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Sustainable solutions for mitigating spring frost effects on grape and wine quality: facilitating digital transactions in the viniculture sector

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In a world grappling with a growing population and shifting climate patterns, ensuring safe and sustainable food production has emerged as a paramount challenge. Extreme climate events, such as late spring frosts (LSFs), have a detrimental impact on productivity, plant growth, and consequently, crop yield. Similarly, viticulture is intricately linked to weather and climate conditions. Frost risk can be a significant issue in viticulture, potentially causing major economic damages with yield losses affecting vast areas or even entire territories from a single event. Chilling temperatures (ranging from 0 to 15 °C) and freezing conditions (below 0 °C) present unique challenges for vineyards, occurring when temperatures deviate from their usual range. These temperature fluctuations can significantly impair viticulture, affecting grapevines and diminishing both the quality and quantity of the grape harvest. In recent years, frost events have become more frequent and severe while winegrowers use various techniques to combat frost. This article aims to summarize the negative effects of extreme frost conditions in a changing climate on grapes and wine production and provide novel solutions and adaptation strategies, including sensing analysis tools, to help vineyards mitigate these impacts and ensure sustainable production.

Sustainability spotlight

Under sustainable management practices, vineyards can foster a biodiversity-rich eco-mosaic that includes both cultivated and spontaneous biodiversity. This approach helps mitigate ecosystem fragmentation, preserving the ecological value of the landscape and contributing to the sustainable use of resources. Geomatics, including Geographic Information Systems (GIS), the Global Positioning System (GPS), and digital photography (such as satellite and aerial imagery), serve as data collection and processing technologies that can assess vineyard terroir units at various scales. To address the effects of late frost damage in wine grapes, a practical remote sensing monitoring framework is proposed, focusing on the application of novel monitoring sensors and applications. This framework aims to monitor late frost damage, estimate the affected area on a large scale, and implement necessary measures. It is part of a distributed platform developed within the EC-funded research project AgriDataValue, which aims to capture and manage agri-environment data from various heterogeneous sources.

1. Introduction

Climate change is characterized any long-term alteration in the state of the climate. It is widely recognized by the scientific community as a major environmental concern confronting humanity in the 21st century and is considered one of the primary factors influencing the sustainable development of agriculture and food.[1] Agriculture is expected to be particularly vulnerable to the risks of climate change as weather conditions significantly influence the life cycles of crops.[2] These conditions are crucial abiotic factors affecting the growth, quantity, and quality of agricultural production, ultimately impacting economic sustainability.

Viticulture is highly reliant on weather and climate. Throughout the centuries, winegrowers have adjusted to climatic conditions and developed optimal practices for successfully cultivating vines in various geographical areas. However, the balance between climate and viticulture may face challenges due to climate change.[3] Ambient temperatures and variability of water availability may have a variety of impacts on management practices with subsequent impacts on yield and grape quality traits.[2] Furthermore, climatic anomalies, such as frosts, heat waves, and associated bushfires, are increasing in number and severity and with a broader window of opportunity.[3–5] One of the most promising solutions for adapting crops to climate change is the substitution of varieties. The vine (*Vitis vinifera* L.) is a species characterized by significant diversity, irrespective of the purpose of its grapes (for wine,

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table, raisins, and other uses). It is estimated that there are thousands of registered varieties of *Vitis vinifera*, encompassing a diverse range of characteristics, flavors, and growing preferences.[6] These varieties are cultivated across numerous wine regions globally, contributing to the rich tapestry of grapevine biodiversity. This biodiversity may help mitigate the impacts of harsh climate changes by enabling the development of new, more climate-resistant hybrids in the future. However, the time required to grow and adapt resistant varieties leads to significant losses in producers' outcomes. The scientific and producer communities are exploring potential future scenarios that involve genetic modifications to enhance adaptive mechanisms in grapevines.[7,8] On the other hand, extreme temperature events can cause substantial damage that cannot be mitigated by using novel robust hybrid varieties.[4] In particular, when they occur during the vegetative and reproductive development of the vine, directly impacting productivity. The substitution of varieties is not enough to counteract the severe effects of frost, especially during the early stages of grape development. Therefore, producers must adopt field-specific solutions to mitigate the impacts of harsh climate events such as spring frost.

Europe is notably responsive, recognizing the grapevine as a crucial crop that plays a key role in both environmental and socio-economic aspects.[9] Viniculture in Europe is characterized by its deep historical roots, diverse climates and soils, strict regulatory frameworks, and a strong emphasis on quality and tradition. However, it also faces modern challenges such as climate change and the need for sustainable practices, driving innovation and adaptation in the industry.[10–12] To achieve these goals, the adoption of Digital Agricultural Technologies (DATs) has become a key element of this transformative process, providing a forward-thinking perspective. Specifically, DATs and the application of AI can revolutionize viniculture by enabling precision agriculture, improving grape and wine quality, promoting sustainability, and facilitating data-driven decision-making.[13] While challenges exist, the potential benefits of AI in enhancing vineyard management and adapting to climate change make it a valuable tool, brightening the future of viniculture and the wine industry. In terms of climate adaptation, AI models can suggest adaptive practices to cope with climate change, such as choosing drought-resistant grape varieties, adjusting vineyard layouts to mitigate the effects of extreme weather, or predicting the appropriate time and space for precautionary measures.[14]

Digital agriculture includes various technologies such as communication, information, and spatial analysis tools. It is evident that agricultural data from diverse sources like sensors, weather stations, and drones can be integrated into a unified platform, offering vineyard managers actionable insights and real-time recommendations to aid decision-making. The advantages of implementing DATs in vineyards are clearly a priority for the near future, and Europe is actively striving to achieve these objectives.

2. Wine production and popularity

Grapes from the *Vitis vinifera* L. species rank among the earliest cultivated and consumed fruits around the world and are frequently hailed as the "*Home of grapes*".[7] Grape's region of origin is the Middle East, extending from the Black Sea to the Caspian Sea, south of the Caucasus Mountains, where cultivation began around 6000–8000 years ago. The ancient Greeks, Romans, and Persians consumed grapes, and it eventually made its way to the Far East, where it was utilized both as a food and a medicinal remedy.[7] Europe, undergoing fervent changes during the Middle Ages, identified monasteries such as Cluny in 910, and Citeaux in 1098 as blissful sanctuaries for vine cultivation—a significant sacred and secular heritage of the Christian religion.[15] Monasteries notably contributed to the advancement of viticulture and wine quality. In the Renaissance, dedicated brokers, known as "gourmets" in Burgundy and "Weinsticher" in Alsace, were tasked with ensuring wine quality and overseeing transactions. This approach minimized fraud and falsification, keeping such incidents rare and isolated. However, these corporations were dissolved during the French Revolution. In 1492, the Corpus Christi brought the cultivation of vines to America as part of the effort to indoctrinate the inhabitants of the New World. Moving to 1655 the cultivation of vines reached the colonies of South Africa and Australia in 1788.[15] Today, grapes continue to be highly popular, and their global production ranks them in fourth place worldwide.[16]

The allure of wine spans through ancient times to the modern era. Dating back to 2200 BC, its medicinal applications make it the oldest known form of medicine. In ancient Greece, philosophers recognized the therapeutic qualities of grapes and grape-based products. Then, in the early 1990s, the French Paradox sparked scientific inquiry, revealing intriguing connections between red wine consumption and the relatively low incidence of coronary heart disease among the French population, despite their high-fat diet and similar risk factors to other populations.[17] This inquiry revealed a significant discovery: "*moderate wine consumption can be correlated with a reduced risk of heart disease*".[9] However, excessive alcohol intake can have adverse health effects, as confirmed by a meta-analysis published in 2011, which established the J-shaped relationship between wine consumption and vascular events, as well as cardiovascular mortality.[18] Consequently, the French Paradox continues to be a subject of debate.

As at the end of the 19th century, the wine industry is facing new challenges being: the consequences of climate change, taking into account respect for the environment, the reduction of inputs, the use of resistant varieties, the quest of authenticity.[19]

Due to the high global wine consumption, the necessity for regulations and specifications became essential. Consequently, the first official definition of wine was provided by article 1 of the law dated August 14, 1889 (Griffe law), which stated that: "*No individual is allowed to transport, sell, or present for sale, under the designation of wine, a product that is not the result of the fermentation of fresh grapes*".[19] According to the European Union regulations, wine is defined as "*the product obtained exclusively from the total or partial alcoholic fermentation of fresh grapes, whether or not crushed, or of grape must*". Among the various regulatory measures introduced to control wine production, one of the most significant strategies involves defining different

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appellations, such as the European Protected Designation of Origin (PDO) and Geographical Indications (GI), regulated by EC N° 607/2009. To qualify under these denominations, production must occur within the designated region, encompassing everything from grape harvest to the wine-making process.[20]

Global wine consumption has been steadily increasing over the years, also verified by the International Organization of Vine and Wine (OIV). Significantly, almost 75% of the world's grapes are used to make wine, as reported by the Food and Agricultural Organization (FAO).[11] In 2019, the estimated global wine consumption reached 244 mhl (million hectoliters), indicating its continued popularity worldwide. On the other hand, data gathered from twenty-nine countries, constituting 94% of global production in 2022, projects world wine production (excluding juices and musts) for 2023 to range between 241.7 mhl and 246.6 mhl, with a mid-range estimate at 244.1 mhl. This reflects a 7% decrease compared to the already below-average volume observed in 2022. Once again, extreme climatic conditions such as early frost, heavy rainfall, and drought have significantly impacted the output of the world vineyard. However, in a context where global consumption is declining and stocks are high in many regions of the world, the expected low production could bring equilibrium to the world market.[11]

The year 2022 was characterized high inflation and disruptions in the global supply chain which caused a substantial slowdown in maritime freight and viniculture production yield.[21] This combination of factors resulted in an overall decrease in the volume of produced wine, accompanied by a much higher average price. Despite this, the overall value of global wine exports reached the highest level ever recorded.[11]

In recent years, the vineyard area of the European Union (EU) appears to be stabilizing and currently amounts to 3.3 million hectares. Concerning EU member states, Spain, boasting the world's largest vineyard, encompasses 955 thousand hectares in 2022, indicating a 0.8% decline compared to 2021. In contrast, France, the second-largest global vineyard, has augmented its vineyard area by 0.8% compared to 2021, totalling 812 thousand hectares. Italy maintains a consistent vineyard area of 718 thousand hectares, sustaining the growth observed between 2016 and 2020.[21] Most other significant EU vineyards have remained stable compared to 2021, as seen in Portugal (193 thousand hectares, −0.5% compared to 2021), Romania (188 thousand hectares, −0.3% compared to 2021), and Germany (103 thousand hectares, 0.0% compared to 2021).

World wine production in 2023, excluding juice and musts, is estimated at 258 mhl, representing a decrease of nearly 3 mhl (−1%) compared to 2021. This decline is attributed to a harvest volume larger than anticipated in Europe and the United States, despite the challenges posed by drought and heat waves in spring and summer, and by average production levels in the Southern Hemisphere. In general, 2022 witnessed dry and warm weather conditions across several regions globally, resulting in early harvests and moderate yields. Global wine production has maintained stability at approximately 260 million hectoliters for the fourth consecutive year, with a slight decline in its average over the past two decades.[21]

In 2022, EU wine production reached 161.1 million hectoliters, showing a 4% increase compared to 2021 and falling within the average of the last five years. The growing season of 2022 was characterized by a series of unfavourable weather events, including spring frost, hail, excessive heat, and drought. Heatwaves during spring and summer in Europe accelerated maturation, raising initial concerns about reduced yields due to extreme heat and inadequate precipitation in many areas. However, the absence of severe grape diseases and late summer rains ultimately compensated for these challenges, resulting in higher yields than initially anticipated across various regions and countries.[21]

3. Challenges in the vinicultural sector

The international vinicultural sector is facing numerous challenges, primarily related to the effects of climate change and the pursuit of sustainable production. A pressing target for European countries is to address the perspectives outlined in the 2030 Sustainable Development Goals (SDGs), developed under the auspices of the United Nations, and to integrate them as soon as possible.[22]

Within the framework of Sustainable Development Goals, organic agriculture has arisen as a response to the impacts of agricultural industrialization.[22] Similarly, organic viticulture, which emphasizes natural processes and avoids synthetic chemicals such as pesticides, herbicides, and fertilizers in favour of organic and sustainable practices, presents a considerable challenge in the viticultural sector, extending to organic winemaking. The principles of organic viticulture are rooted in maintaining soil fertility, preserving biodiversity, and pest control aligned with ecological cycles and processes.[23] These principles can be implemented through various approaches, as organic viticulture is a production system aimed at sustaining ecosystems and soil fertility in the long term, enhancing biodiversity, and protecting natural resources. In addition they promote the use of ecological processes, minimizing or eliminating external interventions while avoiding viticultural practices that require the use of synthetic chemicals.[23] Continuous innovation in organic farming techniques and sustainable practices helps improve the efficiency and effectiveness of organic viticulture.[24] In summary, organic viticulture is an environmentally conscious approach to grape growing that aligns with broader trends towards sustainability and health consciousness in agriculture and food production.

Another major challenge in contemporary viticulture is climate change. Extensive research has investigated how climate variability and change affect grapes, demonstrating how rising temperatures and changing rainfall patterns can impact grape growth. Temperature serves as the primary catalyst for phenology, and a warmer climate has the potential to advance phenological phases and shorten the growing cycle, thereby impacting harvest quality. Alterations in the life cycle timing also elevate the risk of frost, as early budburst coincides with the period when frost events are still probable. Furthermore,

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changes in precipitation patterns can heighten susceptibility to pests and diseases.[3] In line with contemporary viticulture, agroecological production systems aim to enhance the autonomy of agricultural operations and improve their competitiveness.[21] These systems seek to maintain or increase economic profitability, enhance the added value of production, and reduce the consumption of energy, water, fertilizers, plant protection products, and veterinary medicines, with a particular focus on antibiotics. Agroecological production systems are grounded in biological interactions, the utilization of ecosystem services, and the potential offered by natural resources, especially water resources, biodiversity, photosynthesis, soils, and air. They aim to sustain the qualitative and quantitative renewal capacity of these resources. Additionally, these systems contribute to both mitigation and adaptation to the effects of climate change.

There is a general agreement that temperature is the most crucial environmental factor influencing both the vegetative and reproductive growth of grapevines. Climate change has led many European wine-growing regions to experience prolonged dry periods.[25] In general, the Mediterranean region is currently experiencing the impacts of ongoing and anticipated climate change, with effects expected to be particularly severe on both the environmental and human activities.[26,27] Although the vine is known to be one of the most water-efficient among cultivated plants, winegrowers in various regions are already grappling with periods of severe water stress due to climate change.[2] As a result of extremely dry seasons, grapes are produced with lower water content and higher sugar concentration. The provided musts consequently provides higher sugar levels, and high gravity fermentation induces a stress reaction in yeast metabolism, influencing microbial ecology, with only robust yeast surviving.[28] All these effects can increase the likelihood of off-flavors, leading to a subsequent loss in wine quality.[29] In the vineyard, the grapevine is well-adapted to warm Mediterranean-type climates. However, extended and repetitive periods of aridity without irrigation can lead to the mortality of the vines.[29] On the other hand, moderate water stress typically results in an increase in sugar content and a reduction in berry size, contributing to grape maturity. Conversely, prolonged water stress can lead to a decrease in both the quantity and quality of grapes.[30] Conversely, flooding events can also negatively affect grapevines, leading to damaged grapes and consequently lower-quality wine. For example, in Mediterranean countries, typically characterized by dry summers and wet winters, climate change is causing more frequent occurrences of heavy rains, hail, and frost in the region.[31] The optimal threshold of vine water stress depends on the specific qualitative parameter being targeted, whether it's the desired phenolic compounds or aroma precursors.

The implementation of sensor technologies in agriculture, and consequently in viticulture, presents a groundbreaking and highly challenging approach to enhancing both yield and production quality. In general, sensors can be categorized into two types: proximal and remote sensors. Remote sensors operate from a distance, whereas proximal sensors are positioned close to the plants or soil.[32] These technologies encompass a wide range of tools designed to collect data on various aspects of crop growth, soil conditions, environmental factors, and farm operations.[33] However, modern agriculture is currently facing challenges in the application of these novel sensor technologies, primarily revolving around technological, logistical, and economic factors. Developing sensors that are accurate, reliable, and robust across diverse environmental conditions presents a substantial technological hurdle. These sensors must endure harsh weather, soil conditions, and other external factors while delivering precise measurements. Moreover, sensor production faces considerable variability in sensing and AI field applications, particularly in European countries with varied geography. Consequently, implementing standardized sensor monitoring systems may prove challenging. Similarly, certain countries may exhibit diverse geography within their borders. For example, Greece is characterized by a complex mosaic of appellation laws influenced by varied climatic and environmental conditions, resulting in a wide range of terroirs. Another factor that complicates the application of sensors, besides the complex geographic variations in cultivation soils, is the challenge of convincing farmers of the necessity to adopt new practices and depart from their familiar farming methods. Farmers need guidance on how to effectively incorporate sensor data into their decision-making processes.

Yet another challenge arising from the climate crisis and increasingly frequent fire incidents is the impact of smoke on grapes and, consequently, wine. Fire outbreaks can profoundly affect grapevines and the quality of wine derived from these grapes. The effects can differ depending on factors like the fire's intensity, the grapevine's growth stage during the fire, and the duration of exposure to smoke. The higher the incidence and severity of bushfires, the more substantial the challenge for wine producers. Smoke from fires contains volatile phenols and other compounds that can be absorbed by grape skins and impart undesirable flavors and aromas to the wine, a phenomenon known as “smoke taint”.[34] These compounds can lead to off-flavors such as smoky, burnt, or ashy notes in the resulting wine, reducing its quality and market value.[35] Wines, being intricate solutions, contain a diverse array of volatile organic compounds (VOCs) originating from the vinified grapes. Consequently, increased smoke contamination adversely affects the physicochemical components, resulting in lower quality in fresh grapes and wine products and subsequently causing smoke taint in wines.[5,35] A potential risk management strategy could involve the application of novel emerging digital technologies coupled with AI to accurately detect smoke-related compounds in grapes and predict smoke taint before their use in wine production. From another standpoint, the identification of contaminated grapes could be addressed through the use of NIR and e-nose techniques, suggesting implementation in the crushing, fermentation, and winemaking processes for smoke-related compounds. This would enable winemakers to adjust the duration of fermentation in contact with skins and modify other procedures accordingly.[5,36] Beyond the immediate effects on grape quality, fires can also damage vineyard infrastructure, such as trellises, irrigation systems, and buildings. Rebuilding and repairing these structures can be costly and time-consuming for vineyard owners. According to economic

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analyses, losses from the 2020 wildfires could potentially amount to $3.7 billion, impacting the economy for two years thereafter. Additionally, a 2022 report by the United Nations Environment Programme has indicated that fire outbreaks are expected to exacerbate, with the likelihood of large wildfire events increasing by as much as 57% annually.[37] Thus, prevention through fire management and control remains the most effective strategy for protecting vineyards and ensuring the quality of wine production.

4. Effect of spring frost on grape and wine quality

Fresh grapes (*Vitis vinifera* L.) are rich in essential nutrients that can boost the immune system, exert antioxidant effects, regulate blood pressure, reduce high cholesterol levels, and slow down the aging process.[9] These beneficial effects are attributed to key nutrients such as vitamins (C, K, and B), minerals (potassium, calcium, and magnesium), antioxidants, phytonutrients (such as resveratrol, phenols, polyphenols, and carotenoids), and fiber.[16] Grapes also serve as a significant source of bioactive compounds, with their accumulation influenced by various factors including grape variety, maturity, post-harvest storage, environmental conditions (such as location, light exposure, temperature, and water availability), nutrition, microorganisms, and viticulture practices.[38] In winemaking, the quality of grapes often holds more importance than meticulously controlled fermentation processes. Wine grapes exhibit a unique biogeographical model, where microbial biodiversity plays a vital role in determining the inherent components of grape quality and the health of grapevines.[39,40] In terms of the wine produced, key substances include sugar, amino acids, alcohol, organic acids, anthocyanins, and tannins.[41,42] However, grape bioactive compounds are susceptible to degradation due to climate change and harsh environmental conditions, leading to earlier harvesting in many regions.[43]

Spring frost occurs when temperatures drop to levels that can harm or destroy plants, typically following the onset of warmer spring weather. It can pose adverse consequences on viticulture, affecting grapevines and ultimately impacting both the quality and quantity of the grape harvest.[44] Climate change can complicate the occurrence and severity of spring frost events. Chilling temperatures (ranging from 0 to 15 °C) and freezing conditions (below 0 °C) present distinct forms of stress in vineyards, occurring when temperatures fall below the usual range.[45] Recent literature suggests that in recent decades, the occurrence of late-spring frost damage in temperate species near their southern European distribution limit has increased due to warming winters and springs, along with the advancement of phenological stages.[46] These incidents pose a threat to agriculture, particularly for crops like fruits, vegetables, and flowers, which are susceptible to frost damage. Similarly, spring frost can adversely affect grapes and, consequently, the quality of wine.[4,44,47] The initial impact of spring frost can be the damage to bud grapevines, which are crucial for the growth of new shoots and grape clusters. Especially when grapevines bud early in the spring, they become more vulnerable to damage from late frosts. Damage to grapes may occur when budburst precedes the last spring frost event date. Generally, low temperatures, nearing 0 °C, can harm the grapes and subsequently lead to fungal decay, resulting in significantly damaged grapes that yield wine of poor quality.[48] Also, this damage can result in decreased production yields. Frost can also result in delayed growth and ripening of grapes, prolonging the harvest season. This prolonged exposure may subject the grapes to adverse weather conditions, further affecting their quality. Another significant consequence of frost on grape quality is the potential decrease in sugar content resulting from damaged grapes. This reduction can subsequently affect the alcohol content of the wine and impact the naturally occurring microflora, potentially leading to grape decomposition in the vineyard. Decreased sugar levels can result in wines with diminished body and structure, ultimately affecting their overall quality and stability of produced wine.[40] While practices related to vineyard management and frost protection can alleviate the effects of frost damage, the unpredictable nature of spring weather patterns continues to pose a challenge for vineyards.

Spring frosts are generally episodic and, consequently, have been infrequently studied. Available studies indicate that they can cause severe damage to grapes, resulting in reduced production.[4,44] Frosts mainly occur in radiative atmospheric conditions characterized by low wind speed and a clear sky, where significant spatial variations in minimum temperatures are observed.[47] The risk of frost poses a significant challenge in viticulture, leading to substantial economic damages with yield losses affecting extensive areas or even entire "*terroir*", often occurring in a single event (Fig. 1). For example, a recent study showed that frost injury during budburst in Pinot Noir resulted in a 12% reduction in the likelihood of fruit production per vine node.[44]

Late in the plant development, after the grapes have formed, frozen grapes may contain high concentrations of sugars and sustain aromatic and flavor compounds, contributing to wine

Fig. 1 The impact of spring frost on vineyards.

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with a rich and fruity aroma.[49] In some rare cases, there may be some attributed off-flavors, but the damage is not considered as severe as in the early development stages. Without a doubt, after a frost event, microbial biodiversity is likely to alter.[39,40] There are wine producers who have turned to producing a type of wine known as "Ice wine." This product emerged when specific viticulture regions experienced consistent frost effects every year, prompting producers to create novel wine products. Ice wine is a sweet wine produced through the fermentation of naturally frozen grape juice left on the vine when the temperature drops below −7 °C to −8 °C. This product differs in sensory attributes from wines made with naturally grown grapes, as frozen grapes have higher sugar content, and the resulting wine volume is significantly lower.[49] Even though this may be a solution in times of need, there is still a growing demand for solutions to address emerging frost issues, especially early spring frost events.

The timing of early phenological plant development in relation to the occurrence of low-temperature events is crucial for frost damage to occur. During slow freezing, the formation of large ice crystals decreases cell wall resistance and promotes degradation, whereas in cryogenic freezing, the generation of uniform and small ice crystals in the intercellular space results in a lower rate of cell wall damage.[50] Regrettably, during spring frost events, the temperature drop is more severe, leading to the formation of larger ice crystals. When thawing occurs, these crystals can cause significant damage to the cells of grapes by penetrating their cell walls, resulting in nutrient losses. Recent findings suggest that low temperatures can induce varying effects depending on the maturity of the grape.[48] While grapes are classified as non-climacteric fruits with relatively low rates of physiological activity, they remain vulnerable to freezing temperatures but can endure low temperatures (Table 1). Furthermore, the damaged grapes may become more susceptible to infections, particularly microbial biodegradation.[51] The risk of frost damage depends not only on changes in the frequency and occurrence of frost days but also on the shifting phenology of grapevines.[4]

In recent years, there has been an observed increase in the frequency and severity of frost events. Subsequently, frost poses a significant concern for grape producers. During field-based frost events, plants are exposed to temperatures ranging from 0 °C to −2 °C. The dew initially freezes on the exterior of the crop, leading to desiccation damage. Furthermore, the threshold air temperature of −2 °C is widely acknowledged in most vineyards as the temperature that causes grape frost injury during budburst.[44] The freezing process involves the water surrounding the cells, drawing out water from inside and causing dehydration. Within this temperature range, ice crystals may not necessarily form inside the plant cells. Consequently, affected grapes can partially recover from this damage if the cells rehydrate. However, at temperatures below −2.0 °C, rapid ice nucleation occurs, leading to the formation of ice crystals. As these crystals grow, they physically rupture cell walls and membranes, resulting in irreversible damage.[4]

Vitis vinifera L. vines in various global regions experience frost damage during budburst, occurring when the air temperature is below freezing but typically not below −5 °C. The damage results from the freezing of tissue water outside the cells, leading to the extraction of water from the cells and subsequent dehydration of the cytoplasm.[44] Frost injury is influenced by intricate interactions between plant and environmental factors. The critical temperature is defined as the highest temperature at the surface of a plant organ, such as a bud, where injury can be detected after exposure to that temperature for a minimum of 30 minutes. Consequently, remote sensing data play a crucial role in detecting upcoming frost events.

Grapevines display varied responses to freezing temperatures, influenced by the vine variety and the presence of cold/frost genes, which are further affected by weather conditions (Table 1). These responses predominantly involve carbohydrate metabolism, encompassing the breakdown of cell wall pectin and cellulose, sucrose decomposition, raffinose synthesis, and inhibition of glycolytic processes; synthesis of unsaturated fatty acids and metabolism of linolenic acid; and synthesis of secondary metabolites, particularly flavonoids.[53] In terms of grape quality, early frost is expected to adversely affect the ripening period. This is because grape maturity typically occurs earlier during the hottest part of the maturing cycle, typically in the warmest part of the season. This effect is exacerbated under extremely high-temperature regimes, impacting the biochemical and physiological processes of grape ripening and consequently influencing sugar-acid and flavonoid levels, color, and sensory attributes of the resulting grapes.[44,54]

5. Viniculture anti-frost control

Climate predictions and simulations indicate that climate change will pose a significant challenge for wine production in the future. A comprehensive understanding of the characteristics

Table 1 The activity of grapevines to withstand freezing temperatures (0 °C to −10 °C) stress conditions

Vine species/varieties	Vine tissue	Effect/activity
Vitis vinifera cv. Cardinal	Grapes	Change in grape skin transcriptome irrespective of fruit maturity[48]
Vitis amurensis	Amur grapevine	Activate cold-resistance genes and mechanisms[8]
Vitis vinifera L. Cabernet Sauvignon	Intermodal buds	Changes in carbohydrate metabolism, synthesis of unsaturated fatty acids[52]
Vitis vinifera L.	Grapes	High expression of Ca^{2+} (ref. 52)
Vitis vinifera L.	Grapes	High expression of pectinesterase (PME) enzyme[52,53]
Vitis vinifera L.	Grapes and leaves	Hydrolysis of pectin (enhance rigidity of cell wall)[52,53]
Vitis vinifera L.	Grapes	Stimulate degradation of sucrose[52]
Vitis vinifera L.	Grapes	Reduce ability to synthesize long-chain unsaturated fatty acids[52]

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of frost events is essential for early detection, allowing for strategic crop management decisions, such as determining whether the crop should be cut for hay or harvested for grain. However, harvesting grapes is not the only measure a producer can resort to, and even this decision may affect the quality of the produced grapes, considering the possibility that the grapes are still not ready to be harvested. Furthermore, recent climate projection studies indicate that in the near future, the likelihood of late spring frost in grapevines may rise, contingent upon the location and the climate model chain. Moreover, the risk of frost damage is higher in warmer sites compared to cooler regions.[4] This underscores the importance for producers to enact suitable measures to safeguard healthy crop production. Equally important is the careful selection of specific measures to be implemented.

Winemakers are currently utilizing a range of methods to address spring frost appearing on vineyards by encompassing both active and passive frost control techniques. Active frost control techniques may encompass heaters, frost fans, antifreeze towers, wind machines, and water spraying (Fig. 2). Passive frost control techniques may involve selecting suitable vineyard sites with good air drainage and elevation, as well as implementing cover crops, mulching, and soil management. Wind machines are considered a conventional approach to frost protection and find extensive use during temperature inversion conditions created by radiative cooling, characterized by light winds and clear skies.[55] Other designs as alternatives to the traditional wind machine have also been explored. In the mid-1900s, downward-blowing wind machines with a vertical or inclined axis were assessed, but the levels of crop protection achieved were not considered economically feasible. Nevertheless, they significantly impact the heat balance of crops and moderating convective heat transfer across crop surfaces so they are not promoted.[55,56] Frost fans are strategically positioned large fans within the vineyard to circulate air, preventing cold air from settling on the vines. This air movement helps elevate temperatures slightly, mitigating the risk of frost damage. Another method involves employing heaters, such as those powered by propane, gas, or oil, to generate heat and increase temperatures in the vineyard. These heaters can be placed either between rows of vines or spread throughout the vineyard to establish a warmer microclimate.

Fig. 2 Implementing active frost control techniques in vineyards (figure from the area of Saint-Émilion, Union of Producers, France https://vins-saint-emilion.com).

Effective frost protection depends on many factors: type of frost, severity of the frost event, crop sensitivity, soil conditions, topography, and on crop practices.[4,55,56] It also depends heavily on the equipment used in the frost protection system. The application of advanced multidisciplinary technologies in vineyards is yielding promising results.[47,57] For instance, precise monitoring and assessment of late frost damage in wine grapes greatly benefit from understanding the wine grape planting area, achieved through a combination of *in situ* sensors, satellite weather monitoring, and decision-making processes. Satellite data has been extensively utilized for mapping crop planting areas, utilizing diverse data types and features such as sensitive bands, texture features, and vegetation index to provide comprehensive and accurate information in the viniculture sector. Likewise, various machine learning methods, including maximum likelihood, support vector machine, and Random Forest, can be utilized for extracting planting areas.

Aligned with the United Nations 2030 Agenda for Sustainable Development, which aims to foster global collaboration for peace and prosperity for both people and the planet, geographical Information Systems (GIS) have been proposed as advanced tools for managing variability in commercial vineyards.[22] These systems provide a high-resolution spatial perspective on the distribution of crop performance and the underlying factors.[58] In the same perspective the crucial factor of land surface temperature may serves as a late frost monitoring and evaluation parameter. Representative algorithms for deriving land surface temperature from satellite data can be developed.[59] High-resolution remote sensing data sources, such as Moderate Resolution Imaging Spectroradiometer, Landsat, WorldView, and Satellite for Observation of the Terrestrial Environment, may enable the identification of grape parcels and the assessment of risks at the parcel level. Given that the majority of wine grape plantations in the study area cover less than 1 km^2, achieving higher spatial and temporal resolution is essential for effective monitoring and assessment of late frost damage.

Due to the limited distribution of monitoring for late frost damage in wine grapes, we propose a practical remote sensing monitoring framework. This framework aims to monitor late frost damage, estimate the affected area on a large scale, and implement necessary measures. It is part of a distributed platform developed within the EC-funded research project AgriDataValue,[60] which focuses on capturing and managing agri-environment data from various heterogeneous sources (Fig. 3).

The platform follows a bottom-up approach and comprises four building blocks: (a) decentralized data and *in situ* processing tools enable the capture and processing of data close to the sources. It integrates data from diverse sources such as *in situ* (IoT) sensors, RGB and multispectral images from drones, and Earth Observation data (EODATA/EODATA+) from Copernicus Sentinels, Landsat, and Envisat. (b) edge cloud analytics suite utilizes network edge processing and storage capabilities for efficient distributed processing and edge-driven Federated Machine Learning (ML). Explainable AI (XAI) justification is employed to enhance the end-user experience and foster trust in platform

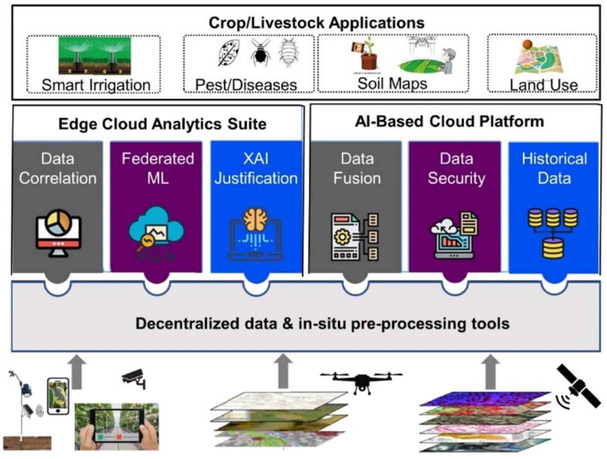

Fig. 3 Sensing platform high level architecture.

recommendations. (c) AI-based Cloud Platform integrates heterogeneous IoT and spatiotemporal data sources while ensuring data security. For batch data analysis requiring scalability, it employs specialized analytics algorithms and advanced indexing techniques tailored for spatiotemporal data and trajectories. (d) Crop/Livestock Application provides specialized apps offering advice and recommendations to end users, including farmers, corporations, and EC Common Agriculture Policy authorities.

6. Conclusions and prospects

Recognizing the potential consequences of climate change on viticulture has become increasingly crucial for the wine industry. Although frost poses a significant risk to vineyards, diligent management and adaptation strategies can help alleviate its impact. Collaboration and holistic sector-wide perspectives will be vital for fostering collective problem-solving efforts. However, the deployment of emerging sensor technologies in the viniculture sector, necessary to address the harsh effects of the climate crisis, may face challenges due to intellectual property overlaps, complicating investment decisions in agricultural R&D. To guarantee the best crop production and execute efficient frost control in vineyards, it's crucial to grasp the intricacies of frost, pinpoint areas susceptible to cold, and gather and assess data on climate, vine growth stages, terrain, and land utilization. Creating indicators to gauge frost risk using this information is vital. Furthermore, it's essential to devise strategies or tools to aid winegrowers in tackling frost. Facilitating the development of frost monitoring systems can provide warning systems and predictive models necessary for producers to take appropriate measures against frost events when needed. As a result, combining short-term measures, like frost fans and irrigation, with long-term strategies, such as selecting frost-resistant grape varieties and using advanced climate monitoring, winemakers can protect their crops and ensure sustainable production.

Conflicts of interest

There are no conflicts to declare.

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References

1 G. Flachowsky, *Anim. Feed Sci. Technol.*, 2013, **182**, 131–133.
2 D. Adelsheim, C. Busch, L. Catena, B. Champy, J. Coetzee, L. Coia, B. Croser, P. Draper, D. Durbourdieu, F. Frank, H. Frischengruber, R. Horvath, A. Lageder, E. Loosen, T. Roberts, M. Strugnell, M. A. Torres and M. Torres, *J. Wine Econ.*, 2016, **11**, 5–47.
3 L. Massano, G. Fosser, M. Gaetani and B. Bois, *Sci. Total Environ.*, 2023, **905**, 167134.
4 M. Meier, J. Fuhrer and A. Holzkämper, *Int. J. Biometeorol.*, 2018, **62**, 991–1002.
5 S. Fuentes, V. Summerson and C. G. Viejo, *BIO Web Conf.*, 2023, **56**, 01007.
6 A. M. Fortes and M. S. Pais, in *Nutritional Composition of Fruit Cultivars*, ed. M. S. J. Simmonds and V. R. Preedy, Academic Press, San Diego, 2016, pp. 257–286, DOI: 10.1016/B978-0-12-408117-8.00012-X.
7 B. Anna and S. Éva, in *Nonvitamin and Nonmineral Nutritional Supplements*, ed. S. M. Nabavi and A. S. Silva, Academic Press, 2019, pp. 461–465, DOI: 10.1016/B978-0-12-812491-8.00061-8.
8 X. Ma, F. Zhao, K. Su, H. Lin and Y. Guo, *BMC Genomics*, 2022, **23**, 551.
9 P. Lekka, E. Fragopoulou, A. Terpou and M. Dasenaki, *Molecules*, 2023, **28**, 7616.
10 ELSTAT, Data are exported from the Vineyard Register maintained by the Ministry of Rural Development and Food, *2020 Vineyard Survey*, Hellenic Statistical Authority, Piraeus, Greece, 2020, https://www.statistics.gr/en/statistics/-/publication/SPG63/.
11 OIV, *Note de Conjoncturevitivinicole Mondiale 2022*, International Organisation of Vine and Wine, 2023, 1st edn, pp. 1–19, https://www.oiv.int/sites/default/files/documents/OIV_Note_de_conjoncture_vitivinicole_mondiale_2022_0.pdf.
12 G. M. Dimitri and A. Trambusti, *Heliyon*, 2024, e31648, DOI: 10.1016/j.heliyon.2024.e31648.
13 J. MacPherson, A. Voglhuber-Slavinsky, M. Olbrisch, P. Schöbel, E. Dönitz, I. Mouratiadou and K. Helming, *Agron. Sustainable Dev.*, 2022, **42**(4), 70.
14 G. Papadopoulos, S. Arduini, H. Uyar, V. Psiroukis, A. Kasimati and S. Fountas, *Smart Agric. Technol.*, 2024, **8**, 100441.
15 M. Fiorilo, G. Tempesta, D. Barison, M. Boselli and A. Venturi, *BIO Web Conf.*, 2023, **56**, 03009.
16 Ş. I. Câmpean, G. A. Beşchea, M. B. Tăbăcaru, L. M. Scutaru, G. Dragomir, A. I. Brezeanu, A. Şerban and G. Năstase, *Heliyon*, 2023, **9**, e17740.

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17 E. Fragopoulou and S. Antonopoulou, *Clin. Chim. Acta*, 2020, **510**, 160–169.
18 S. Costanzo, A. Di Castelnuovo, M. B. Donati, L. Iacoviello and G. de Gaetano, *Eur. J. Epidemiol.*, 2011, **26**, 833–850.
19 E. Meistermann, V. Lempereur, F. Charrier and P. Cottereau, *BIO Web Conf.*, 2023, **56**, 03005.
20 P. Martins-Lopes and S. Barrias, in *Advances in Botanical Research*, Academic Press, 2024, DOI: 10.1016/bs.abr.2024.02.012.
21 OIV, *In 2023, world wine production is expected to be the smallest in the last 60 years*, International Organisation of Vine and Wine, 2023, https://www.oiv.int/press/2023-world-wine-production-expected-be-smallest-last-60-years.
22 G. Yumnam, Y. Gyanendra and C. I. Singh, *Sustainable Futures*, 2024, **7**, 100192.
23 OIV, *Focus OIV the World Organic Vineyard*, International Organisation of Vine and Wine Intergovernmental Organisation, 2021, pp. 1–19, https://www.oiv.int/sites/default/files/2022-09/en-focus-the-world-organic-vineyard.pdf.
24 K. P. Purnhagen, S. Clemens, D. Eriksson, L. O. Fresco, J. Tosun, M. Qaim, R. G. F. Visser, A. P. M. Weber, J. H. H. Wesseler and D. Zilberman, *Trends Plant Sci.*, 2021, **26**, 600–606.
25 F. Droulia and I. Charalampopoulos, *Atmosphere*, 2022, **13**, 837.
26 M. Curmi and V. Axiak, *Mar. Pollut. Bull.*, 2021, **166**, 112200.
27 L. Bresinsky, J. Kordilla, T. Hector, I. Engelhardt, Y. Livshitz and M. Sauter, *J. Hydrol.: X*, 2023, **20**, 100153.
28 A. Terpou, M. Dimopoulou, A. Belka, S. Kallithraka, G. J. E. Nychas and S. Papanikolaou, *Microorganisms*, 2019, **7**(12), 666.
29 S. Feifel, J.-P. Hensen, I. Weilack, F. Weber, P. Wegmann-Herr and D. Durner, *BIO Web Conf.*, 2023, **56**, 01016.
30 I. Vigo, R. Marcos, M. Terrado, N. González-Reviriego, A. Soret, M. Teixeira, N. Fontes and A. Graça, *Clim. Serv.*, 2023, **32**, 100418.
31 H. E. Beck, N. E. Zimmermann, T. R. McVicar, N. Vergopolan, A. Berg and E. F. Wood, *Sci. Data*, 2018, **5**, 180214.
32 T. Mizik, *Heliyon*, 2023, **9**, e16322.
33 A. Morchid, R. El Alami, A. A. Raezah and Y. Sabbar, *Ain Shams Eng. J.*, 2024, **15**, 102509.
34 D. Kelly, A. Zerihun, D. P. Singh, C. Vitzthum von Eckstaedt, M. Gibberd, K. Grice and M. Downey, *Food Chem.*, 2012, **135**, 787–798.
35 K. R. Kennison, M. R. Gibberd, A. P. Pollnitz and K. L. Wilkinson, *J. Agric. Food Chem.*, 2008, **56**, 7379–7383.
36 L. C. Schroeder, I. L. Pessenti, H. G. J. Voss, R. A. Ayub, M. E. Farinelli, H. V. Siqueira and S. L. Stevan, *Smart Agric. Technol.*, 2023, **6**, 100343.
37 E. Tomasino, D. C. Cerrato, M. Aragon, J. Fryer, L. Garcia, P. L. Ashmore and T. S. Collins, *Food Chemistry Advances*, 2023, **2**, 100256.
38 A. Sabra, T. Netticadan and C. Wijekoon, *Food Chem.: X*, 2021, **12**, 100149.
39 K. Chen, L. Zhang, S. Qiu, X. Wu, J. Li and L. Ma, *Food Chem.*, 2022, **384**, 132553.
40 A. Terpou, V. Ganatsios, M. Kanellaki and A. A. Koutinas, *Microorganisms*, 2020, **8**(5), 764.
41 S. Christofi, S. Papanikolaou, M. Dimopoulou, A. Terpou, I. B. Cioroiu, V. Cotea and S. Kallithraka, *Appl. Sci.*, 2022, **12**(3), 1405.
42 P. Fraile, J. Garrido and C. Ancín, *J. Agric. Food Chem.*, 2000, **48**, 1789–1798.
43 P. Sancho-Galán, A. Amores-Arrocha, V. Palacios and A. Jiménez-Cantizano, *BIO Web Conf.*, 2023, **56**, 02010.
44 K. J. Evans, P. K. Bricher and S. D. Foster, *Aust. J. Grape Wine Res.*, 2019, **25**, 201–211.
45 M. Aslam, B. Fakher, M. A. Ashraf, Y. Cheng, B. Wang and Y. Qin, *Agronomy*, 2022, **12**, 702.
46 G. Sangüesa-Barreda, A. Di Filippo, G. Piovesan, V. Rozas, L. Di Fiore, M. García-Hidalgo, A. I. García-Cervigón, D. Muñoz-Garachana, M. Baliva and J. M. Olano, *Sci. Total Environ.*, 2021, **775**, 145860.
47 M. Madelin and G. Beltrando, *Meteorol. Appl.*, 2005, **12**, 51–56.
48 R. Rosales, I. Romero, C. Fernandez-Caballero, M. I. Escribano, C. Merodio and M. T. Sanchez-Ballesta, *Front. Plant Sci.*, 2016, **7**, 1020.
49 P. Li, Y. Jia, D. Cai, X. Wang, J. Liu, R. Zhu, Z. Wang, Y. He and L. Wen, *Food Chem.: X*, 2023, **20**, 101016.
50 M. Zielinska, E. Ropelewska and P. Zapotoczny, *Food Bioprod. Process.*, 2018, **110**, 40–49.
51 H. Zhang, M. T. Apaliya, G. K. Mahunu, L. Chen and W. Li, *Trends Food Sci. Technol.*, 2016, **51**, 88–97.
52 X. Han, Y.-H. Li, M.-H. Yao, F. Yao, Z.-L. Wang, H. Wang and H. Li, *Int. J. Mol. Sci.*, 2023, **24**, 3884.
53 H. Xin, W. Zhu, L. Wang, Y. Xiang, L. Fang, J. Li, X. Sun, N. Wang, J. P. Londo and S. Li, *PLoS One*, 2013, **8**, e58740.
54 C. S. Eric Duchêne, *Agron. Sustainable Dev.*, 2005, 3–99.
55 M. C. Battany, *Agric. For. Meteorol.*, 2012, **157**, 39–48.
56 K. Kimura, D. Yasutake, K. Nakazono and M. Kitano, *Biosyst. Eng.*, 2017, **164**, 98–109.
57 W. Li, J. Huang, L. Yang, Y. Chen, Y. Fang, H. Jin, H. Sun and R. Huang, *Remote Sens.*, 2021, **13**, 3231.
58 A. Graça, J. V. Porto, D. Rioux, N. Oliveira and C. Bateira, *BIO Web Conf.*, 2023, **56**, 01010.
59 Y. Mo, Y. Xu, H. Chen and S. Zhu, *Remote Sens.*, 2021, **13**, 2838.
60 Smart Farming digital transformation and agri-enviromental monitoring, https://agridatavalue.eu/.