REVIEW ARTICLE Agricultural Reviews, Volume 47 Issue 2: 258-266 (April 2026)

Integrated Management Practices for the Recovery Process in Fruit Trees and Grapevines Exposed to Late Spring Frosts: A Review

Ali İkinci[1]

10.18805/ag.RF-391

ABSTRACT

Late spring frosts cause significant physiological disruptions and substantial yield losses in fruit trees and grapevines cultivated in temperate climates. This review delves into the complex mechanisms of frost injury, including ice crystal formation, membrane instability, dehydration and oxidative stress, which lead to irreversible cellular and tissue damage. The threat is exacerbated by accelerated climate change, which shifts spring phenology earlier and increases the frequency and intensity of frost events. This article provides a comprehensive review of integrated management strategies designed to minimize damage and promote recovery in frost-affected orchards and vineyards. The review systematically examines various methods, including systematic damage assessment, post-frost pruning timing and techniques, water and nutrient management and the use of biostimulants. The paper also discusses proactive measures to prevent secondary stress factors and outlines physiological and structural strategies to ensure long-term productivity. The synthesis of existing literature demonstrates that a combination of integrated management strategies is crucial for accelerating the recovery process of frost-affected plants. The review concludes that the timely and accurate assessment of damage, coupled with strategic cultural practices such as post-frost pruning and careful management of water and nutrients, is essential for mitigating yield losses and maintaining long-term productivity and economic viability.

Key words: Climate change, Frost, Fruit trees, Grapevines, Management strategies, Recovery.

Fruit trees and grapevines are perennial crops cultivated in temperate climate zones, holding significant economic and nutritional importance. During their annual life cycle, the vegetative and generative growth period that begins in spring after winter dormancy represents a critical phase during which these plants are most vulnerable to environmental stress factors (Yadav, 2015; Matzneller *et al*., 2016; Charrier *et al*., 2018; Vitasse *et al*., 2018; Masaki, 2020). Sudden temperature drops and late frost events occurring during these sensitive periods-especially at crucial phenological stages such as flowering or early fruit/cluster formation-can cause severe damage to plant tissues and lead to substantial yield losses, thereby negatively impacting agricultural production. In addition to fruit crops, frost is also recognized as a major abiotic stress in ornamental plants such as roses, where it not only impairs flower opening and induces wilting but also leads to visible symptoms including leaf curling, chlorosis and reduced aesthetic value, ultimately lowering their commercial quality (Khaskheli *et al*., 2021).

The accelerating effects of global climate change have resulted in the advancement of spring phenology (Bigler and Bugmann, 2018; Vitasse *et al*., 2018; Lamichhane *et al*., 2021) and an increase in unpredictable variability in weather patterns, complicating and challenging frost risk management (Augspurger, 2013; Faust and Herbold, 2017; Parker *et al*., 2021). The likelihood of frost events coinciding more frequently and severely with the early developmental stages during which plants are highly susceptible to frost has increased. In Türkiye, a key country for fruit and viticulture production, spring late frosts have become a recurrent problem with serious socio-economic consequences due to climate change (Kayan, 2025; Yıldırım, 2025). The severe frost events across Türkiye in April 2025 caused significant yield losses ranging from 50% to 80% in many fruit species such as apple, pear, apricot, almond, cherry, peach, hazelnut, mulberry, walnut and olive, as well as in vineyards, underscoring once again the destructive impact of frost on agricultural production and the urgency of addressing this risk (Anonymous, 2025; Kayan, 2025; Yıldırım, 2025).

Frost damage not only jeopardizes the current year's yield but also adversely affects the physiological health, growth form and yield potential of trees and vines in subsequent years. This amplifies the importance of implementing effective, science-based post-frost management strategies. This paper comprehensively examines the

[1]Department of Horticulture, Faculty of Agriculture, Harran University, Şanlıurfa, Türkiye.

Corresponding Author: Ali İkinci, Department of Horticulture, Faculty of Agriculture, Harran University, Şanlıurfa, Türkiye. Email: aliikinci@harran.edu.tr

How to cite this article: İkinci, A. (2026). Integrated Management Practices for the Recovery Process in Fruit Trees and Grapevines Exposed to Late Spring Frosts: A Review. *Agricultural Reviews*. **47(2):** 258-266. doi: 10.18805/ag.RF-391.

Submitted: 28-05-2025 **Accepted:** 21-10-2025 **Online:** 28-10-2025

physiological effects of spring late frosts on fruit trees and grapevines, discusses accurate assessment methods for frost damage and evaluates integrated cultural and management strategies that should be applied to accelerate plant recovery, restore health and secure next year's yield in frost-affected orchards. The aim is to provide growers and agricultural professionals with a practical guide grounded in up-to-date scientific knowledge to optimize post-frost recovery and long-term yield management processes.

Physiological and biochemical mechanisms of frost damage in plant tissues

Damage in plant tissues exposed to freezing temperatures is the result of complex physiological and biochemical processes. These processes are triggered by the freezing of intracellular or intercellular water, which can lead to irreversible injuries in plant tissues (Yadav, 2015; Salazar-Gutiérrez *et al*., 2014; Faust and Herbold, 2017; Choi *et al*., 2025). The main mechanisms of frost injury are detailed below:

Formation of extracellular ice crystals and dehydration

Freezing typically initiates in the extracellular spaces between plant cells. Water in these regions has a higher freezing point compared to intracellular water, facilitating ice nucleation more readily (Baek and Skinner, 2012; Yadav, 2015; Matzneller *et al*., 2016). The formation and expansion of extracellular ice crystals decrease the solute concentration and osmotic potential of the surrounding solution. To restore osmotic equilibrium, water inside the cells-where water potential is higher-passively moves through the plasma membrane toward the ice surfaces in the extracellular matrix (Yadav, 2015; Baek and Skinner, 2012; Matzneller *et al*., 2016; Faust and Herbold, 2017).

This water loss leads to severe dehydration within the cell, resulting in plasmolysis, where the plasma membrane detaches from the cell wall and shrinks (Matzneller *et al*., 2016; Baek and Skinner, 2012). Severe dehydration disrupts the structural and functional integrity of the plasma membrane, leading to cellular imbalances and a breakdown of metabolic activity (Baek and Skinner, 2012; Faust and Herbold, 2017).

Intracellular ice formation and irreversible cellular injury

If the temperature drops rapidly or if plant tissues lose their ability to supercool (*i.e*., remain liquid below freezing point), ice crystals may form inside the cytoplasm (intracellular ice formation) (Baek and Skinner, 2012; Yadav, 2015; Faust and Herbold, 2017; Bigler and Bugmann, 2018; Poni *et al*., 2022). Intracellular ice is generally lethal, as it causes direct physical rupture of the plasma membrane and organelle membranes (*e.g*., mitochondria and chloroplasts) (Salazar-Gutierrez *et al*., 2014; Yadav, 2015; Faust and Herbold, 2017). This mechanical damage irreversibly disrupts vital cell functions and quickly leads to cell death.

Destabilization of the plasma membrane and electrolyte leakage

Low temperatures can alter the physical properties of membrane lipids, which are the main components of the plasma membrane. Under freezing conditions, the lipid bilayer transitions from a fluid-crystalline state to a more rigid and ordered gel phase (Baek and Skinner, 2012; Faust and Herbold, 2017; Bigler and Bugmann, 2018; Poni *et al*., 2022). This phase transition impairs membrane fluidity, permeability and integrity, compromising the membrane's ability to regulate intracellular and extracellular exchange. Consequently, essential ions (*e.g*., K^+,Ca^{2+}) and solutes (sugars, amino acids) leak out of the damaged membrane, a phenomenon known as electrolyte leakage (Baek and Skinner, 2012; Faust and Herbold, 2017; Bigler and Bugmann, 2018; Poni *et al*., 2022). The extent of electrolyte leakage is commonly used as a physiological indicator to assess the severity of frost injury.

Accumulation of reactive oxygen species (ROS) and oxidative stress

Abiotic stresses such as frost can disrupt metabolic activity and electron transport chains, leading to an overproduction of reactive oxygen species (ROS) (Baek and Skinner, 2012; Faust and Herbold, 2017; Masaki, 2020). ROS-including superoxide anions (O_2^-), hydrogen peroxide (H_2O_2) and hydroxyl radicals (OH·)- are highly reactive molecules that cause macromolecular damage such as lipid peroxidation, protein denaturation and DNA injury, ultimately triggering cell death (Baek and Skinner, 2012; Faust and Herbold, 2017; Bigler and Bugmann, 2018; Masaki, 2020; Poni *et al*., 2022). Plants have developed defense mechanisms against ROS damage, including enzymatic antioxidants like superoxide dismutase (SOD), catalase (CAT) and peroxidases (POD), as well as non-enzymatic antioxidants such as ascorbic acid, glutathione and tocopherols (Baek and Skinner, 2012; Faust and Herbold, 2017; Masaki, 2020). However, severe or prolonged freezing stress may overwhelm these systems, exacerbating oxidative stress-induced cell injury.

Disruption in the photosynthetic system and carbohydrate metabolism

Chloroplasts are among the most frost-sensitive organelles. Low temperatures can cause damage to chloroplast membranes, disrupt thylakoid structures and lead to the degradation of photosynthetic pigments such as chlorophyll and carotenoids (Baek and Skinner, 2012; Faust and Herbold, 2017; Masaki, 2020). In particular, the activity of Photosystem II (PSII) is negatively affected by low temperatures, disrupting the photosynthetic electron transport chain. This results in reduced production of energy carrier molecules like ATP and NADPH and a decline in CO_2 assimilation (carbon fixation) (Baek and Skinner, 2012; Bigler and Bugmann, 2018; Poni *et al*., 2022). The decrease in photosynthesis severely limits the production of carbohydrates (sugars and starch), which are essential

for plant growth, repair and energy storage. During post-frost recovery, plants require sufficient carbohydrate reserves and active photosynthetic function to regenerate new tissues and repair damaged ones.

Sensitivity differences based on phenological stage and plant organs

Plants' sensitivity to frost varies significantly depending on species, cultivar, degree of cold hardiness and the phenological stage at which frost occurs (Rodrigo, 2000; Larsen, 2010; Yadav, 2015; Faust and Herbold, 2017; Bigler and Bugmann, 2018; Charrier *et al*., 2018; Poni *et al*., 2022). During winter dormancy, plant organs exhibit high resistance to frost due to low water content and the accumulation of protective compounds (*e.g*., soluble sugars, proline, antifreeze proteins) (Baek and Skinner, 2012). However, with rising spring temperatures, plants undergo a dehardening process, increasing tissue water content and raising the freezing point, which significantly increases frost sensitivity (Larsen, 2010; Matzneller *et al*., 2016).

As plant development progresses, sensitivity to frost increases and the critical freezing temperatures (Tc) vary among different organs. In agreement with this, Rimpika *et al*. (2021) reported that insufficient winter chill leads to irregular flowering, poor pollination and even complete crop failure in temperate fruit trees, highlighting the increasing vulnerability of traditional production areas. The most sensitive phenological stages are typically bud break, flowering and early fruit/cluster development (Rodrigo, 2000; Larsen, 2010; Baek and Skinner, 2012; Bigler and Bugmann, 2018). For instance, in apples, critical temperatures for flower organs vary between -2.2°C and -3.7°C depending on the phenological stage, but temperatures below -2°C during full bloom can cause severe damage (Larsen, 2010; Masaki, 2020). In pears, the king bloom (first-opening flowers in the cluster) is usually the most vulnerable (Larsen, 2010).

Flower buds and flowers

Reproductive organs are the most frost-sensitive plant parts due to their high water content and thin membranes (Rodrigo, 2000; Larsen, 2010). During flowering, pistils, stamens and petals can freeze easily. Freezing of the pistil is typically indicated by internal browning, which directly prevents fertilization and results in complete loss of fruit set (Larsen, 2010; Faust and Herbold, 2017; Bigler and Bugmann, 2018; Charrier *et al*., 2018; Poni *et al*., 2022). Sensitivity to frost during flowering varies greatly among different fruit species and cultivars.

Young fruits/clusters

Young fruits and grape clusters developing after flowering are also highly susceptible to frost damage (Larsen, 2010; Yıldırım, 2025). Frosted young fruits may exhibit tissue necrosis, deformities (frost rings), or complete abscission (Larsen, 2010). In cherries, young fruits may die completely (Larsen, 2010). In peaches, frost-damaged young fruits may develop into misshapen fruits that fail to grow beyond the size of a walnut (Larsen, 2010). In apples and pears, frost can lead to the formation of characteristic "frost rings" on the fruit surface, reducing fruit quality (Larsen, 2010). In grapevines, the fresh shoots and cluster primordia that carry that season's crop are extremely frost-sensitive; their damage often means the total loss of yield for that year (Larsen, 2010; Poni *et al*., 2022).

Leaves and shoots

Young, soft leaves and shoot tips during active growth are also sensitive to frost. Freezing can cause tissue necrosis, darkening and stunted growth (Larsen, 2010; Yadav, 2015; Lowder, 2025). Damage to leaf tissues directly reduces the plant's photosynthetic capacity, limiting energy production and weakening recovery ability.

Post-frost damage assessment: Methods and practical approaches

Following a frost event, timely and accurate assessment of the extent, severity and spatial distribution of damage across an orchard or vineyard is the first and most critical step in planning effective post-frost management strategies. A detailed and systematic damage assessment helps prevent unnecessary and costly interventions, ensures optimal use of available resources and allows for the identification of appropriate cultural practices to support plant recovery.

Timing of assessment

The full extent of frost damage does not usually become apparent immediately after the event. It often requires a period during which affected tissues undergo desiccation and discoloration (Larsen, 2010; Lowder, 2025). Therefore, it is recommended to wait approximately 24 to 48 hours-or in some cases, several days-before conducting a comprehensive assessment. This delay allows for the manifestation of visual symptoms such as browning and blackening of damaged tissues (Larsen, 2010; Lowder, 2025).

Systematic sampling

To accurately evaluate frost injury, samples should be collected systematically from different zones within the orchard or vineyard, including varying elevations, canopy layers and orientations (Larsen, 2010; Lowder, 2025). Special attention should be given to frost-prone areas such as depressions, cold air accumulation zones and poorly ventilated sections. Given that frost susceptibility varies among fruit species, cultivars and even clones within the same cultivar, separate assessments should be conducted for each type (Larsen, 2010; Yadav, 2015; Lowder, 2025).

Visual ınspection and tissue evaluation

Initial assessment involves observing external symptoms of frost injury on plant organs, such as shriveling, discoloration, necrosis and tissue collapse (Larsen, 2010; Lowder, 2025). This is followed by anatomical evaluation, where cross- or longitudinal-sections of buds, flowers,

young fruits, shoots, or branches are made using sharp tools (*e.g.*, razor blade, scalpel, or dissecting scissors) (Larsen, 2010; Lowder, 2025). The color of the exposed tissue surfaces is examined: healthy tissues typically appear bright green, yellowish, or creamy, while frost-damaged or necrotic tissues are brown, grayish, or blackened (Larsen, 2010; Lowder, 2025). Use of a hand lens or dissecting microscope is recommended for detailed inspection of small tissues (Larsen, 2010).

Bud evaluation

Bud dissection involves examining the color of internal floral or foliar primordia. In grapevines, where compound buds contain primary, secondary and tertiary meristems, each bud component must be evaluated individually (Pool and Martinson, 2011; Essary, 2023). As suggested by Pool and Martinson (2011) and Essary (2023), samples can be taken from unpruned canes and successive transverse sections can be made to assess the viability of primary, secondary and tertiary buds. The percentage of primary bud mortality directly influences pruning strategy.

- **0-15% mortality**

  Minimal damage; standard pruning is recommended to maintain balanced vine structure and optimize fruit quality.

- **15-80% mortality**

  Significant loss of primary buds; leaving more buds during pruning may enhance the likelihood of fruit production from secondary and even tertiary buds.

- **Over 80% mortality**

  Extensive damage; likelihood of structural injury (*e.g.*, splits or discoloration in trunks or shoots) increases. Minimal pruning is advised to reduce stress and promote vine survival. In cases of severe structural damage, vine removal and replanting may be necessary (Lowder, 2025).

Flower assessment

The pistil, being the most frost-sensitive part of the flower, is dissected to evaluate internal discoloration. Browning of the pistil is a definitive indicator of frost damage (Larsen, 2010).

Young fruit/cluster assessment

In immature fruits, cross-sections are examined for internal darkening, particularly around the seed cavity, which signifies frost injury. In vineyards, necrotic lesions on developing inflorescences are also assessed.

Shoot, cane, trunk and cordon evaluation

In young shoots, visual symptoms such as blackening and wilting are assessed. In thicker woody tissues (branches, cordons, trunks), the bark is gently scraped to observe cambial layer vitality through color changes or the presence of cracks (Larsen, 2010; Lowder, 2025). Cracks on grapevine cordons and trunks may serve as entry points for pathogens and should be carefully monitored (Lowder, 2025).

Estimation of damage percentage and expected yield loss

Based on sampling results, the percentage of frost damage and the estimated yield loss across the orchard or vineyard is calculated. These estimates are crucial for determining subsequent management decisions such as pruning severity or fertilization schedules (Larsen, 2010). Reference to species- and cultivar-specific critical temperature thresholds (Murray, 2011) aids in interpreting the potential extent of damage caused by the recorded temperature drops.

Integrated recovery and yield management strategies following frost damage

The restoration of plant health after frost injury necessitates the integrated implementation of various cultural and management strategies aimed at accelerating physiological recovery and securing the yield potential for the upcoming growing season. These strategies are designed to enhance plant resilience to stress, remove or repair damaged tissues, stimulate new growth and fruit bud initiation and protect the plant from secondary stress factors.

Pruning for removal of damaged tissues and structural rehabilitation

Post-frost pruning is a critical intervention in the recovery of frost-damaged fruit trees and grapevines. The main objectives and recommended post-frost pruning strategies include the following:

Objectives

The primary goals are: To remove completely frozen, necrotic, or irreversibly damaged branches, shoots, cordons and other plant organs; to eliminate necrotic and infected tissues that serve as potential entry points for pathogens and pests; to redirect the plant's limited energy reserves to vital and regenerative tissues; and to encourage new shoot emergence from latent or secondary buds, thus reconstructing and rebalancing the plant's architecture (Poni *et al.*, 2022; Lowder, 2025).

Timing

The optimal timing for pruning is when the full extent of frost injury has become apparent and the plant begins to show signs of renewed growth (Poni *et al.*, 2022). This period typically occurs several weeks after the frost event. Pruning too early may exacerbate energy depletion during a phase when the plant is already under stress, thereby delaying recovery. However, clearly necrotic and desiccated tissues should be removed as soon as the plant resumes metabolic activity. In grapevines, especially in regions prone to late spring frosts, the application of delayed winter pruning is an effective strategy to reduce the risk of damage to primary buds and enhance the potential for fruiting from secondary buds in case of frost injury (Poni *et al.*, 2022; Lowder, 2025).

Pruning intensity and technique

The severity of pruning must be adjusted according to the extent of frost injury, as well as the species, age and vigor of the affected plants. In cases of minor damage, pruning may be limited to the removal of scorched shoot tips or injured flower and fruit clusters. In contrast, severe frost injury may require cuts to be made deeper into the main scaffold branches or trunk, back to the point where healthy, viable tissue is observed (Poni *et al*., 2022). Cuts should be made with clean, sharp tools and should avoid slicing through dead tissue. Large pruning wounds should be protected with appropriate wound sealants to prevent pathogen intrusion. In young trees or vines severely damaged by frost, more radical pruning approaches such as crown renewal or cane retraining from the base may be necessary to regenerate the canopy or vine structure (Poni *et al*., 2022; Lowder, 2025).

Specific pruning approaches in grapevines

In grapevines, if primary buds are killed by frost, emergence from secondary and tertiary buds becomes critical. Based on an assessment of primary bud mortality, the pruning strategy should be adjusted accordingly (Pool and Martinson, 2011; Poni *et al*., 2022; Essary, 2023). When a high rate of primary bud death is detected, pruning intensity is reduced and more nodes are retained to facilitate fruiting from secondary buds. A study by Keller and Mills (2007) demonstrated that both the timing and severity of post-frost pruning significantly affect the recovery and productivity of cold-injured Merlot vines. Specifically, delayed pruning and increased node retention improved yield outcomes. Following the removal of dead canes and trunks, efforts should be directed toward regenerating new cordons or trunks (Poni *et al*., 2022). The application of copper-based fungicides such as copper sulfate immediately after pruning can help prevent pathogen entry through wound sites (Poni *et al*., 2022). In fruit trees (apple, pear, peach, apricot) and grapevines, the use of Bordeaux mixture or similar copper formulations is a common and effective practice to minimize pruning-related disease incidence.

Optimization of water and nutrient management and supportive practices

Frost stress can impair the root system and vascular tissues of plants, negatively affecting water and nutrient uptake. In the post-frost period, the rapid recovery of the plant, the restoration of metabolic activity necessary for new growth and the development of next season's fruit buds depend critically on the availability of balanced and accessible water and nutrient resources (Snyder and de Melo-Abreu, 2005; Larsen, 2010; Yadav, 2015).

Irrigation

To prevent water stress and support root activity in frost-damaged plants, soil moisture levels should be regularly monitored and irrigation should be applied judiciously according to the plant's needs (Rai *et al*., 2015). Adequate soil moisture facilitates water and nutrient uptake by the roots, supports photosynthetic processes and promotes new shoot development. However, over-irrigation must be avoided as it can reduce soil aeration, increase the risk of root rot and other diseases and exacerbate overall plant stress. Maintaining moist soil before or during frost-prone nights can mitigate freeze damage by enhancing latent heat release from the soil (Snyder and de Melo-Abreu, 2005; Yadav, 2015). On the other hand, post-frost irrigation should avoid wetting the foliage at night, as evaporation-induced surface cooling may aggravate leaf damage (Snyder and de Melo-Abreu, 2005).

Fertilization

Following frost events, additional nutrient support may be necessary to promote plant recovery and regrowth. A balanced fertilization program should be implemented to support new tissue formation, vegetative development and enhanced stress tolerance (Rai *et al*., 2015). Macronutrients such as nitrogen (N) and phosphorus (P) are vital for shoot and root development. However, excessive nitrogen can lead to the formation of weak shoots with poor cold hardiness and should be applied cautiously (Yadav, 2015). Potassium (K) plays a critical role in water regulation, photosynthesis and stress tolerance and it supports plant recovery following frost injury (Rai *et al*., 2015). Micronutrients such as zinc (Zn), boron (B) and iron (Fe) are also essential for metabolic processes and growth and their deficiencies can delay recovery. Nutrient supplementation should be based on soil analysis. Foliar application may be particularly effective in rapidly supplying essential nutrients independent of soil conditions (Rai *et al*., 2015; Yadav, 2015).

Soil management

Healthy soil structure, adequate organic matter content and proper drainage support root function and enhance the plant's ability to cope with post-frost stress. Soil compaction should be avoided and soil tillage should be minimized. Tillage operations should be avoided during frost-risk periods, as tilled soils with loose structure have lower heat capacity compared to firm and moist soils and tend to cool down more rapidly during the night (Yadav, 2015). This can result in a sharper and earlier drop in surface temperature, increasing the risk of frost injury.

Integrated management against ıncreased pest and disease risk

Frost stress weakens plants physiologically and increases their vulnerability to diseases and pests (Yadav, 2015). Frost-damaged tissues (wounds, cracks, necrotic areas) provide entry points for various fungal and bacterial pathogens. Therefore, regular monitoring and proactive protection against increased pest and disease threats are crucial in the post-frost period.

Monitoring and early diagnosis

After frost events, wounds, necrotic tissues, weakened plants and newly emerging tender shoots should be

carefully monitored for signs of disease and pest infestation (Yadav, 2015; Lowder, 2025). In grapevines, for instance, frost-induced cracks in cordons and trunks pose a significant risk for trunk pathogens such as *Botryosphaeria* spp. and crown gall (*Agrobacterium vitis*) (Lowder, 2025).

Integrated pest management (IPM) approach

Upon detection of any pest or disease symptoms, appropriate interventions should be applied based on IPM principles. This includes cultural practices (*e.g.*, removal and destruction of infected tissues), biological control methods and, when necessary, targeted chemical treatments. The application of protective fungicides or bactericides to pruning wounds can help prevent pathogen entry. Frost-weakened plants may attract certain pests, so pest monitoring and timely control should not be overlooked.

Potential role of biostimulants and plant growth regulators in the recovery process

Biostimulants are substances or microorganisms that enhance plant nutrient use efficiency, stress tolerance and/or crop quality independently of their nutrient content (Snyder and de Melo-Abreu, 2005; Du Jardin, 2015; García-García *et al*., 2020). The use of biostimulants during the post-frost recovery period holds great potential for accelerating physiological restoration.

Modes of action

Biostimulants can modulate plant stress responses, activate antioxidant defense systems to reduce oxidative damage, stimulate root and shoot growth, optimize nutrient uptake and utilization, enhance photosynthetic efficiency and support cellular repair mechanisms (Snyder and de Melo-Abreu, 2005; Du Jardin, 2015; García-García *et al*., 2020). Biostimulant groups with promising post-frost applications include amino acids, seaweed extracts, humic and fulvic acids and beneficial microorganisms (*e.g.*, mycorrhizal fungi and plant growth-promoting rhizobacteria - PGPRs). Amino acids serve as building blocks for protein synthesis and also help in osmotic regulation. Seaweed extracts contain natural plant hormones (*e.g.*, cytokinins), polysaccharides and minerals that enhance growth and stress tolerance. Humic and fulvic acids improve soil structure, chelate nutrients and stimulate root development.

Application methods

Biostimulants can be applied via foliar sprays or soil applications (via irrigation or in solid form) (Snyder and de Melo-Abreu, 2005; Du Jardin, 2015). Foliar applications offer rapid delivery of nutrients and active compounds, making them beneficial for immediate support after frost events. Soil applications, on the other hand, promote long-term recovery by strengthening root systems and improving soil health.

Plant growth regulators (PGRs)

In cases of severe frost damage, plant growth regulators may be used to initiate or accelerate vegetative regrowth (Yadav, 2015; Drepper *et al*., 2021). Cytokinins and gibberellins, for example, can stimulate bud break and shoot elongation. However, the use of PGRs requires careful consideration of species, cultivar, plant physiological status and precise dosage. Improper or excessive use may disturb plant hormonal balance and lead to adverse outcomes. Therefore, consulting with an experienced advisor is strongly recommended when applying PGRs.

Other supporting cultural practices

Optimizing the environmental conditions of the plant after frost damage is critical to support the recovery process.

Mulching

Application of organic or inorganic mulch around tree bases or along vineyard rows can help conserve soil moisture, thereby reducing water stress, moderating soil temperature and stimulating root activity-all of which contribute to plant recovery (Snyder and de Melo-Abreu, 2005; Yadav, 2015; Drepper *et al*., 2021). Moreover, mulching assists with weed control, minimizing competition for nutrients and water and further promoting recovery.

Windbreaks

For young or sensitive plants, installing windbreak barriers can reduce the desiccating effects of wind, minimize water loss from leaves and shoots and help establish a more stable microclimate that favors plant recuperation.

Managing next season's yield potential and long-term strategies

The primary goal of post-frost management is not only to mitigate the current damage but also to ensure healthy and productive crops in subsequent growing seasons.

Supporting fruit bud formation

In many fruit trees and grapevines, flower (fruit) buds differentiate during the preceding growing season. Thus, sufficient and healthy vegetative growth after frost damage is vital for enabling photosynthesis, replenishing carbohydrate reserves and ultimately ensuring the formation of adequate quantity and quality of fruit buds for the next season (Yadav, 2015; Bigler and Bugmann, 2018). Practices such as balanced fertilization, adequate irrigation, effective pest and disease management and proper pruning directly influence this process.

Managing biennial bearing (alternate bearing)

Severe frost damage can lead to an "off-year," where the plant prioritizes recovery and vegetative development, potentially triggering an excessive flowering and fruit load in the subsequent "on-year." This tendency toward biennial bearing (alternation) can be intensified by such stress events (Yadav, 2015). To manage this, strategic flower or fruit thinning in the following season should be planned to balance crop load and prevent plant exhaustion caused by overbearing.

Structural recovery

In cases of severe frost injury, it may take several years for trees or vines to fully regain their original form and productivity

(Keller and Mills, 2007). During this period, ensuring the long-term health and sustainable productivity of the plant should be a top priority.

Long-term risk mitigation

To reduce the risk of future frost damage, long-term strategies should be considered. These include selecting and cultivating fruit varieties and rootstocks that are better adapted to the regional climate and more tolerant to frost (Yadav, 2015). The use of advanced frost forecasting and early warning systems, along with feasibility studies and implementation of active frost protection methods (*e.g.*, sprinkler irrigation, wind machines, heaters, fogging), is crucial for minimizing the potential impact of future frost events (Snyder and de Melo-Abreu, 2005; Drepper *et al*., 2022). Integrating passive frost protection strategies (*e.g.*, site selection, pre-winter plant nutrition) with active protection methods forms a comprehensive frost risk management plan.

Spring late frosts, exacerbated by global climate change, increasingly pose a serious and complex threat to fruit and vineyard cultivation in temperate climates. The widespread and severe frost events observed in recent years in Türkiye have clearly demonstrated the potentially devastating impacts of this climatic risk on agricultural production and highlighted the urgent need for effective post-frost management. Understanding the complex physiological and biochemical mechanisms of frost damage in plants-from cellular level effects to the overall health and reproductive capacity of the plant-is essential.

The integrated management strategies presented in this review-including accurate post-frost damage assessment, appropriate pruning techniques, optimized water and nutrient management, proactive pest and disease control, use of biostimulants and preparations for the following growing season-offer a scientifically based approach to accelerate plant recovery, restore plant health and minimize the long-term effects of frost injury. In particular, biostimulants hold promising potential in post-frost recovery by enhancing the plant's natural defense mechanisms and stress tolerance, supporting cellular repair processes and promoting new growth. Foliar applications during the post-frost period facilitate the direct uptake of essential nutrients and compounds necessary for rapid recovery. Practices such as late winter pruning in vineyards are recognized as effective strategies for managing frost risk and securing yield from secondary buds after frost damage (Keller and Mills, 2007; Poni *et al*., 2022; Lowder, 2025). Experimental studies by these authors have demonstrated the effects of pruning severity after frost on the recovery and productivity of cold-damaged vines, underscoring the critical role of management strategies in modulating plant responses.

However, detailed laboratory and field-level protocols for the "rapid recovery, revitalization and return to pre-damage developmental status" of frost-affected plants remain scarce in the literature (Snyder and de Melo-Abreu, 2005). This highlights the need for deeper investigation into the molecular, genetic and biochemical mechanisms underlying physiological recovery processes and for developing targeted interventions and practical protocols to accelerate these processes. Future research should focus on changes in plant metabolism after frost, stress signaling pathways and the genetic and epigenetic mechanisms facilitating recovery, thereby contributing to the development of more effective and scientifically grounded recovery strategies.

For growers in Türkiye, adapting and integrating these summarized strategies according to local ecological conditions, soil types, affected plant species/cultivars and specific characteristics of frost damage is of great importance. Long-term risk mitigation should include the selection of frost-tolerant varieties and rootstocks, improved frost forecasting and early warning systems and the widespread adoption of active frost protection methods such as irrigation and wind machines (Snyder and de Melo-Abreu, 2005; Yadav, 2015). The combination of an effective post-frost management plan with forward-looking risk reduction strategies is critical to minimizing the adverse effects of spring late frosts on agricultural production and enhancing the resilience and sustainability of the fruit and vineyard sectors. Cooperation and knowledge exchange among growers, agricultural advisors and researchers are essential for the adoption of best practices and the development of region-specific solutions.

CONCLUSION

Spring late frosts represent a significant and increasing threat to fruit trees and vineyard cultivation globally. Understanding the physiological and biochemical mechanisms of frost damage and accurately assessing the extent of injury form the foundation for effective post-frost management strategies. These strategies encompass an integrated suite of cultural practices, including the removal of frozen tissues by pruning, optimization of water and nutrient management, management of increased pest and disease risks, use of biostimulants and potentially growth regulators and securing the yield potential for the following season. Although existing literature provides valuable information on cultural and management strategies applicable after frost, there is a clear need for further research to establish specific and detailed application protocols to accelerate physiological recovery in plants. Increasing the scientific knowledge in this field will facilitate the development of more effective and targeted post-frost interventions. The integration of proactive post-frost management with long-term adaptation strategies to climate change is critical to mitigating the negative impacts of spring late frosts on agricultural production and improving the resilience and sustainability of fruit and vineyard sectors. Collaboration among growers, advisors and researchers remains the most effective path to overcoming this challenging climatic risk.

ACKNOWLEDGEMENT

The author acknowledges no external funding or support for the preparation of this review article. The author would like to thank all the researchers whose work was referenced in this manuscript.

Disclaimers

The views and conclusions expressed in this article are solely those of the author and do not necessarily represent the views of the author's affiliated institutions. The author is responsible for the accuracy and completeness of the information provided within this review.

Informed consent

This is a review article based on published literature and does not involve any human or animal participants, therefore informed consent is not applicable.

Conflict of interest

The author declares that there are no conflicts of interest regarding the publication of this article. The preparation of the manuscript was not influenced by any commercial or financial relationships.

REFERENCES

Anonymous (2025). Zirai don 36 ilde etkili oldu. Retrieved April 14, 2025, from https://www.aa.com.tr/tr/gundem/zirai-don-36-ilde-etkili-oldu/3537066.

Augspurger, C.K. (2013). Reconstructing patterns of temperature, phenology and frost damage over 124 years: Spring damage risk is increasing. *Ecology.* **94:** 41-50. https://doi.org/10.1890/12-0200.1.

Baek, K.H. and Skinner, D.Z. (2012). Production of reactive oxygen species by freezing stress and the protective roles of antioxidant enzymes in plants. *Journal of Agricultural Chemistry and Environment.* **1(1):** 34-40. https://doi.org/10.4236/jacen.2012.11006.

Bigler, C. and Bugmann, H. (2018). Climate-induced shifts in leaf unfolding and frost risk of European trees and shrubs. *Scientific Reports.* **8:** 9865. https://doi.org/10.1038/s41598-018-27893-1.

Charrier, G., Chuine, I., Bonhomme, M. and Améglio, T. (2018). Assessing frost damages using dynamic models in walnut trees: Exposure rather than vulnerability controls frost risks. *Plant, Cell and Environment.* **41(5):** 1008-1021. https://doi.org/10.1111/pce.12935.

Choi, Y.M., Kim, S.B., Choi, D.G., Kim, S.H. and Song, J.H. (2025). Effects of meteorological factors and frost injury on flowering stage of apples and pears across regions at varying altitudes. *Horticulturae.* **11(3):** 249. https://doi.org/10.3390/horticulturae11030249.

Drepper, B., Bamps, B., Gobin, A., Beckers, J., Meersmans, J. and Nicolai, G. (2021). Strategies for managing spring frost risks in orchards: Effectiveness and conditionality-A systematic review protocol. *Environmental Evidence.* **10:** 32. https://doi.org/10.1186/s13750-021-00247-7.

Du Jardin, P. (2015). Plant biostimulants: Definition, concept, main categories and regulation. *Scientia Horticulturae.* **196:** 3-14. https://doi.org/10.1016/j.scienta.2015.09.021.

Essary, A. (2023). Assessing Grapevine Bud Winter Injury (HLA-6262). Oklahoma Cooperative Extension Service, Oklahoma State University. Retrieved May 2, 2025, from https://extension.okstate.edu/fact-sheets/print-publications/hla/assessing-grapevine-bud-winter-injury-a.pdf

Faust, E. and Herbold, J. (2017). Spring frost losses and climate change-Not a contradiction in terms. *Munich Re Topics Geo.* 24-29.

García-García, A.L., García-Machado, F.J., Borges, A.A., Morales-Sierra, S., Boto, A. and Jiménez-Arias, D. (2020). Pure organic active compounds against abiotic stress: A biostimulant overview. *Frontiers in Plant Science.* **11:** 575829. https://doi.org/10.3389/fpls.2020.575829.

Kayan, K.E. (2025). Zirai don Türkiye'yi vurdu! Çiftçiler zararın boyutunu tespit etmeye çalışıyor. Dünya Gazetesi-Ekonomi. Retrieved April 22, 2025, from https://www.dunya.com/ekonomi/zirai-don-turkiyeyi-vurdu-ciftciler-zararin-boyutunu-tespit-etmeye-calisiyor-urun-az-fiyatlar-yuksek-olabilir-haberi-772094.

Keller, M. and Mills, L.J. (2007). Effect of pruning on recovery and productivity of cold-injured merlot grapevines. *American Journal of Enology and Viticulture.* **58(3):** 351-357.

Khaskheli, A.J., Khaskheli, M.I., Zhang, L., Khaskheli, A.A. and Qing, L.H. (2021). Frost stress tolerances and cut roses: A review. *Agricultural Reviews.* **42(2):** 215-219. https://doi.org/10.18805/ag.R-181.

Lamichhane, J.R. (2021). Rising risks of late-spring frosts in a changing climate. *Nature Climate Change.* **11:** 554-555. https://doi.org/10.1038/s41558-021-01090-x.

Larsen, H.J. (2010). Evaluating Tree Fruit Bud and Fruit Damage from Cold (Fact Sheet No. 7.426, Gardening Series | Trees and Shrubs, 7 p.). Colorado State University Extension. Retrieved May 2, 2025, from https://www.bctfpg.ca/files/Evaluating%20Tree%20Fruit%20Bud%20and% 20 Fruit%20Damage%20from%20Cold%20-%20Colorado%20 State%20University%20Extension.pdf.

Lowder, S. (2025). Monitoring for Damage After a Cold Event. The University of Georgia College of Agricultural and Environmental Sciences, Viticulture. Retrieved May 2, 2025, from https://viticulture.uga.edu/2025/01/monitoring-for-damage-after-a-cold-event/.

Masaki, Y. (2020). Future risk of frost on apple trees in Japan. *Climatic Change.* **159(3):** 407-422. https://doi.org/10.1007/s10584-019-02610-7.

Matzneller, P., Götz, K.P. and Chmielewski, F.M. (2016). Spring frost vulnerability of sweet cherries under controlled conditions. *International Journal of Biometeorology.* **60(1):** 123-130. https://doi.org/10.1007/s00484-015-1010-1.

Murray, M. (2011). Critical Temperatures for Frost Damage on Fruit Trees (IPM-012-11). Utah State University Extension and Utah Plant Pest Diagnostic Laboratory. Retrieved May 2, 2025, from https://extension.usu.edu/productionhort/files/CriticalTemperaturesFrostDamageFruitTrees.pdf.

Parker, L., Pathak, T. and Ostoja, S. (2021). Climate change reduces frost exposure for high value California orchard crops. *Science of the Total Environment.* **762:** 143971. https://doi.org/10.1016/j.scitotenv.2020.143971.

Poni, S., Sabbatini, P. and Palliotti, A. (2022). Facing spring frost damage in grapevine: Recent developments and the role of delayed winter pruning - A review. *American Journal of Enology and Viticulture.* **73(4):** 211-226. https://doi.org/10.5344/ajev.2022.22011.

Pool, R. and Martinson, T. (2011). Assessing Winter Cold Injury to Grape Buds. Cornell University, College of Agriculture and Life Sciences. Retrieved May 2, 2025, from https://bpb-us-e1.wpmucdn.com/blogs.cornell.edu/dist/0/7265/files/2017/01/Assessing-Winter-Cold-Injury-to-Grape-Buds-2g1xayi.pdf.

Rai, R., Joshi, S., Roy, S., Singh, O., Samir, M. and Chandra, A. (2015). Implications of changing climate on productivity of temperate fruit crops with special reference to apple. *Journal of Horticulture.* **2(2):** 1000135. https://doi.org/10.4172/2376-0354.1000135.

Rimpika, Sharma, D.P. and Ajender. (2021). Vulnerability of temperate fruit production to climate change: Adaptation and mitigation measures: A review. *Agricultural Reviews.* **42(2):** 190-196. https://doi.org/10.18805/ag.R-2016.

Rodrigo, J. (2000). Spring frosts in deciduous fruit trees-morphological damage and flower hardiness. *Scientia Horticulturae.* **85(3-4):** 155-173. https://doi.org/10.1016/S0304-4238(99)00150-8.

Salazar-Gutiérrez, M.R., Chaves, B., Anothai, J., Whiting, M. and Hoogenboom, G. (2014). Variation in cold hardiness of sweet cherry flower buds through different phenological stages. *Scientia Horticulturae.* **172:** 161-167. https://doi.org/10.1016/j.scienta.2014.04.002.

Snyder, R.L. and Melo-Abreu, J.P. (2005). Frost Protection: Fundamentals, Practice and Economics (Vol. 1). Food and Agriculture Organization of the United Nations Retrieved June 20, 2025, from https://www.fao.org/4/y7223e/y7223e00.pdf.

Vitasse, Y., Schneider, L., Rixen, C., Christen, D. and Rebetez, M. (2018). Increase in the risk of exposure of forest and fruit trees to spring frosts at higher elevations in Switzerland over the last four decades. *Agricultural and Forest Meteorology.* **248:** 60-69. https://doi.org/10.1016/j.agrformet.2017.09.005.

Yadav, A. (2015). Frost, Frost Protection and Winter Injury. In Usha, K., Thakre, M., Goswami, A.K. and Deepak, G.N. (Eds.), Fundamental of Fruit Production Division of Fruits and Horticultural Technology, ICAR-Indian Agricultural Research Institute. (pp. 34-51).

Yıldırım, A.E. (2025). Zirai don çiftçinin kâbusu oldu. Tarım Dünyası. Retrieved April 18, 2025, from https://www.tarimdunyasi.net/haber/zirai-don-ciftcinin-kabusu-oldu/.