Bioscience Evidence 2026, Vol.16, No.2, 104-113
http://bioscipublisher.com/index.php/be

Feature Review **Open Access**

Effects of Rain Shelter Cultivation on Cherry Fruit Cracking and Quality

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Bioscience Evidence, 2026, Vol.16, No.2 doi: 10.5376/be.2026.16.0009
Received: 20 Feb., 2026
Accepted: 27 Mar., 2026
Published: 16 Apr., 2026

Preferred citation for this article:
Wang H.P., and Yu S.Y., 2026, Effects of rain shelter cultivation on cherry fruit cracking and quality, Bioscience Evidence, 16(2): 104-113 (doi: 10.5376/be.2026.16.0009)

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).

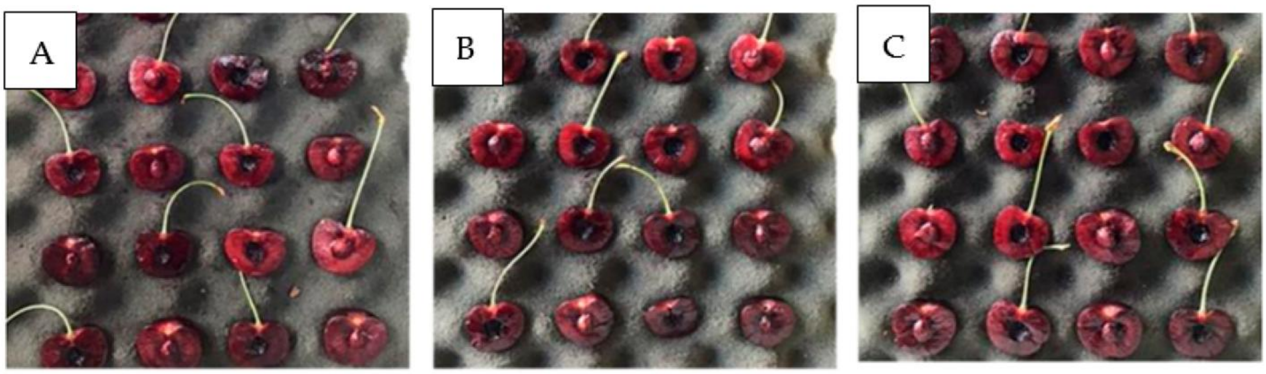

Figure 1 Fruit condition at post-harvest of sweet cherries (cv. Regina) subjected to one control (without reflective film) (A), one treatment with reflective film placed at 21 DBH (B), and a second treatment with reflective film placed at 34 DBH (C) (Adopted from Muñoz-Alarcón et al., 2025)

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).

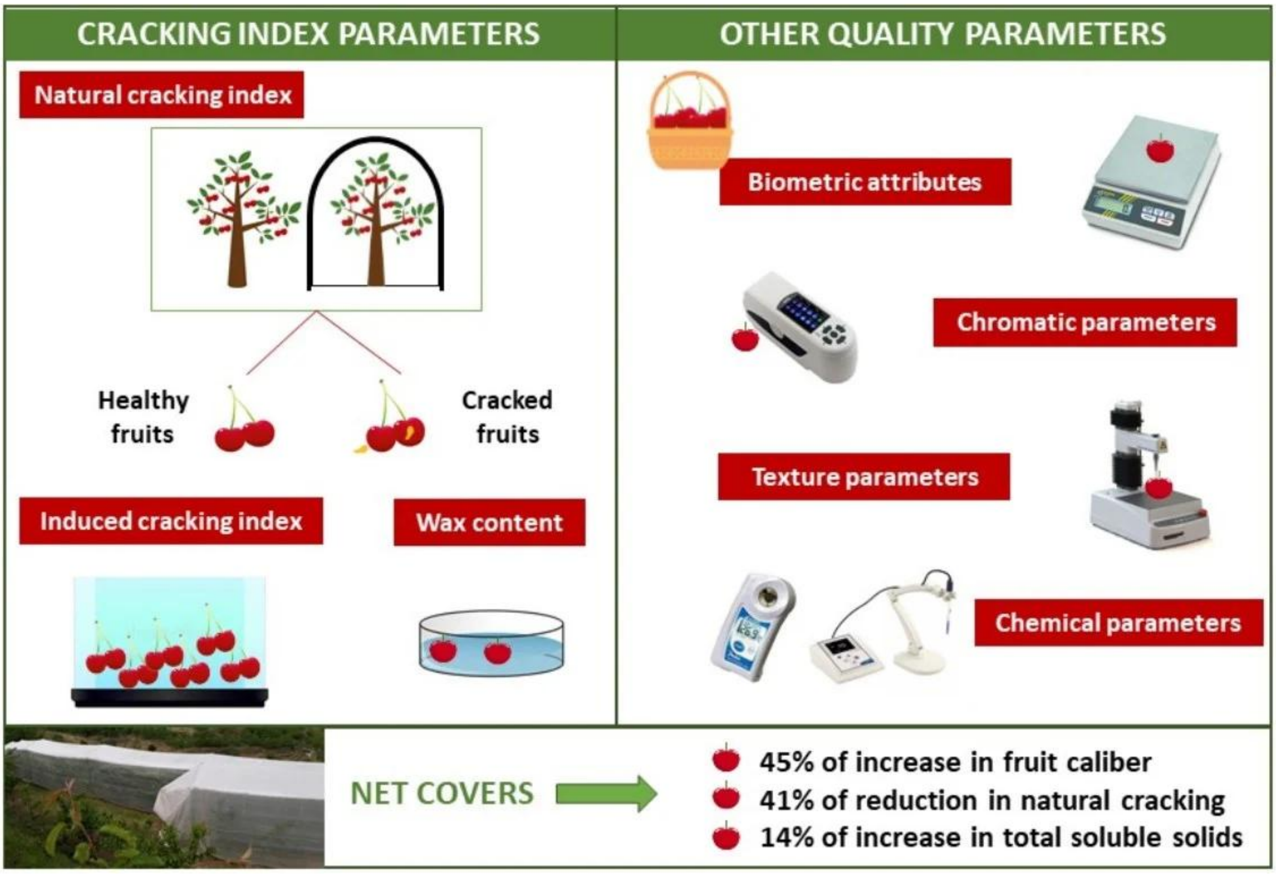

Figure 2 Comparison of fruit cracking and quality parameters of cherries under protective net covering systems (Adapted from Gonçalves et al., 2023)

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).

Author Contributions

We extend our sincere gratitude to the anonymous reviewers for their valuable and insightful comments, which have greatly strengthened this manuscript.

Conflict of Interest Disclosure

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

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