Article

Frost Protection Strategies in Agriculture: Insights from the 2025 Niğde Frost Event in Türkiye

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Abstract

Late spring frost events represent a major climatic hazard for perennial crop production, particularly in regions with continental climatic conditions. In April 2025, Niğde Province in central Türkiye experienced a severe frost episode that caused extensive damage to fruit orchards during critical phenological stages. This study examines the characteristics of the frost event and evaluates frost protection practices implemented in the affected agricultural areas. A qualitative case study approach was employed, integrating meteorological observations, official damage assessments, field observations, and a comparative analysis of frost protection methods reported in the literature. Meteorological data indicate that the frost event persisted for approximately 12 hours, with temperatures declining to −9.3 °C during the most severe phase. The prolonged exposure to sub-zero temperatures resulted in substantial damage, particularly in flowering fruit trees across several districts of Niğde. Observations show that active protection measures, including sprinkler irrigation and combustion-based heating practices, were widely implemented by producers; however, their effectiveness was limited under prolonged and severe frost conditions. Passive measures such as site selection, cultivar choice, and soil management contributed to long-term risk mitigation but were insufficient as standalone solutions during extreme events. These findings highlight the need for integrated frost risk management strategies combining preventive agronomic planning, appropriate active protection technologies, and improved early warning systems in frost-prone agricultural regions.

Keywords: Agricultural frost; Frost protection; Late spring frost; Orchards; Climate adaptation; Frost risk

Citation: Ata O., Onay Ö. Frost Protection Strategies in Agriculture: Insights from the 2025 Niğde Frost Event in Türkiye. *Impact in Agriculture*. **2026**, *2*, 1. https://doi.org/10.65500/agriculture-2026-001

Received: 17 December 2025 | Revised: 15 January 2026 | Accepted: 27 January 2026 | Published: 02 February 2026

1. Introduction

Temperature is a fundamental environmental factor governing plant growth, development, and crop productivity [1]. Among temperature-related hazards, frost events represent one of the most critical climatic risks for agricultural systems, particularly in temperate and continental climates. Frost occurs when air temperature falls below the freezing point, leading to the formation of ice crystals within plant tissues and resulting in cellular damage, physiological stress, and impaired metabolic processes [2]. Such damage may cause significant yield reductions and, under severe conditions, complete crop loss [3,4]. The risk is particularly high when frost coincides with sensitive phenological stages such as bud break, flowering, or early fruit development, during which plant tissues exhibit limited tolerance to freezing temperatures [5,6]. Consequently, frost events play a crucial role in determining the effective growing season, defined by the interval between the last spring frost and the first autumn frost, and therefore strongly influence agricultural productivity and crop distribution patterns [2,7–9].

Understanding frost formation processes and developing effective protection strategies have been the focus of extensive research in agricultural and environmental sciences. Previous studies have examined frost detection methods, frost formation mechanisms, and technological approaches for monitoring frost conditions in agricultural environments. For example, Song et al. [10] analyzed frost formation mechanisms and detection techniques on plant surfaces and highlighted the importance of improved monitoring systems for frost risk management. Similarly, Tadić et al. [5] reviewed agricultural engineering technologies used to mitigate frost damage, categorizing frost protection measures into active, passive, and chemical approaches. Active methods typically involve direct intervention during frost events through technologies such as heating systems, sprinkler irrigation, or wind machines, while passive methods aim to reduce frost risk through long-term agronomic planning, including site selection, cultivar choice, and soil management. Chemical approaches attempt to enhance plant tolerance to freezing stress through protective compounds, although their field-scale effectiveness remains uncertain.

In Türkiye, several studies have investigated frost occurrence patterns and the vulnerability of agricultural systems to frost-related hazards. For instance, Yeşilırmak [11] analyzed long-term frost probability patterns across multiple locations in Aydın Province using climatological records, while Yılmaz and Çakır [12] examined farmers' disaster-risk-reduction practices in response to meteorological hazards. More recently, Bulut [13] analyzed the agricultural impacts of the severe frost event that occurred in Niğde Province in April 2025, focusing primarily on crop-specific damage patterns based on meteorological observations and economic loss assessments. While these studies provide valuable insights into frost occurrence and its agricultural consequences, comparatively limited attention has been given to the practical evaluation of frost protection strategies applied during extreme frost events at the regional production level.

Against this background, the present study investigates the severe late-spring frost event that affected Niğde Province, Türkiye, in April 2025. Niğde is characterized by continental climatic conditions and a significant concentration of fruit orchards, making the region particularly vulnerable to temperature-related agricultural hazards. The study aims to examine the frost protection practices implemented during this event and to evaluate their effectiveness and sustainability under severe frost conditions. Specifically, this research addresses two key questions: (i) how do active, passive, and chemical frost protection methods differ in terms of operational effectiveness, resource requirements, economic feasibility, and environmental implications, and (ii) which approaches provide more sustainable and context-appropriate solutions for agricultural systems exposed to continental climatic conditions? By combining a case-based assessment of the Niğde frost event with a comparative evaluation of frost protection strategies reported in the literature, the study seeks to provide practical insights that may support improved frost risk management in frost-prone agricultural regions.

2. Materials and Methods

2.1 Study Design

This study employed a qualitative case study approach combined with a comparative analytical framework to evaluate frost protection practices implemented during the severe late-spring frost event that affected Niğde Province, Türkiye, in April 2025. Case study approaches are widely used in agricultural risk research to investigate complex environmental events occurring within specific regional and production contexts. The analysis focused on documenting frost protection practices used by producers during the event and evaluating their practical effectiveness and sustainability under severe frost conditions.

2.2 Study Area and Frost Event Description

Niğde Province is located in central Türkiye and is characterized by a continental climate with cold winters, warm summers, and substantial diurnal temperature variability. The region hosts extensive fruit production systems, particularly apple, apricot, and walnut orchards, which are highly sensitive to late spring frost events during flowering and early fruit development stages.

The frost event investigated in this study occurred between 11 and 12 April 2025, during which air temperatures declined rapidly during nighttime hours and remained below freezing for an extended period. Meteorological observations obtained from the Turkish State Meteorological Service indicated that temperatures fell to approximately −9.3 °C during the most severe phase of the event and remained below 0 °C for approximately 12 hours. Such prolonged exposure to sub-zero temperatures during critical phenological stages resulted in widespread frost damage across multiple districts of Niğde Province.

2.3 Data Sources

Multiple sources of information were used to characterize the frost event and evaluate frost protection practices. These included:

- meteorological data obtained from the Turkish State Meteorological Service,
- official reports and preliminary damage assessments provided by the Niğde Provincial Directorate of Agriculture and Forestry,
- field observations and documented frost protection practices reported during local agricultural coordination meetings,
- visual documentation of frost protection practices implemented in orchards during the event,
- relevant national and international scientific literature addressing frost protection technologies and frost risk management.

Although detailed crop- and parcel-level quantitative damage statistics were still under evaluation at the time of the study, the most recent officially available information was used to identify affected crops, districts, and commonly applied frost protection practices.

2.4 Classification of Frost Protection Methods

Frost protection practices observed during the Niğde frost event were classified into three main categories commonly used in the agricultural engineering literature:

1. Active protection methods, which involve direct intervention during frost events through technologies such as heating systems, sprinkler irrigation, and wind machines.
2. Passive protection methods, which aim to reduce frost vulnerability through long-term agronomic planning, including site selection, cultivar choice, and soil management practices.
3. Chemical protection methods, which attempt to enhance plant tolerance to freezing stress through protective compounds or anti-frost formulations.

This classification framework is widely adopted in frost protection research and enables systematic comparison of different mitigation strategies applied under field conditions.

2.5 Comparative Evaluation Framework

To evaluate frost protection strategies used during the Niğde frost event, a qualitative comparative assessment framework was developed. Each protection method was assessed according to five key criteria derived from the scientific literature on agricultural frost mitigation:

- Effectiveness in reducing frost damage
- Resource requirements (energy, water, and labor)
- Economic feasibility
- Environmental impacts
- Operational applicability under local climatic and production conditions

These criteria were selected to capture both the practical performance of protection methods and their sustainability implications within regional agricultural systems.

2.6 Analytical Approach

The analysis consisted of two complementary components. First, the characteristics of the 2025 Niğde frost event and the protection practices implemented by producers were documented based on available meteorological data, official reports, and field observations. Second, these locally observed practices were evaluated through a comparative analysis with frost protection strategies reported in previous scientific studies.

By integrating regional observations with established knowledge from the literature, the study aimed to identify consistencies, limitations, and practical constraints associated with different frost protection methods under severe frost conditions. Given the absence of finalized quantitative damage statistics at the time of the study, the analysis primarily relied on qualitative evaluation; however, the use of clearly defined comparison criteria and multiple information sources helped ensure analytical transparency and methodological reliability.

3. Frost Protection Approaches in Agricultural Production

Numerous modelling, simulation, and statistical approaches have been developed to monitor and predict frost events across different temporal and climatic scales [14–23]. While these tools improve forecasting capabilities, effective frost risk management in agricultural systems ultimately depends on the selection and implementation of appropriate protection strategies. Frost protection approaches are generally categorized into passive, active, and chemical measures, each differing in timing, operational requirements, and effectiveness under varying frost conditions.

3.1 Mechanisms of Agricultural Frost Formation and Risk Factors

Frost formation results from interactions between atmospheric conditions, surface energy balance, and plant physiological processes. It occurs when near-surface air temperatures fall below the freezing point, leading to the formation of ice crystals either on plant surfaces or within plant tissues. Previous studies describe frost formation as a process consisting of three stages: nucleation, crystal growth, and development of a fully formed frost layer. During these stages, frost crystals may develop into needle-like, feathery, flaky, or irregular structures whose morphology determines key thermal properties such as density, surface roughness, and heat transfer capacity [11,12,24–27].

Agricultural frost events are commonly classified into radiative and advective frost types. Radiative frost occurs under clear and calm atmospheric conditions, where long-wave radiation loss from the ground leads to rapid cooling of the surface air layer and the development of temperature inversions. Under such conditions, frost protection methods that rely on air mixing or heat retention may be effective. In contrast, advective frost results from the movement of cold air masses accompanied by wind, producing more severe temperature declines and limiting the effectiveness of most protective interventions.

Frost risk in agricultural systems is influenced by several environmental and biological factors, including microclimatic conditions, soil characteristics, moisture availability, wind patterns, and crop phenology. Plants are particularly vulnerable during sensitive developmental stages such as bud break, flowering, and early fruit formation. Regions with continental climatic conditions, including Niğde Province in central Türkiye, often experience rapid nocturnal temperature declines combined with calm atmospheric conditions and topographic features that facilitate cold-air accumulation. These factors significantly increase frost susceptibility and highlight the need for site-specific frost management strategies.

3.2 Passive Frost Protection Methods

Passive frost protection methods consist of preventive agronomic practices implemented prior to frost events in order to reduce crop vulnerability to freezing temperatures. These measures typically involve orchard design, site selection, and crop management practices that improve microclimatic conditions and reduce frost exposure.

One of the simplest passive approaches involves the use of plant coverings made from natural or synthetic materials such as straw, peat, fabric, or plastic films. These coverings reduce long-wave radiative heat loss from plant surfaces and can provide limited protection under mild frost conditions. Experimental studies indicate that such coverings may protect plants at temperatures approaching approximately −3 °C depending on local environmental conditions, although their use is generally restricted to small-scale or high-value crops [28].

Several experimental materials have also been investigated for passive frost protection. Fuller et al. demonstrated that protective films formed using hydrophobic particles could reduce frost damage, whereas acrylic polymers showed limited effectiveness compared with untreated controls. Similarly, an organic coating derived from sugar fibers developed at the University of Perugia was reported to provide protection for grapevine shoots and may represent a more environmentally sustainable alternative to combustion-based frost mitigation practices [29].

Topographic characteristics and orchard location play a critical role in frost risk management. Cold air tends to flow downslope and accumulate in low-lying areas, increasing frost risk in depressions and valley bottoms. Consequently, orchard establishment on sloped terrain with adequate cold-air drainage can reduce frost exposure. In many temperate production systems, north-facing slopes are preferred for deciduous crops because they delay phenological development and reduce the probability of frost damage during early spring [30,31].

Soil properties and moisture status also influence frost susceptibility. Moist soils absorb heat during daytime and release it during nighttime, thereby moderating temperature declines near the ground surface. In contrast, vegetation cover or mulch layers may reduce soil heat absorption and increase frost risk. Experimental studies have reported temperature differences of up to 2 °C between bare soil and grass-covered surfaces approximately 5 cm in height [32]. Maintaining soil moisture near field capacity during frost-prone periods is therefore commonly recommended as a passive mitigation practice.

Additional passive strategies include the selection of late-flowering cultivars, optimized pruning schedules, balanced nutrient management, trunk protection through painting or insulation, and the removal of obstacles that restrict cold-air drainage. Although these approaches contribute significantly to long-term frost risk reduction, they are generally insufficient to prevent damage during severe or prolonged frost events.

The principal passive frost protection practices and their characteristics are summarized in Table 1.

Table 1. Passive frost protection methods: advantages, limitations, and suitability

Passive method	Advantages	Limitations under severe frost	Suitability
Site selection & topography	Long-term risk reduction, no energy input	Ineffective once planting is established	Preventive planning
Soil moisture management	Improves soil heat storage	Weather- and timing-dependent	Radiative frost conditions
Cover crops removal	Enhances soil heat absorption	Limited effect during extreme frost	Orchards and vineyards
Plant covers	Simple and low-cost	Limited to small areas	Short-stature or high-value crops
Cultivar selection	Delays sensitive phenological stages	Cannot prevent extreme frost damage	Moderate frost risk

3.3 Active Frost Protection Methods

Active frost protection methods involve direct intervention during frost events in order to maintain plant temperatures above critical damage thresholds. These approaches typically require mechanical systems, water applications, or external energy inputs to modify the microclimate surrounding crops.

3.3.1 Air-Mixing Technologies

Air-mixing technologies aim to disrupt temperature inversions by mixing warmer air from higher atmospheric layers with colder air near the surface. This approach is commonly implemented using wind machines, large fans, or helicopters. Under strong inversion conditions, such systems can increase canopy temperatures and reduce frost damage. However, their effectiveness declines significantly under weak inversions or during advective frost events [33-35].

Several studies have demonstrated the effectiveness of wind machines in orchard systems. Ribeiro et al. [36] reported substantial reductions in frost damage to apple blossoms under strong inversion conditions. Battany et al. [37] found that conventional wind machines produced greater temperature increases in vineyards than upward-suction fans. Similar improvements in canopy thermal balance have been observed in tea plantations using oscillating frost-prevention fans [38]. The efficiency of these systems depends on operational factors including installation height, rotation speed, and airflow characteristics [39].

3.3.2 UAV-Based Air Disturbance

Recent studies have explored the use of unmanned aerial vehicles (UAVs) for frost mitigation. Rotor-induced downwash generated by UAVs can disturb stable cold-air layers and promote vertical air mixing. Computational fluid dynamics analyses indicate that such airflow patterns may disrupt temperature inversions and reduce frost formation during radiative frost events [40,41]. Despite their potential flexibility and coverage, UAV-based systems remain limited by operational complexity and relatively high costs.

3.3.3 Heating Systems

Heating systems prevent frost damage by maintaining air temperatures above the freezing point through the use of combustion-based heaters or fan-assisted heating devices. Although effective under short-duration frost conditions, heating systems often require substantial fuel consumption and may produce environmental impacts related to emissions [5,33].

Recent technological developments have investigated alternative heating approaches. Studies conducted in New Zealand demonstrated that solar-powered water-based heating systems can increase soil and near-surface air temperatures, thereby reducing frost risk [43]. In Canada, a microwave-based heating system tested in vineyard settings represents an experimental approach aimed at slowing nocturnal cooling. However, its biological effects have not yet been clearly established [44]. Similarly, portable impulse-jet orchard heaters have been shown to increase ambient orchard temperatures by approximately 2–5 °C under favorable conditions [45]. Nevertheless, heating efficiency remains highly dependent on meteorological conditions, particularly wind speed and frost duration.

3.3.4 Sprinkler Irrigation Systems

Sprinkler irrigation is one of the most widely used frost protection techniques in fruit production. This method relies on the release of latent heat during water freezing to maintain plant tissue temperatures near 0 °C.

When properly applied, sprinkler systems can provide effective protection against moderate frost events. However, improper application may result in excessive ice accumulation and mechanical damage to plant tissues [5,42].

Sprinkler systems may operate continuously or intermittently and can be configured for over-tree or under-tree irrigation. Their effectiveness depends on environmental factors such as wind speed, humidity, and dew point temperature. Clear ice formation typically indicates successful frost protection, whereas opaque ice may signal ongoing freezing injury [5].

3.3.5 Smoke and Traditional Methods

Smoke generation represents a traditional frost mitigation practice aimed at reducing radiative heat loss by creating a smoke layer above crops. Although this method may provide limited protection under mild frost conditions (approximately −4 °C), it does not actively increase temperature and is generally considered unreliable due to labor requirements, environmental impacts, and rapid smoke dispersion under windy conditions [46-51].

Overall, the performance of active frost protection methods is strongly influenced by frost intensity, duration, wind conditions, and the presence of temperature inversions. The relationship between frost characteristics and the effectiveness of major active protection methods is summarized in Table 2.

Table 2. Relationship between frost intensity, duration, and the effectiveness of major active frost protection methods

Frost condition	Effective methods	Main limitations
Radiative frost (clear, calm nights)	Wind machines, fans, UAVs, heaters	Energy demand, limited coverage
Moderate frost duration	Sprinkler irrigation systems	High water demand
Prolonged frost events	Reduced effectiveness of all active methods	Operational constraints
Advective frost (windy, cold air masses)	Limited effectiveness	High failure risk

3.4 Chemical Frost Protection Methods

Chemical frost protection methods aim to reduce freezing damage by increasing plant tolerance to low temperatures or by inhibiting ice formation. Various products have been developed for this purpose, including antitranspirants, cryoprotectants, and compounds affecting ice nucleation processes [50,56].

These substances may function by reducing transpiration, modifying plant surface properties, or altering intracellular water composition to improve freezing tolerance. Typically, such products are applied as foliar sprays or root-zone treatments prior to frost events.

Despite promising results under experimental conditions, field-scale application of chemical frost protection remains limited. Environmental concerns, regulatory constraints, and inconsistent effectiveness under variable field conditions have restricted their widespread adoption. Consequently, chemical approaches are generally considered supplementary measures rather than primary frost protection strategies in sustainable agricultural production systems.

3.5 Technological and Innovative Approaches

Recent advances in digital agriculture have introduced new tools for frost monitoring, prediction, and early warning. Machine learning-based prediction models, sensor networks, and Internet-of-Things technologies are increasingly integrated into decision-support systems for agricultural risk management.

Several studies have demonstrated that machine learning algorithms such as random forest and support vector machines can predict frost occurrence with relatively high accuracy using meteorological datasets [51–53]. Sensor-based monitoring systems can provide real-time environmental data, enabling predictive algorithms to identify frost risk conditions and support timely management decisions [54].

Although these technologies offer significant potential for improving frost preparedness, their widespread adoption is constrained by infrastructure requirements, implementation costs, and challenges related to data availability and long-term maintenance [55]. Effective integration of digital frost monitoring systems therefore depends on regional economic capacity and compatibility with existing agricultural management practices.

4. Frost Events and Protection Practices in Niğde, Türkiye (2025)

4.1 Meteorological Characteristics of the Spring Frost Event

4.1.1 Temporal Evolution of the Frost Event

According to hourly meteorological observations obtained from the Turkish State Meteorological Service, air temperatures in Niğde Province began to decline rapidly during the evening of 11 April 2025. Based on the analysis reported by Bulut [13], frost conditions developed shortly after 20:00, when temperatures began to approach the freezing threshold.

At approximately 21:00, the air temperature dropped to −5.5 °C, continuing to decline to approximately −8.0 °C by 23:00. The frost event intensified during the night and reached its most severe phase at approximately 02:00 on 12 April, when the minimum temperature of −9.3 °C was recorded. These extremely low temperatures coincided with critical phenological stages of several orchard crops, particularly bud break and flowering, which significantly increased plant vulnerability to freezing injury.

After reaching this minimum temperature, air temperatures gradually increased during the early morning hours, rising to approximately −1.7 °C by 07:00 and returning to positive values around 08:00, marking the end of the frost episode.

4.1.2 Temperature Thresholds and Frost Duration

The meteorological data indicate that air temperatures remained below 0 °C for approximately 12 hours during the frost event. Several critical frost thresholds were exceeded during this period. Temperatures below −2 °C are known to damage sensitive reproductive tissues of many fruit crops, while temperatures approaching −8 to −9 °**C** can cause severe freezing injury to buds, flowers, and young fruit tissues.

Extended exposure to freezing conditions is a key determinant of frost damage severity. Although some plant tissues may tolerate short-duration frost events, prolonged exposure significantly increases the likelihood of irreversible damage to cell membranes and reproductive organs. The approximately 12-hour duration of sub-zero temperatures during the night of 11–12 April 2025 therefore contributed substantially to the widespread crop damage observed across the region.

Based on meteorological conditions characterized by clear skies, calm winds, and strong nocturnal cooling, the frost episode can be classified primarily as a radiative frost event. The temporal dynamics of the frost event are illustrated in Figure 1, which shows the rapid evening temperature decline and a prolonged sub-zero period reaching approximately −9.3 °C, responsible for severe crop damage.

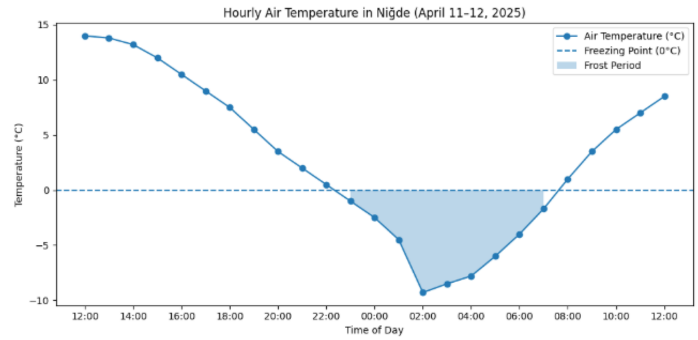

Figure 1. Hourly air temperature during the 11–12 April 2025 frost event in Niğde [13].

4.1.3 Summary of Meteorological Characteristics

The key meteorological characteristics of the Niğde frost event are summarized in Table 3.

Table 3. Meteorological characteristics of the Niğde frost event (11–12 April 2025)

Parameter	**Observed value**	**Implication for crop damage**
Frost onset	~21:00 (11 April 2025)	Early onset increased plant exposure
Minimum temperature	−9.3 °C	Severe freezing injury risk
Duration below 0 °C	~12 hours	Prolonged frost exposure
Duration below −4 °C	Several hours	High probability of blossom damage
Temperature recovery	~08:00 (12 April 2025)	End of frost conditions

The combination of very low minimum temperature and prolonged frost duration created conditions highly conducive to severe agricultural damage, particularly in orchards containing crops at sensitive reproductive stages.

4.2 Agricultural Impacts of the 2025 Frost Event

4.2.1 Affected Crop Types

The spring frost event caused widespread agricultural impacts across several districts of Niğde Province, an important fruit-producing region in central Türkiye. According to preliminary information obtained from the Niğde Provincial Directorate of Agriculture and Forestry, frost damage was observed primarily in orchard-based production systems.

Crops particularly affected by the event included apple, apricot, walnut, and other fruit tree species, which dominate agricultural production in the region. These crops are highly sensitive to frost damage during bud break and flowering stages, when reproductive tissues exhibit limited freezing tolerance.

Fruit blossoms and young buds of many temperate fruit species may suffer irreversible injury when temperatures fall below approximately −2 to −4 °C. Therefore, the minimum temperature of −9.3 °C recorded during the frost event greatly exceeded the critical damage thresholds for most orchard crops. This explains the extensive injury observed across many production areas.

4.2.2 Quantitative Indicators of Agricultural Damage

Preliminary institutional assessments indicate that the 2025 frost event resulted in severe agricultural losses across Niğde Province. The most substantial losses were reported in orchard-based production systems, which represent a major component of the regional agricultural economy.

Among the affected crops, apple production experienced the most severe decline, with provincial yield losses estimated at approximately 95% for the 2025 season. Other fruit crops, including cherry and nectarine, also experienced substantial damage during the frost event.

These quantitative indicators confirm that the April 2025 frost event represented not only severe meteorological anomaly but also a major agricultural production shock in the province, significantly disrupting fruit production and regional agricultural markets.

4.2.3 Damage Assessment Procedures

Following the frost event, official damage assessment activities were conducted by expert personnel from the Provincial and District Directorates of Agriculture and Forestry. These assessments involved field inspections, documentation of frost-affected orchards, and evaluation of damage to plant tissues.

Producers were also able to submit applications reporting frost damage to their crops. Field inspections focused primarily on flower buds, blossoms, and early fruit structures, which are particularly vulnerable to freezing injury during early spring.

The spatial distribution of frost-affected areas across different districts of Niğde Province was documented through field observations and preliminary damage reports. Examples of these damage assessment activities are illustrated in Figures 4–8.

4.3 Frost Protection Methods Implemented in Niğde

4.3.1 Sprinkler-Based Frost Protection Practices

During the frost event, several producers implemented sprinkler irrigation systems as an active frost protection method. This approach relies on the release of latent heat during water freezing, which helps maintain plant tissue temperatures near the freezing point and reduces frost injury.

Examples of sprinkler-based frost protection practices implemented in Niğde orchards during the frost period between 12 and 15 April 2025 are presented in Figures 2 and 3.

(a) (b)

Figure 2. Sprinkler-based frost protection applied on (a) Apple Tree, (b) Peach Tree

Figure 3. Sprinkler-based frost protection practices in Niğde

Sprinkler systems were typically activated in orchards where irrigation infrastructure was already available. However, the effectiveness of this protection method depends strongly on appropriate operational conditions, including continuous water application and favorable meteorological conditions.

4.3.2 Effectiveness and Limitations of Protection Measures

Despite the use of sprinkler irrigation systems in some orchards, the severity and duration of the frost event limited the effectiveness of many protection practices. Temperatures approaching −9 °C, combined with prolonged exposure, created conditions under which several commonly used frost protection methods may become less effective.

In addition, the availability of frost protection infrastructure varies considerably among producers. Orchards lacking irrigation systems or other protection technologies were particularly vulnerable to damage. These observations highlight the importance of integrating passive preventive strategies with active protection technologies in order to improve frost resilience in agricultural production systems.

4.3.3 Post-Frost Agronomic Management Recommendations

Following the frost event, an evaluation meeting was organized under the coordination of the Niğde Provincial Directorate of Agriculture and Forestry in order to assess agricultural impacts and provide technical guidance to producers.

During this meeting, agricultural experts recommended several management practices intended to support crop recovery and reduce secondary stress. These recommendations included:

- avoiding water stress throughout the plant growth period
- adjusting fertilization programs based on reduced crop load
- avoiding excessive nitrogen fertilization in subsequent growth stages
- prioritizing phosphorus-based fertilization
- implementing controlled summer pruning practices

These management strategies aim to restore vegetative growth and improve orchard recovery following frost damage [56].

4.4 Spatial Distribution of Frost Damage Across Districts

Preliminary data provided by the Niğde Provincial Directorate of Agriculture and Forestry indicate that frost damage affected multiple agricultural districts across the province. Although detailed quantitative assessments were still ongoing at the time of this study, initial reports identified several districts where orchard damage was particularly significant. The spatial distribution of frost impacts across Niğde Province is illustrated in Figures 4–8.

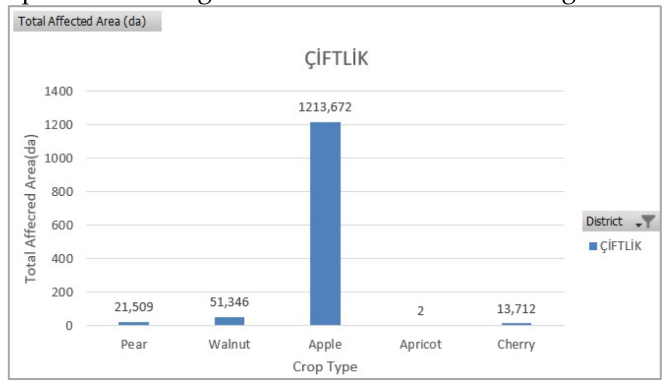

Figure 4. Frost-affected areas and crop types in Çiftlik District.

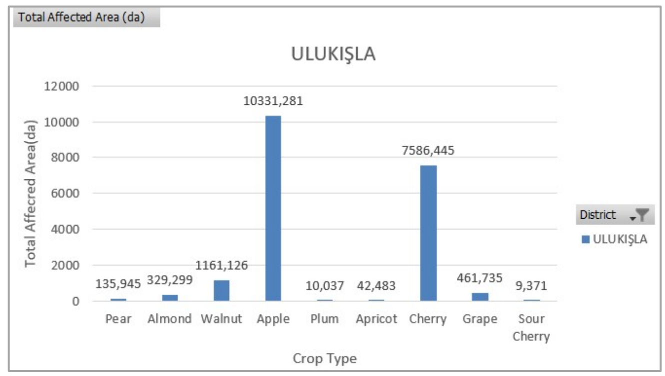

Figure 5. Frost-affected areas and crop types in Ulukışla District.

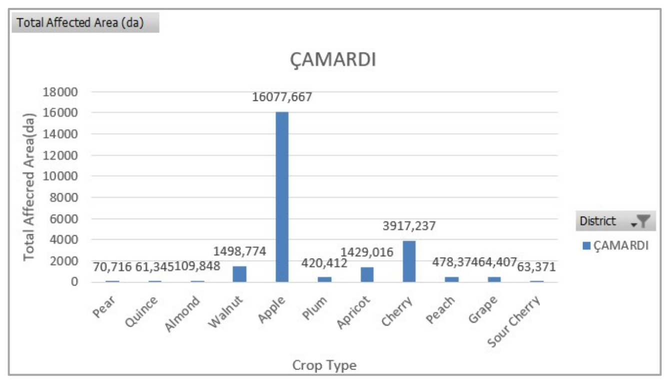

Figure 6. Frost-affected areas and crop types in Çamardı District.

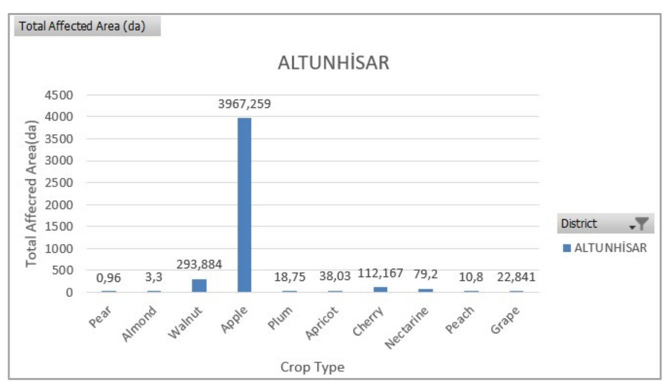

Figure 7. Frost-affected areas and crop types in Altunhisar District.

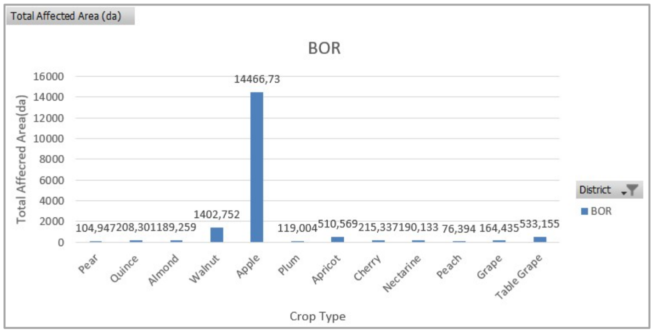

Figure 8. Frost-affected areas and crop types in Bor District.

The figures illustrate that frost damage was observed across several districts, although the extent and severity varied depending on local topographic conditions, crop types, and the availability of frost protection measures. Such spatial variability is consistent with previous studies indicating that frost risk is strongly influenced by microclimatic and topographic factors within agricultural landscapes.

5. Discussion

5.1 Frost Protection Practices in Niğde Province

The 2025 spring frost event in Niğde Province revealed several important insights regarding the effectiveness and limitations of existing frost protection practices in continental agricultural regions. As demonstrated in Section 4, frost conditions persisted for approximately twelve hours and reached a minimum temperature of −9.3 °C. Such extreme and prolonged frost conditions significantly exceeded the critical damage thresholds of most fruit crops cultivated in the region, particularly those at bud break and flowering stages. Consequently, the effectiveness of available frost protection methods was strongly constrained by both frost intensity and duration.

In Niğde Province, producers employ a combination of active and passive frost protection measures, with the selection of methods largely depending on orchard size, available infrastructure, and local climatic conditions. However, the observed practices indicate that frost protection strategies are often implemented independently rather than as part of an integrated frost risk management system.

5.2 Effectiveness of Traditional Heating and Smoke-Based Methods

One of the most commonly applied frost protection methods across the province involves heating and smoke generation through the burning of straw bales or other combustible materials. This practice aims to raise ambient temperature through combustion while simultaneously reducing radiative heat loss by creating a smoke layer above orchards.

Although this method is widely used in small- and medium-scale orchards, its effectiveness remains limited. Field observations indicate that heating and smoke generation may partially reduce frost damage during short-duration frost events. For example, in a walnut orchard located in the Altunhisar district, this approach reportedly limited crop losses during the frost event that occurred between 12 and 15 April. Nevertheless, this practice is associated with several important limitations, including high labor requirements, difficulty in maintaining uniform heat distribution, and environmental concerns related to air pollution. These factors significantly reduce the long-term sustainability of combustion-based frost protection methods.

Furthermore, the effectiveness of smoke-based protection is highly dependent on atmospheric conditions. Under windy conditions, smoke disperses rapidly and fails to form a protective layer above crops. As a result, this method provides only limited protection in open agricultural landscapes, which explains its relatively restricted adoption in certain parts of Niğde Province.

5.3 Performance of Sprinkler Irrigation Systems

Sprinkler irrigation represents one of the most widely implemented frost protection technologies in large-scale fruit orchards within the region. As illustrated in Figures 1 and 2, this method relies on the latent heat released during water freezing to maintain plant tissue temperatures near the freezing point.

Consistent with previous studies on frost protection in orchard systems, sprinkler irrigation was observed to provide relatively effective protection during short-duration frost conditions. However, the effectiveness of this method decreases when frost events persist over extended periods. During the April 2025 frost episode, several frost nights occurred consecutively, and prolonged sub-zero temperatures significantly reduced the protective capacity of sprinkler systems. Under such conditions, continuous operation is required until the ice layer formed on plant surfaces melts completely. Interruptions in water supply or improper system operation may result in rapid temperature decline and increased tissue damage.

These observations indicate that while sprinkler irrigation can serve as an effective frost protection method under moderate frost conditions, its effectiveness may be limited during severe and prolonged frost events such as those recorded in Niğde.

5.4 Limitations of Air-Mixing Technologies

In certain locations within the province, particularly in areas surrounding Hasaköy, air-mixing techniques using wind machines or fan systems have been introduced as frost protection measures. These systems operate by mixing relatively warmer air from upper atmospheric layers with colder air near the surface, thereby reducing temperature inversion effects.

However, the effectiveness of this technology in Niğde appears to be limited. Frost events in the region are often characterized by substantial temperature declines that exceed the temperature increases typically produced by fan-based systems. Under such conditions, the temperature rise of approximately 1–2 °C generated by air-mixing technologies may be insufficient to prevent frost damage. This limitation is considered one of the primary reasons for the relatively limited adoption of wind machine systems within the province.

5.5 Implications for Integrated Frost Risk Management

The findings of this study indicate that existing frost protection practices in Niğde are capable of reducing crop losses during mild or short-duration frost events but remain insufficient under severe frost conditions involving large temperature drops and prolonged exposure.

The 2025 frost event demonstrates the importance of adopting integrated frost risk management strategies that combine preventive passive measures with active protection technologies. Passive strategies such as appropriate site selection, cultivar choice, and soil management can reduce long-term frost risk, while active protection methods can provide immediate protection during frost events.

In addition, the results highlight the potential importance of early warning systems and decision-support technologies that enable producers to implement timely frost protection interventions. The integration of meteorological monitoring, digital prediction tools, and modern frost protection technologies could significantly improve the resilience of agricultural production systems in frost-prone regions such as Niğde Province.

Overall, the Niğde frost event underscores the need for region-specific frost management approaches that consider local climatic conditions, orchard structure, and the economic feasibility of protection technologies.

6. Conclusion

This study evaluated frost protection strategies in agricultural production through a case study of the severe spring frost event that occurred in Niğde Province, Türkiye, in April 2025. Meteorological analysis revealed that air temperatures declined rapidly during the night of 11–12 April, reaching a minimum of −9.3 °C and remaining below the freezing threshold for approximately twelve hours. The prolonged duration and high intensity of the frost event resulted in significant damage to orchard crops that were at sensitive phenological stages, particularly during bud break and flowering.

Field observations and institutional reports indicate that producers in Niğde employ a combination of passive and active frost protection methods, including sprinkler irrigation systems, combustion-based heating practices, and limited use of air-mixing technologies. While these methods may provide partial protection during mild or short-duration frost events, the findings of this study suggest that their effectiveness decreases substantially under severe and prolonged frost conditions such as those recorded in 2025.

The results highlight the importance of adopting integrated frost risk management strategies that combine preventive agronomic measures with appropriate active protection technologies. In addition, improving access to early warning systems and decision-support tools could significantly enhance producers' capacity to respond to frost risks in a timely manner.

Overall, the Niğde frost event illustrates the increasing vulnerability of agricultural systems to extreme climatic conditions and emphasizes the need for region-specific frost management approaches that consider local climatic characteristics, orchard structure, and economic feasibility. Future research should focus on the development of more efficient frost protection technologies, improved forecasting systems, and sustainable management strategies to enhance the resilience of agricultural production systems in frost-prone regions.

Funding: This work did not receive any external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are not publicly available due to administrative and confidentiality restrictions but may be requested from the Niğde Provincial Directorate of Agriculture and Forestry, subject to approval.

Acknowledgments: ChatGPT (OpenAI, GPT-5.2) was used solely for English language editing and grammar checking.

The authors retain full responsibility for the content and conclusions of the manuscript.

Conflicts of Interest: The authors declare no conflicts of interest.

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