-for example, Ca, Mg, Fe, and N levels in leaves and soil can significantly affect fruit weight, soluble solids, and titratable acidity-pruning systems can indirectly interact with these factors by adjusting leaf area per fruit and improving assimilate use efficiency (Huang et al., 2021). Fruits treated with paper bags showed the highest soluble sugar content and the lowest titratable acidity, with a sugar-acid ratio nearly twice that of unbagged fruits. Aluminum bags and aluminum-polyethylene composite bags slightly increased titratable acidity and some amino acids, but still improved the overall sugar–acid balance and enhanced fruit firmness.

6.3 Nutritional quality and market value

Larger fruits with a higher flesh proportion can increase economic returns, as buyers are more willing to pay a premium for loquats that are large, have small seeds, and show good appearance. Double-heading pruning, by promoting vigorous shoot growth and larger fruits, can indirectly enhance nutrient accumulation, mainly due to the increase in the edible portion of each fruit. Bagging treatments significantly improve the “health” level of fruit-that is, the proportion of undamaged, marketable fruits-by reducing sunburn, decay, black spots, and insect or bird damage. The proportion of healthy fruits increases by 75%~144% compared with unbagged controls, depending on the type of bag (Zhi et al., 2021). Aluminum-polyethylene bags are associated with higher carotenoid content and various amino acids, while paper and aluminum bags show positive relationships with phenolic compounds and proline, suggesting that microenvironment regulation can also influence bioactive compounds related to antioxidant capacity and nutritional value. Since fruit quality (size, flavor, and nutritional composition) directly determines grading and commercial value, pruning strategies that promote effective thinning and facilitate bagging can significantly increase overall market value per unit area, even when total fruit number is reduced.

7 Comparative Evaluation of Pruning Systems

7.1 Trade-off between yield and fruit quality

Comparative evaluation of loquat pruning systems clearly shows that yield, fruit quality, labor efficiency, and long-term orchard performance are jointly determined by how pruning regulates crop load, canopy structure, and vegetative vigor. Flower thinning in loquat reflects a typical "yield-quality" continuum: when 12 flower buds are retained per panicle, cluster weight and yield per tree reach their maximum; reducing to 4 buds per panicle lowers total yield but significantly increases individual fruit weight, fruit size, and sweetness. This indicates that stronger crop load regulation shifts production from yield-oriented to high-quality fruit production (Nordi et al., 2025). The double heading-back pruning system produces more vigorous fruiting shoots with more leaves and thicker branches. By concentrating resources on fewer but more efficient fruiting units, this system not only enlarges fruit size but also improves yield, and to some extent alleviates the traditional trade-off between fruit size and yield by enhancing early cell division.

7.2 Suitability of pruning systems under different orchard conditions

In high-density orchards of olive, apple, and similar species, combining winter structural pruning with summer pinching or hedging can control tree size and improve the balance between vegetative and reproductive growth, while maintaining or even increasing yield. However, if mechanical pruning is too frequent or too severe, yield or fruit size may decrease under limited light conditions. In high-density or overly vigorous loquat orchards, a pruning system with periodic heavy heading-back or partial renewal, combined with mechanized operations and manual fine adjustments, is more suitable for maintaining canopy openness, controlling tree height, and achieving uniform high-quality production. In contrast, in low-density orchards or those with weak vigor, a simpler and lighter pruning approach can be adopted.

7.3 Effects of tree age and vigor on pruning outcomes

The double heading-back pruning system in loquat has been developed in mature commercial orchards. By conducting summer pruning and a second heading-back in late summer or autumn, strong new shoots are induced, which can form larger inflorescences and fruits in subsequent years. In older citrus and apricot trees, strong renewal pruning combined with adequate nutrient supply can restore canopy growth, improve fruit set, and rebuild productivity. However, in young or weak trees, excessive pruning may have negative effects, delaying fruiting and reducing yield (Sharma et al., 2025). Experiments in high-density olive cultivation show that staged pruning (winter plus summer) is particularly effective in young and vigorous trees, helping to stabilize yield and maintain a compact canopy structure (Lodolini et al., 2023).

8 Practical Applications in Loquat Orchard Management

8.1 Pruning strategy recommendations for high-yield production

Under high-yield production conditions, pruning should prioritize maintaining a sufficient number of fruiting shoots and a stable source-sink relationship, rather than simply pursuing larger individual fruit size. In traditional cultivation systems, post-harvest pruning from spring to early summer promotes the formation of summer shoots, which undergo flower bud differentiation in late summer. Under this system, usually only about half of the inflorescences are retained for commercial production. Double-heading refers to the first heading after harvest, followed by a second pruning of the resulting summer shoots, removing about half of the branches. This method produces fewer but stronger fruiting shoots with thicker branches and higher leaf chlorophyll index, thereby enhancing carbohydrate supply. Compared with single heading, it can improve both fruit size and overall yield. For orchards where yield is the main goal, moderate control of inflorescence number helps increase cluster weight and yield per plant, although the average fruit size may decrease. Combined with a reasonable nitrogen-potassium fertilization ratio, it can promote vigorous shoot growth while avoiding excessive vegetative growth and shading.

8.2 Pruning strategies for improving fruit quality

When high-quality fruit production is the main objective, pruning and load regulation should be adjusted toward "fewer but better," producing fewer fruits that are larger, sweeter, and more uniform. During full bloom, thinning flower buds to retain only a few per cluster can consistently result in larger fruit, higher soluble solids content, and better appearance quality, although total yield will be lower compared with treatments retaining more buds. Double-heading promotes strong branch growth, enhances early cell division, and downregulates the expression of cell division inhibitors EjFWL1/2 in flower buds, significantly increasing single fruit weight and the proportion of premium-grade fruit. In practice, combining these measures (such as cultivating strong fruiting shoots through annual double-heading pruning and applying moderate flower thinning) can significantly improve average fruit weight and the proportion of high-quality fruit. Pruning also improves canopy ventilation and light penetration (by removing diseased, weak, crossing, and inner canopy branches and maintaining proper spacing of fruiting shoots), which promotes fruit coloration, reduces disease incidence, and enhances fruit uniformity—critical for meeting the high standards of the fresh fruit market. In addition, bagging fruit clusters with breathable paper or plastic bags can be used; studies have shown that this practice significantly improves fruit firmness, soluble solids content, and peel color (Hussain et al., 2024).

8.3 Integration with other management practices (fertilization, irrigation, planting density)

Effective pruning must be integrated with fertilization, irrigation, and planting design to achieve synergistic effects and avoid management imbalance. There is a significant interaction between autumn pruning and nitrogen-potassium management: maintaining an appropriate N-K ratio after pruning helps promote shoot growth, flower bud differentiation, cell division, and fruit enlargement, thereby improving yield and quality in the next season. Excessive nitrogen supply combined with insufficient pruning can lead to excessive vegetative growth, canopy shading, and reduced fruit quality. In contrast, combining light to moderate pruning with optimized nitrogen application can significantly improve tree vigor, fruit set, and productivity in older apricot trees (Sharma et al., 2025). Post-harvest and pre- plus post-harvest deficit irrigation strategies can advance flowering and harvest time, save about 18%~30% of irrigation water, and in some cases increase early yield; when drought periods are properly scheduled, fruit size is little affected or not negatively affected (Hueso et al., 2021). In semi-arid regions, combining such deficit irrigation with canopy size control through pruning is particularly important, as water resources must be allocated among multiple crops. Planting density and canopy structure determine the intensity and timing of pruning: high-density orchards require more frequent topping and lateral pruning to control tree height and maintain good light conditions. In high-density olive and mango systems, staged pruning has been shown to improve yield and water use efficiency (Hahn et al., 2022).

8.4 Common mistakes and optimization strategies

Common problems in loquat pruning include: excessive retention of inflorescences and flower buds, resulting in small fruit and low sugar content; improper or overly intense structural pruning, causing tree stress and reduced short-term yield; and neglect of canopy structure management, leading to overly tall trees, dense inner canopies, and outward migration of fruiting sites. Poor coordination between pruning and fertilization may result in either poor recovery of heavily pruned trees due to insufficient nutrients, or excessive vegetative growth and suppressed fruiting under excessive nitrogen supply. In regions using deficit irrigation, failure to adjust pruning intensity accordingly may cause excessive pruning to exacerbate water stress and hinder tree recovery.

Optimization strategies include: adopting standardized and easily applicable pruning systems, such as renewal pruning or double-heading techniques, to systematically update fruiting branches and improve scaffold branch quality; adjusting flower thinning intensity based on market goals (e.g., retaining four flower buds per cluster for high-quality production, or increasing slightly for higher yield); using digital or empirical canopy light assessment methods to guide branch angle and density adjustments; and dynamically adjusting nitrogen–potassium ratios and irrigation regimes according to pruning intensity to support vigorous and balanced regrowth (Ballester et al., 2018). In addition, strengthening training for pruning personnel and implementing a phased approach—testing new techniques in small orchard areas before wider application—can help reduce risks while continuously optimizing pruning systems suited to local varieties and ecological conditions.

9 Conclusion and Prospects

Loquat shows a high response to pruning, and a well-designed pruning system is one of the key factors determining fruit yield and quality. Pruning mainly works by regulating canopy structure, light distribution, and the balance between vegetative and reproductive growth. Light and moderate pruning are generally beneficial for maintaining a stable balance between shoot renewal and flower bud formation. Although heavy pruning and renewal pruning may reduce yield in the short term, they can rejuvenate the tree, improve canopy ventilation, and restore long-term productivity. The timing of pruning, as well as its coordination with other orchard management practices, has a significant impact on both fruit appearance and internal quality.

From a practical perspective, growers should avoid adopting a single, rigid pruning pattern. Instead, pruning strategies should be flexibly adjusted according to tree age, tree vigor, cultivar, and planting density. For young trees, training pruning should be the main focus, aiming to establish a well-structured and evenly distributed framework, and to form an open and moderately dense canopy that allows sufficient light penetration. During the full bearing period, moderate annual pruning should be applied, mainly removing overly vigorous branches, crowded branches, and crossing branches, in order to maintain good ventilation and light conditions and promote the formation of fruiting shoots on well-exposed branches. At the same time, appropriate flower and fruit thinning should be combined to regulate crop load and improve fruit size and uniformity. In old or declining orchards, heavy pruning or renewal pruning can be implemented in stages, renewing part of the canopy to stimulate new shoot growth while maintaining a basic level of yield. Throughout the whole growth cycle, pruning should also be coordinated with fertilization, irrigation, pest and disease control, and harvest scheduling, so as to reduce plant stress and avoid excessive vegetative growth.

Looking ahead, improving pruning efficiency and orchard productivity in loquat requires integrating physiological understanding, technological innovation, and precision management. Future research should further clarify the quantitative relationships among pruning intensity, canopy light environment, and source–sink relationships, so as to establish more predictive models for yield and quality responses. The application of remote sensing, digital canopy imaging, and three-dimensional modeling is expected to enable objective evaluation of canopy structure and provide a scientific basis for precision pruning. Mechanized or semi-mechanized pruning tools adapted to loquat canopy characteristics can help reduce labor costs and improve operational consistency. In addition, decision support systems that integrate meteorological data, tree vigor indicators, and historical yield records can assist growers in optimizing pruning timing and intensity under changing climate conditions. By combining these technological advances with improved cultivar breeding, high-density planting systems, and sustainable soil and water management, loquat orchards are expected to achieve higher productivity, better fruit quality, and stronger adaptability to environmental and market changes in the future.

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