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Review Article

Frost Management in Fruit Trees and Vineyards: Prevention, Assessment, and Post-Frost Care

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Abstract

Spring frosts pose a significant and recurring threat to fruit trees and grapevines, particularly when they occur during phenologically sensitive stages such as budbreak, flowering, and early fruit development. Climate change has intensified this risk by advancing spring phenology while increasing thermal instability, thereby extending the vulnerability window of perennial crops. This review synthesizes the current understanding of frost-induced physiological damage—including cellular dehydration, membrane disruption, and oxidative stress—that impairs water and nutrient uptake, photosynthesis, and reproductive success. It further examines methods for assessing frost injury, ranging from visual symptom identification to remote sensing technologies. Passive and active frost protection strategies are critically evaluated, including site and cultivar selection, pruning timing, irrigation, and the use of heaters or wind machines. Post-frost recovery techniques such as balanced fertilization, biostimulant applications, and pest and disease management are also addressed. The widespread agricultural losses following the April 2025 frost event in Türkiye underscore the urgency of implementing integrated, climate-resilient frost management frameworks. The review concludes with forward-looking recommendations for enhancing crop resilience through cultivar improvement, early warning systems, and region-specific adaptation strategies.

Keywords: Spring frost; Climate change; Frost management; Fruit crops; Physiological damage; Adaptation strategies

Introduction

Fruit trees and vines are highly sensitive to low temperatures, especially in spring, when they emerge from winter dormancy and become physiologically active and buds, flowers, young leaves and shoots develop [16,20]. Temperatures below freezing during this critical period cause cell damage in these sensitive organs, resulting in significant yield losses and economic losses [1,6].

Frost causes a range of damage to fruit trees, starting at the cellular level and affecting all physiological processes. Low temperatures lead to the formation of ice crystals in plant cells. These crystals can physically destroy cell membranes and trigger intracellular dehydration. As water outside the cell freezes, the outward movement of water inside the cell causes a water stress-like situation in the plant. This disrupts the overall water balance of the plant, negatively affecting photosynthesis and other metabolic activities.

Climate change further complicates this risk by bringing spring phenology forward and increasing temperature fluctuations [15,23]. Observed global warming trends are leading to earlier onset of spring phenology (e.g. bud burst, flowering) in many plant species [12,15,20,23]. However, despite the early shift in the spring phenology of plants (e.g., budding and flowering times), factors such as the lack of a similarly rapid early shift in the occurrence dates of late spring frosts or increased temperature variability may increase, rather than decrease, the risk of frost exposure during sensitive developmental stages of plants in certain regions [6,15,22,23]. Indeed, recent severe late spring frosts in Europe and Türkiye (e.g. 2017, 2021 and 2025) are concrete examples of this increased risk [6,12]. In particular, the frost disaster in April 2025, which was effective across Türkiye with temperatures dropping as low as -15°C in some regions, was recorded as one of the worst frost disasters of the last 30-40 years and negatively affected agricultural production in about 36 provinces. Such damage can affect not only the current year's crop, but also the overall health of the tree/shoot, its long-term health and the yield potential of subsequent years [1,24]. Proper and timely management strategies following frost damage are critical to mitigate the effects of damage, ensure rapid plant recovery, support fruit bud formation for the next season, and maintain long-term productivity.

Mechanism of Frost Damage and Physiological Effects on Plants

The primary physiological effect of frost on plant tissues is the freezing of water in extracellular spaces resulting in the formation of ice crystals [9]. These ice crystals lower the extracellular osmotic potential, causing the movement of intracellular water out of the cell (dehydration). Excessive water loss can disrupt the integrity of the cell membrane and lead to a phase change of membrane lipids (e.g. from liquid crystalline phase to gel). This causes the cell membrane to lose its selective permeability, allowing electrolytes, sugars and other intracellular compounds to leak out of the cell (electrolyte leakage) [9]. Electrolyte leakage is an important indicator of cell viability and is

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used to determine the severity of frost damage. Cell membrane damage disrupts intercellular communication through plasmodesmas and affects enzyme activity. Furthermore, the formation of intracellular ice crystals (intracellular freezing) is often fatal because it causes direct mechanical damage to cell organelles [4,23].

Frost Susceptibility of Different Plant Organs and Developmental Stages

Different plant organs and developmental stages show different sensitivity to frost:

Flowers: Opened flowers and flower buds are usually the most sensitive parts. Pollen, ovules and other reproductive organs are very sensitive to critical temperatures. Freezing leads directly to yield loss by preventing fertilization or stopping embryo development [21]. Even temperatures as low as -2 °C at full flowering can cause severe damage.

Young Fruits: The tissues in the small fruit stage following flowering have a high water content and are not yet fully hardened, making them vulnerable to frost. Young fruits that freeze shrivel, blacken and fall off. Those that survive may show deformities or superficial damage (frost rings).

New Shoots and Leaves: Actively growing, young and fresh shoot tips and immature leaves contain more water and have thinner cell walls than mature tissues. Freezing causes necrosis (tissue death) in these tissues. Damage to leaf tissue reduces the rate of photosynthesis, negatively affecting the plant's carbohydrate production and overall energy balance. Shoot tip death limits the growth potential for that season and can affect the shape of the plant [14].

New Shoots in Vineyards: In vineyards, frost particularly targets new shoots, which contain potential fruit clusters. Freezing of the shoots can mean a complete loss of that year's crop and strains the plant's ability to shoot again.

Effects of Frost Damage on Plant Physiology

Frost damage also triggers secondary stress responses in the plant. Oxidative stress increases, reactive oxygen species (ROS) accumulate, which can lead to further cell damage. Nutrient and water uptake mechanisms can be disrupted. The plant is forced to use energy resources to repair damaged tissues or to form new shoots, which diverts resources from other important physiological processes such as root development and nutrient storage [2]. Dehydration caused by extracellular extraction of water in freezing plants can lead to symptoms similar to those of water stress. This increases the importance of post-frost irrigation strategies. However, it should be kept in mind that overwatering should be avoided as it can lead to problems such as root rot and nutrient loss.

Frost can also negatively affect nutrient uptake by plants. Low temperatures can reduce the activity of the roots, making it difficult for them to take up nutrients from the soil. This can lead to a shortage of nutrients, especially those needed for the development of new shoots. Frost can also damage leaves, reducing their capacity to produce nutrients through photosynthesis [14]. Frost can cause delays and abnormalities in shoot development, especially affecting early developing buds and young shoots [21]. Low temperatures can cause buds and young shoots to freeze and die. This can affect the overall growth of the tree and next year's fruit eye formation. Depending on the severity of frost damage, trees may experience drying of shoot tips, leaf deformation and general growth retardation. Overall, frost is a multifaceted stress that disrupts the plant's growth, development and reproductive cycle.

Identification and Assessment of Frost Damage

An accurate assessment of frost damage is essential to formulate an effective response plan. Understanding the full extent of damage is usually possible within a few days after a frost event [24].

Signs of Damage

Frozen tissues usually first appear water-soaked, then wither, turn brown or black and dry [16,24]. In flowers, the female organ (pistil) is particularly vulnerable and its browning is an indication of irreversible damage [16]. Young leaves and shoot tips are usually the first to be affected [24]. The wood tissue (branches, trunk) should also be checked for cracks or discoloration under the bark, as cambium damage can lead to long-term problems [24].

Time and Method of Assessment

A minimum of 2-3 days should be allowed after the frost event for definitive damage assessment. This time allows for the potential recovery of slightly damaged tissues or for damage to become more pronounced. Assessment should be made by examining samples from different parts of the garden/vineyard and from organs (buds, flowers, leaves, shoots, fruit) at different heights. The percentage (%) of organs affected and the severity of damage (mild, moderate, severe) should be recorded. In large areas, remote sensing techniques and vegetation indices can be used to determine the extent of damage [3,13,19].

Vitality Check

The viability of the cambium (green color) can be checked by gently scraping or sectioning the bark on suspicious branches or shoots [24]. The vigor of buds can be assessed by cross-sectioning and looking at the color of their inner parts (green/brown) or by waiting for them to give shoots under controlled conditions. In vineyards, the vigor of secondary and dormant eyes below damaged primary buds is particularly important [8,19].

Pre-Frost Management Strategies (Passive and Active Protection)

There are various measures that farmers can take to prevent or minimize frost damage. These are divided into passive and active methods [24].

Passive Protection Methods

Site Selection: The choice of location for the garden is critical. Low-lying areas where cold air accumulates, known as frost pits, should be avoided [24]. Higher altitudes and gently sloping terrain are generally safer as they allow cold air to drain away [23]. Proximity to water bodies can also reduce the risk of frost [19].

Variety and Rootstock Selection: In areas at risk of late frost, selection of frost-resistant or late-flowering varieties and rootstocks is an important strategy to reduce frost damage [20,24]. For example, in fruit species such as apples, pears, peaches and apricots, the selection of varieties with late flowering or high chilling requirements contributes to the reduction of damage caused by late spring frosts in temperate climates. Varieties with low chilling requirements may flower early in late winter and be more exposed to late spring frosts, which increases the risk of fruit loss. Furthermore, the rootstocks used can also have an impact on the phenology and frost tolerance of the plant [24].

Cultural Practices:

Soil Management: It is recommended to avoid tillage practices during periods of frost risk. This is because cultivated, loosely structured soils have a lower heat capacity and tend to cool faster overnight compared to firm, moist soils [24]. This causes the air temperature at the surface to drop earlier and more severely, increasing the risk of frost damage to plants. Areas with a cleared, weed-free surface and sufficient soil moisture absorb more solar energy during daylight hours. The dissipation of this energy into the environment during the night can increase the temperature in the plant environment by several degrees, reducing the severity of frost effects [19]. However, cover crops and some surface mulches can limit the heating of the soil by direct sunlight. This can lead to insufficient soil warming and lower surface temperatures during night frost conditions [24]. However, mulches, especially organic-based mulches, can reduce the risk of root freezing by acting as insulation to stabilize temperature fluctuations in the root zone [24]. Therefore, the effect of mulching practices varies depending on the type and thickness of the material used and climatic conditions.

Irrigation: If frost is expected, it is beneficial to water the soil in advance. Moist soil retains more heat than dry soil and the latent heat of fusion released during freezing provides protection [18,24].

Fertilization and Pruning: Yadav [24] states that pruning and fertilization in autumn or early winter should be avoided, as practices during this period will promote the growth of new shoots that are most sensitive to cold. Excessive nitrogen fertilization and early pruning in autumn or early winter have been shown to promote premature vegetative growth, leading to immature tissues that are more susceptible to frost damage.

These practices can compromise plant cold hardiness by delaying the induction of dormancy and increasing shoot elongation at a time when plants should be entering dormancy. Poni et al. [19] emphasize the benefits of "delayed winter pruning" to reduce the risk of spring frost in grapevines. Delayed winter pruning is defined as a physiological tool that aims to prevent frost damage by delaying the awakening of the vines, by performing it at or beyond the "woolly" stage of the buds. This method is based on the natural "acrotonia" of the vine, i.e., even if the developing terminal shoots are damaged by frost, the unawakened buds at the base of the vine cane are protected [19].

Windbreaks: Windbreaks can reduce the risk of frost by blocking cold air currents [18,24].

Protection of Tree Trunks: The trunks of young trees can be painted with white latex paint or wrapped with special materials to prevent winter sunscald and frost cracking [18, 24].

Active Protection Methods

These methods are usually applied at night when frost is expected and are effective against radiation frosts [24].

Heaters (Heaters/Smudge Pots): Heaters placed in the garden provide protection by increasing the ambient temperature [18,24]. They can be oil or propane fueled [24]. However, they are costly, polluting and labor-intensive [16,24].

Wind Machines/Helicopters: In radiation frosts, a temperature inversion occurs between cold air at ground level and warmer air higher up [24]. Wind machines or helicopters move this layer of warm air downwards, increasing the temperature at ground level [6,17,19, 22,24]. The effectiveness of air mixing practices depends on the strength of the temperature inversion [24].

Overhead Irrigation (Sprinklers): Water is sprayed continuously over plants at temperatures close to freezing [24]. The latent heat of fusion released when water freezes keeps the temperature of plant tissues around 0°C [6,17-19,22,24]. Continuous and sufficient water application is critical; otherwise evaporative cooling can occur, increasing damage [16,18,24]. It requires large amounts of water [22]. Drip irrigation does not provide frost protection.

Covers: Covering plants with special covers (plastic, fabric, etc.) can provide protection by reducing heat loss [18,24].

Fogging (Foggers): Creating artificial fog can provide protection by reducing heat loss [18,24].

Delayed Pruning: Delaying winter pruning later than usual, when buds are beginning to swell or the first shoots appear, can reduce the risk of frost by delaying bud burst [19]. This method takes advantage of the vine's acrotony characteristic (more dominant terminal buds); with delayed pruning, even if the terminal shoots are exposed to frost, the bottom buds, which have not yet awakened, are protected [19]. Poni et al. [19] reported that delaying pruning until 2-3 leaf opening on apical shoots delayed bud burst by 15-20 days on average and had little effect on yield.

This delay can sometimes continue until harvest, shifting fruit ripening to a cooler period. In cord training systems with spur pruning, the arms can be shortened over 7-8 eyes by mechanical preliminary pruning at any time in winter. The final spur pruning is done manually when the apical shoots have 2-3 leaves [19]. In cane pruning systems, the previous year's fruiting canes are removed in winter, but at least two renewal canes are left vertical and longer than necessary. These rods are shortened and tied to the horizontal wire when the apical shoots have 2-3 leaves. For the success of this method, it is important that the rods left are as vertical as possible and longer than needed for production [19].

Post-Frost Management Strategies and Cultural Practices

After frost damage occurs, correct and timely cultural practices are critical to mitigate the effects of damage and ensure plant recovery [4,19,24]. These strategies aim to stimulate the plant to regrow, protect it against secondary stress factors and secure its productivity for the next season [40].

Damage Assessment and Evaluation

The first step is to accurately assess the extent and distribution of damage a few days after frost. The color of the inside of flowers/fruit (browning, blackening), areas of necrosis on shoot tips and leaves are observed. This assessment is important to determine which trees/vines are affected and to what extent, and the extent of subsequent treatments [24].

Pruning

It is important to prune away branches and shoots that have completely dried out or lost vitality due to frost [4,10,11]. This prevents the spread of diseases and helps the plant to redirect its energy to the parts that remain alive. The timing of pruning should be delayed until the period when the plant starts to re-shoot and the live parts become clear [4]. Hasty pruning can also potentially result in the removal of living tissue. The severity of pruning should be adjusted according to the degree of damage and the type of plant. In mild damage, only tip drying may be removed, whereas in severe damage it may be necessary to cut further back. In severely damaged trees, hard pruning to healthy tissue may be necessary. In vineyards, when primary shoots freeze, special pruning techniques are applied to manage shoots developing from secondary or dormant eyes [10,11,19]. These shoots are usually less productive but can provide some yield for the current season. After pruning, it is recommended to apply protective paste to large cut surfaces. Excessive pruning can cause dense vegetative growth (gluttonous branches), especially in the following period, and these shoots may require management. Excessive pruning can lead to intensive vegetative growth and periodicity in subsequent years.

Irrigation and Nutrient Management

Adequate water supply is critical for recovery after frost stress. Soil moisture should be checked regularly and water needs of the plant should be met. However, overwatering can increase the risk of root diseases [24]. Adequate water is critical, especially during new shoot and leaf development. The feeding program should be geared towards compensating for nutrient loss caused by frost and supporting new growth periods. Excessive nitrogen application can lead to excessive vegetative growth, especially in a season of crop loss [24]. A balanced NPK fertilization and microelement supplementation is recommended. Leaf analysis is useful in determining the actual nutrient requirements of the plant. Foliar feeding can ensure rapid uptake of nutrients [7]. Since the fruit load will be low in damaged trees, the fertilization program should be adjusted accordingly. Adequate levels of phosphorus (for root development) and potassium (for general stress tolerance) and microelements should be ensured. Therefore, post-frost fertilization strategies are of great importance. A fertilization program appropriate to the degree of damage can help the plant recover and build new tissue.

Disease and Pest Management

Frost-damaged, stressed plants are more vulnerable to diseases and pests [24]. Damaged tissues create a favorable entry gate and breeding ground for pathogens. Damaged tissues can create entry points for pathogens. Especially in the post-frost period, there may be an increase in the population of fungal and bacterial diseases (e.g. monilia, fever blight) as well as pests that appear on weak plants. The garden should be regularly monitored, disease and pest symptoms should be detected early and necessary control practices should be applied [24]. When necessary, preventive or therapeutic fungicides and insecticides should be applied. Diseased plant residues removed by pruning should be destroyed. Weak plants may be particularly vulnerable to fungal diseases or pests that enter the wood tissue.

Biostimulants

Biostimulants such as amino acids, seaweed extracts, humic and fulvic acids can support plant recovery after frost stress [5]. By stimulating the plant's physiological processes, these substances can increase stress tolerance, facilitate nutrient uptake and promote new growth periods.

Other Treatments

In some cases, practices such as lime whitewashing of the trunk and main branches can help reduce stress caused by temperature changes. Tillage can promote recovery by aerating the roots, but damage to the roots should be avoided.

Yield and Long-Term Impacts of Frost Damage

In addition to directly affecting the current year's flowers and thus fruit yield, frost can also negatively affect next year's fruit eye formation [20]. Low temperatures can cause freezing of flower buds and damage to opened flowers, reducing or completely preventing fruit set [16,21]. Furthermore, frost stress can deplete the tree's energy stores, leading to an inability to form enough fruit eyes for the following year. This can trigger or exacerbate the periodicity problems seen in some fruit species, which can result in abundant crops one year and low crops the next [16,21].

Severe frost damage can negatively affect not only that year's flowers and young fruits, but also the formation of next year's fruit buds [20]. Frost stress and the plant's effort to repair damaged tissues deplete energy stores, which can result in insufficient resources for flower bud differentiation. This can lead to a pronounced "lean year" or severely reduced yields in the year following a frost, especially in species prone to periodicity [24].

The right cultural practices in the post-frost period help the plant to recover quickly, develop new and healthy shoots and reach sufficient photosynthetic capacity to maintain next year's yield potential [4,19]. Controlling excessive vegetative growth and balanced nutrition helps the plant to direct its energy towards fruit eye formation. In the following growing season, if some fruit set occurs, careful fruit thinning can be carried out to avoid fruit overload and alleviate periodicity.

Repeated or very severe frost damage can permanently impair the overall health and structure of the tree, shorten its lifespan and require complete tree replacement. Damage to wood tissue (blackheart), especially in young trees, can affect the conduction bundles, impairing water and nutrient transport and leading to long-term growth retardation [24]. Therefore, post-frost management should aim not only to compensate for the current season's damage, but also to ensure the long-term health and sustainable productivity of the tree/shoot.

Discussion

Severe agricultural frost events in Türkiye in April 2025 once again highlighted the potentially devastating impacts of climate change on agricultural production, with severe crop losses, particularly in orchards and vineyards. These events highlight how late spring frosts are a major risk factor, especially when they occur during the most vulnerable phenological stages of crops (bud burst, flowering, young fruit/bunch development). In some regions, the risk of frost appears to increase as plants wake up earlier in spring due to rising temperatures and bud burst occurs faster than during the period when frost risk ends [12,23]. Starting at the cellular level, frost damage triggers complex physiological processes that disrupt the plant's water balance, nutrient uptake, photosynthesis and hormonal balance. Damage to reproductive organs, such as flowers and young fruit, leads directly to the loss of that year's yield, while leaf and shoot damage affects the plant's ability to recover and the next year's yield potential. Permanent damage to wood tissue can threaten the long-term health and longevity of the tree [24].

Effective and integrated management strategies in the post-frost period play a critical role in mitigating the effects of frost and ensuring crop recovery. Accurate and timely identification of damage is the basis for subsequent interventions. Pruning relieves the plant by removing dead and damaged tissues and encourages new shoot development, but correct timing and know-how are crucial [4,19]. Irrigation and balanced feeding provide the necessary resources for plant recovery; excessive applications should be avoided [24]. Biostimulants can accelerate recovery by increasing plant stress tolerance [5]. In addition, vigilance and proactive control methods should be applied against the increased disease and pest risk of post-frost weakened plants. Another important aspect of post-frost management is to secure next year's yield. Ensuring healthy plant growth after the current year's crop loss, promoting adequate nutrient storage and flower bud differentiation helps alleviate periodicity problems.

Strategies to prevent future crop loss include passive and active protection methods, as well as the selection of frost-resistant or late-flowering varieties, appropriate site selection and the development of climate change adaptation strategies offer long-term solutions [15,17,23]. Early warning systems and accurate frost forecasts also allow growers to take timely measures. In the long term, preventive strategies such as the use of more frost-tolerant varieties, appropriate site selection and the integration of advanced frost prediction systems will play a key role in reducing future frost risk.

Conclusion

The April 2025 frost event in Türkiye demonstrated the need for continuous review and development of frost management strategies in the agricultural sector. Implementing the right post-frost cultural practices in the light of scientific knowledge and in accordance with local conditions is vital for the recovery of damaged orchards and vineyards, reducing the risk of diseases and pests, and securing next season's productivity. Increasing the level of awareness of growers and relevant stakeholders against frost risk, using modern forecasting systems and disseminating agricultural practices that adapt to climate change are important steps to be taken to minimize the negative impacts of such extreme weather events.

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