Leveraging Artificial Intelligence to Manage a Sustainable Transition In Viticulture "STIV"

Sustainable Viticulture:

gaps, mismatches and challenges

A guide developed by the STIV project consortium to promote a green and healthy approach to the working environment, recognising the critical importance of addressing environmental challenges and climate change.

The STIV consortium

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1. Introduction

Viticulture, a millennia-old practice for human beings, is currently facing unprecedented challenges, largely due to climate change. Viticulture is an essential agricultural practice key for economic and social sustainability worldwide, mainly in the Mediterranean region (Ohana-Levi and Netzer, 2023). This practice is intimately based on the relationship between the environment and the grapevine. Multiple factors either environmental or edaphic factors impact vineyard productivity, grape, and quality of wine (Torres et al., 2021; Villalobos-Soublett et al., 2022), taking part of the terroir idea.

Across the agricultural sector, various strategies have been implemented to address climate change mitigation. These approaches focus on optimizing certain aspects such as water resources, energy and carbon management, nutrient utilization, weather-responsive techniques and crop-specific smart management. The widespread adoption and continuous refinement of these methods have significantly increased the potential for more environmentally responsible farming practices. These climate-smart techniques often intersect with other agricultural concepts, including sustainable agriculture regenerative agriculture, environmentally friendly agriculture, nature-based solutions, and clean agricultural production technologies. By embracing these practices, the agricultural industry is moving towards a more sustainable and climate-resilient future, reducing its environmental footprint while maintaining productivity (Oladele and Ngidi, 2025).

On the one hand, sustainable vitiviniculture is defined by the OIV (2011) in their Resolution OIV-VITI 422-2011 as a "*Global strategy on the scale of the grape production and processing systems, incorporating at the same time the economic sustainability of structures and territories, producing quality products, considering requirements of precision in sustainable viticulture, risks to the environment, products safety and consumer health and valuing of heritage, historical, cultural, ecological and landscape aspects*".

On the other, and directly extracted from Resolution OIV-VITI 641-2020 by OIV (2020), the three main challenges for the vitivinicultural sector in adapting sustainability approach are:

i. Sustainable market and societal expectations: "*Maintain a sustainable market in line with societal expectations both inside and outside the organization, while supporting competitive productive and economic issues"* (OIV 2020).

The contents (Amah et al., 2021), the typologies and message adequacy and the alignment to users' needs (Kumar et al., 2020) are included in the necessary

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information from the farmers. Most of the research on information should highlight some key aspects such as production and market risks (Komarek et al., 2020), the adequacy of measures required by end-users (Nwafor et al., 2020), the emerging needs (Chen and Lu, 2019) and the specific information for different stages of the value chain (Diemer et al. 2020).

ii. Society's confidence in vitivinicultural companies: *"Improve society's confidence in vitivinicultural companies through the implementation of a sustainability approach"* (OIV 2020).

A key aspect to consider linked to society's confidence is communication. The basic risk communication theories are trust determination, negative dominance, mental noise, and risk perception. They are critical for communication with the public and should be considered (Oladele and Ngidi, 2025).

The theories highlight that for an efficient communication it has to be built with the public. Moreover, risk information and messaging should be short and improved using visual skills to reinforce recall. It is also necessary to avoid negative words and contents (Oladele and Ngidi, 2025).

iii. Climate change: *"Develop a sustainable vitiviniculture with a dual objective of preventing negative environmental impacts and adapting to climate change, thanks to the adaptation of production practices"* (OIV 2020).

Grapevines grown around the world, from latitudes 6° to 45° in the Southern Hemisphere and 4° to 51° in the Northern hemisphere (Santos et al., 2020). The ambient influences as well as the primary environmental constraints for grape production vary significantly from region to region.

Climate change impacts negatively on communities that depend on agro-based livelihoods, including wine growers. The global challenges posed by climate change are characterized by unknown nature and the unpredictability and catastrophic impacts (FAO, 2021).

Adaptation strategies in this context are needed, such as the use of early warning systems, agrometeorology information, resilient varieties, water-smart, and soil health technologies are integral components of climate-smart agriculture. They appear as methodologies for sustainability of productivity, adaptative capacity, incomes, and resilience to potential shocks (Batchelor, et al. 2019), especially considering the potential for more frequent events.

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2. Sustainable viticulture

Faced with these three challenges, sustainable viticulture emerges as a promising strategy to adapt the wine industry to new climatic conditions and reduce its environmental impact. This approach seeks to balance high-quality wine production with ecosystem preservation and local community well-being by promoting social responsibility (Mariani and Vastola, 2015). Sustainable viticulture is therefore based on three fundamental pillars: environmental sustainability, economic viability, and social equity (Santini et al., 2013). The key principles of sustainable viticulture include:

- Conservation of natural resources
- Protection of biodiversity
- Integrated pest and disease management
- Energy efficiency
- Responsible water management
- Fair and safe work practices

Despite its benefits, the implementation of sustainable viticulture faces several challenges, such as initial transition costs, lack of knowledge and training, communication mismatches, and climate variability. But these difficulties also present opportunities for innovation and the development of new solutions.

In most cases of the practices listed below, it is not so much about studying the aforementioned practices but rather incentivizing the need for their implementation by winegrowers. With this objective, communication campaigns and support to put all these activities into practice are considered essential.

2.1. Soil management

The implementation of sustainable soil management practices is fundamental to improving vineyard resilience in the face of the climate change challenge. In a work of interest, Döring et al., (2022) summarized and discussed the effects of integrated, organic, and biodynamic management on soil compaction, erosion, water quality and supply, contamination, biodiversity conservation, biomass production, and climate regulation. Among the challenges related to soil management, we would find:

- The need to reduce soil erosion, to improve water retention, and to increase vineyard biodiversity.

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- The improvement of soil structure, increasing its water retention capacity, and providing nutrients to the vineyard always in a sustainable manner.

- The preservation of soil structure and the increase of its organic matter content if necessary.

- The preservation of microbial life in the soil.

2.2. Water management

Efficient water management is crucial in a context of increasing water scarcity. Romero et al. (2022) reviewed the state of the art of different water-saving irrigation strategies and methods used to improve productive water use efficiency. Challenges to be achieved would be:

- Improving water use efficiency without significantly compromising grape quality.

- Implementing soil moisture monitoring technologies to manage irrigation more precisely.

- The possibility of capturing and storing rainwater, in order to provide an additional source of water for irrigation during dry periods.

2.3. Biodiversity

The promotion of biodiversity is a key component of sustainable viticulture. For example, Zielonka et al. (2024), to benefit biodiversity within vineyards, recommend that sustainability accreditation schemes should include requirements to reduce the ecotoxicity of used agrochemicals, and promote higher ground vegetation cover and height by reducing herbicide use. The aims are:

- Conservation of natural areas, maintaining ecological corridors within and around vineyards.

- Diversification of crops, including planting native species and creating habitats for pollinators.

- Crop rotation, to improve soil health and reduce pest and disease pressure.

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2.4. Integrated pest and disease control

The adoption of integrated pest and disease management strategies can reduce dependence on chemical pesticides. To achieve this, it would be necessary to spread the following strategies among winegrowers:

- The use of beneficial insects as natural enemies to control pests.
- The implementation of sexual confusion techniques using pheromones to increase efficiency in controlling certain insect pests.
- The planting of selected and disease-resistant grapevine varieties by winegrowers could reduce the need for phytosanitary treatments.
- The promotion of biodiversity to maintain ecological balance.
- The selective and reduced use of pesticides in order to minimize environmental impact and protect human health.
- Encouraging the possibility of applying elicitors as a defensive agent for the vineyard against possible attacks (Apolinar-Valiente et al., 2018).

2.5. Technological innovations

The incorporation of advanced technologies plays a crucial role in the transition towards more sustainable viticulture. Although these technologies exist, they need to be known and applied by winegrowers: this is part of the challenge.

Precision viticulture uses geographic information technologies and remote sensors to optimize vineyard management. For example, the use of satellite images and drones allows the identification of zones with different characteristics within the vineyard, facilitating more precise management. However, to make this use, the winegrower must both have a drone and know how to operate it, or hire a company to carry out this activity. Matese et al. (2015) demonstrated the effectiveness of drone-based remote sensing systems for monitoring the water and nutritional status of vineyards. Shieck et al., (2023) studied the economic impact of drones in viticulture, an area that has not been previously researched. These authors calculate the economic impact of drones in viticulture.

Regarding artificial intelligence and machine learning, these are being applied in various aspects of viticulture. For example, there are machine learning models that can predict disease risk based on climate and vineyard data, allowing for more precise and timely interventions. Likewise, artificial intelligence algorithms can help determine the optimal harvest time based on multiple parameters.

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Research on the impact of climate variability and change on viticulture has been comprehensive, covering both historical weather patterns and future climate projections. For example, studies have examined observed weather conditions and potential future scenarios. More recently, Pérez-Zanón et al. (2024) have focused on providing real-time sub-seasonal climate forecasts to European vineyard managers, integrating these with models that predict grape development stages and disease risks, as seen in work by Oldani et al. (2023). This approach helps the wine industry adapt to climate shifts and maintain quality standards.

Similarly, the implementation of internet-connected sensors is revolutionizing vineyard monitoring and management. For example, certain sensors allow continuous tracking of parameters such as soil moisture, temperature, and plant water status. The integration of sensor data with predictive models can provide early warnings about risks of frost, diseases, or water stress.

Modern advancements in viticulture and agricultural technology are paving the way for grape growers to tackle climate challenges head-on. Cutting-edge methods like high-precision vineyard management tools, solar panel integration with grape cultivation, and techniques to stimulate new growth in vines show great potential for helping vineyards adapt to changing environmental conditions. However, the road from experimental concepts to widespread adoption in commercial wine production is not without its hurdles. Implementing these forward-thinking solutions in real-world vineyard operations raises important questions about their economic impact on wine producers and the social implications for traditional wine-growing communities. These complex issues demand thorough research and careful consideration as the wine industry navigates the path toward a climate-resilient future (Reta et al., 2025).

2.6. Varietal adaptation and new cultivation techniques

Adapting grapevine varieties to climate change is a key strategy for long-term sustainability. Research is focusing on identifying and developing grapevine varieties and hybrids that are more resilient to changing climatic conditions while maintaining positive characteristics from an oenological perspective (Apolinar-Valiente et al., 2017). For example, in regions that are becoming warmer, late-ripening varieties can help maintain wine quality by delaying ripening until cooler periods. Researchers are also seeking clones that maintain adequate levels of acidity and phenolic compounds under heat conditions. Wolkovich et al. (2018) analyzed the potential of grapevine varietal diversity for climate change adaptation, highlighting the importance of conserving and utilizing existing genetic diversity.

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Similarly, new cultivation techniques are being explored to adapt viticulture to changing conditions:

- **Alternative training systems:** Modifying training systems can help protect grapes from excessive solar radiation, improve water use efficiency, and maintain an adequate microclimate in the cluster zone. Practices such as certain pruning adjustments, leaf removal, shoot positioning, canopy management, controlled deficit irrigation, and the application of solar protectors are being investigated to modulate grape composition. Bonada et al. (2015) evaluated the effectiveness of artificial shading systems to mitigate the effects of heat stress in vineyards. Palliotti et al. (2014) studied canopy management strategies to mitigate the effects of climate change in viticulture, highlighting the importance of maintaining a balance between exposure and protection of clusters. Reta et al. (2025) largely reviewed canopy management practices, suggesting a holistic, microclimate/site-driven approach that integrates varietal biodiversity, precision irrigation, and sustainable soil management.

- **Vineyard relocation:** As previously mentioned, in some regions, growing vines at higher altitudes (high-altitude viticulture) or different latitudes is being considered as an adaptation strategy to global warming. In these areas, climatic conditions allow for maintaining the desired balance in grape composition.

2.7. The future of sustainable viticulture

As the wine industry continues to face the challenges of climate change and the growing demand for sustainable practices, we are likely to see significant evolution in the sector in the coming decades. Several trends are shaping the future of sustainable viticulture.

Regenerative viticulture represents a step beyond sustainability, focusing not only on maintaining the current state of the ecosystem but on actively improving it. This approach seeks to restore soil health, increase biodiversity, and enhance the resilience of the viticultural ecosystem as a whole. Moreover, this viticulture practices can help sequester carbon in the soil, contributing to climate change mitigation (Brunori et al., 2016). Their focus on biodiversity can create more resilient and ecologically rich vineyards.

The application of circular economy principles in viticulture and wine production is gaining traction (Soares et al., 2025). Two key points of the circular economy applied to viticulture would be valorization of by-products and the use of sustainable packaging. The use of winemaking residues to produce other value-

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added products can reduce waste and create new sources of income, whereas the innovation in wine packaging, including lighter bottles and recyclable materials, is reducing the sector's carbon footprint.

The cultivation of vines in urban and peri-urban environments is emerging as an interesting trend. Among the challenges that this viticulture aspires to address are the utilization of urban spaces and the more direct connection with consumers: bringing wine production closer to consumers, fostering a greater understanding and appreciation of the process.

Finally, it should be noted that research will be crucial to address future challenges in sustainable viticulture. On one hand, studies are being conducted to better understand the molecular mechanisms that regulate the accumulation of various compounds in grapes under different environmental conditions. Additionally, research in vine genetics could lead to the development of more resilient varieties and hybrids in order to significantly reduce the need for pesticides. The creation of varieties better adapted to changing climatic conditions will be crucial for the long-term sustainability of the sector.

As mentioned in the Introduction section, the three main challenges for the vitivinicultural sector in adapting sustainability approach (OIV 2020) are:

i. Sustainable market and societal expectations

ii. Society’s confidence in vitivinicultural companies

iii. Climate change

In this document, we will extensively develop each of these three points.

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3. Sustainable market and societal expectations

The common view of climate change is that it's a far-off danger with impacts primarily affecting distant locations and other people, often seen as a matter for governmental action rather than individual concern (Ma et al. 2023). But climate change is a widespread phenomenon that needs societal-level effectiveness and collective action for mitigation (Wang, 2023). Interestingly, when managers and policymakers become more aware of the vulnerabilities associated with climate change, they tend to be more receptive to carbon offset initiatives and more committed to achieving carbon neutrality aims.

The United Nations emphasizes that climate change communication should focus on educating and inspiring audiences to take action against the climate crisis, utilizing credible scientific data, presenting both the challenges and solutions, and encouraging concrete steps (UN, 2023). Effective climate change communication should prioritize empowering individuals, promoting equitable solutions, and avoiding misleading claims or stereotypes.

Rather than amplifying threats and instilling fear, climate change messaging should motivate individual and collective responses to address the issue (Depoux et al., 2017). The relationsphip between mass media, climate science, and policy plays a crucial role in shaping public perception of global climate change within communication studies. The choice of terminology, language, and framing significantly impacts the message's effectiveness and the resulting behavioral changes regarding climate issues. Consequently, policymakers, researchers, and communicators should investigate various communication models that bridge expert knowledge with public understanding to enhance the impact of their climate change messaging.

The actionable guidelines promoted environmentally friendly production practices by emphasizing concepts such as sustainability, fairness, mitigation, recycling, and holistic health for soil, society, and animals. These guidelines were analyzed through the lens of extended parallel process and construal level theory, focusing on how they communicated cleaner production, agroecological principles, and climate-smart agriculture.

Unlike typical climate change communications that often emphasize future threats and theoretical concepts, these guidelines stood out by highlighting efficacy, immediate intentions, and practical activities. This approach suggests that to effectively encourage the adoption of climate-smart practices, guidelines and policies should focus on outlining concrete, present-day actions in a feasible manner. Similarly, climate change risk communication efforts should aim to convey information that prompts behavioral shifts towards cleaner production processes, rather than solely focusing on distant threats.

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Concerning the transition towards more sustainable viticulture, it not only has environmental implications but also significant economic and social ones.

The adoption of sustainable practices can offer the following long-term economic advantages:

- **Cost reduction:** Optimization in the use of inputs and resources can lead to a reduction in production costs.
- **Added value:** Sustainably produced wines can command higher prices in the market, especially among environmentally conscious consumers.
- **Economic resilience:** Sustainable practices can increase the resistance of vineyards to extreme weather events, reducing economic losses.

Despite its potential benefits, the transition to sustainable viticulture faces several economic challenges. The implementation of sustainable practices often requires significant initial investments. The adoption of new technologies and practices can involve substantial short-term costs. Additionally, there is uncertainty in the return on investment: the economic benefits of sustainable practices may not be immediately evident, which may deter some producers.

Changes in climatic conditions are therefore affecting wine production and quality, which has significant economic implications for producers and wine-growing regions. Variations in the quality and quantity of production can influence wine prices and the competitiveness of different regions in the global market. Farmers are increasingly making structural adjustments and cost management changes (Henri et al., 2016), along with finding new paths of enterprise development to cope with the challenges of market, climate, and policy pressures (Barlas et al., 2001). Ashenfelter and Storchmann (2016) estimated that a 1°C increase in average temperature during the growing season could notably increase the value of vineyards in the Mosel region of Germany.

A comprehensive analysis, incorporating both qualitative and quantitative approaches, must be conducted to explore various critical aspects of the wine industry's sustainability efforts (as reviewed by Alessandri et al., 2024). This examination delved into several key areas, including the expenses associated with carbon emissions, strategic placement of wine bottling facilities, the adoption of certification programs (Stranieri et al., 2021), and the impact of consumer behavior and preferences on driving the transition towards a more sustainable supply chain. The primary goal of this multifaceted analysis was to identify and evaluate potential sustainable compromises within the industry, providing valuable insights for future decision-making and strategy development.

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Concerning social aspects, adopting agroecological approaches has far-reaching positive impacts beyond just environmental benefits. These practices contribute significantly to improving the overall quality of life in rural communities, providing stable and fulfilling employment opportunities, and promoting fairness across gender and social divides (Barrios et al., 2020).

Among the factors in which sustainable viticulture can help wine-growing communities, the assistance in maintaining local wine-making traditions and the associated cultural landscape could be highlighted. Similarly, issues of employment and rural depopulation arise, to which sustainable viticulture could contribute in some way to the maintenance and creation of jobs in rural areas. The reduction in the use of pesticides and other chemical products can also improve the health and safety of vineyard workers and surrounding communities.

Potential barriers due to lack of knowledge and technical skills can be an obstacle to the adoption of sustainable practices. On one hand, some sustainable practices require a high level of technical knowledge and experience. On the other hand, the effectiveness of sustainable practices can vary according to local conditions, and the lack of region-specific research can be a hindrance.

The attitudes and perceptions of producers and consumers can also influence the adoption of sustainable practices, acting as cultural barriers. Among these, I would highlight resistance to change: some producers may be reluctant to abandon traditional practices in favor of more sustainable approaches. Likewise, a lack of understanding or appreciation by consumers for sustainably produced wines could limit their demand.

The agricultural and food industries have shown a recent and notable shift towards prioritizing sustainability, a change that has reshaped both consumer behavior and corporate approaches (Cecchini et al., 2018). This movement stems from an enhanced understanding of how farming and food production practices affect our planet, communities, and economies.

Today's discerning consumers, armed with greater knowledge and environmental consciousness, are no longer satisfied with products that merely taste good or look appealing. Instead, they actively seek out food items that are produced using eco-friendly methods and socially responsible practices (Modica et al., 2023). This evolving consumer mindset has prompted businesses to reevaluate their operations and adapt to meet these new expectations.

Recent studies in economics and marketing reveal a growing inclination among consumers to choose products that are environmentally responsible, with sustainable wine showing an expanding niche in the market (Fiore et al., 2017). This trend reflects a broader shift in consumer behavior towards more eco-conscious purchasing decisions.

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The sustainable wine sector has become a focal point for researchers examining consumer preferences. A review of interest by Modica et al. (2025) synthesizes numerous studies on this topic, underscoring the rising demand for sustainable wine options.

In today's market, wine enthusiasts are becoming more knowledgeable about the ecological footprint and social implications of wine production. However, this willingness to pay a higher price is not unconditional. Consumers expect a tangible return on their investment, whether it's in the form of superior taste, enhanced quality, or the satisfaction of knowing their purchase contributes to environmental conservation. This increased interest is not uniform across all demographics but is influenced by a combination of factors.

For instance, factors such as the quality and prestige of the wine rather than its sustainability seem to have more impact on men (Bonn et al., 2020). On the contrary, and according to Wolf and Higgins (2017), women are more likely to choose sustainable wines and would pay a premium for them. Concerning the age, younger consumers would prefer sustainable wines supporting sustainable practices and choosing eco-friendly products (Kelley et al., 2022).

Evidently, financial factors also influence purchasing decisions in the sustainable wine market. Those with higher levels of disposable income are more likely to invest in top-tier sustainable wines, often viewing them as premium products worth the extra cost (Mauracher et al., 2019). In contrast, consumers in the middle-income bracket approach their wine purchases with a more nuanced perspective. These buyers often seek a compromise between affordability and sustainability (Polzin et al., 2023). Additionally, education plays a significant role in attitudes towards sustainable wine. Consumers with advanced academic backgrounds tend to exhibit a deeper understanding of environmental concerns and are more inclined to opt for eco-friendly wine choices (Stanco et al., 2020). Moreover, people in peripheral areas give priority to the quality of wine, over sustainability aspects (Palumbo et al., 2020), whereas urban residents show a stronger interest in these latter.

A comprehensive review by Oladele and Ngidi (2025) synthesizes research indicating that individuals' awareness of climate change-related risks and their perceived ability to address these risks play crucial roles in motivating adaptive and mitigative actions. Furthermore, the review highlights that the specific content, language, and conceptual frameworks used in climate communication can significantly influence the adoption of more environmentally friendly production methods. This suggests that carefully crafted messaging and thematic elements in climate change discourse have the potential to drive tangible shifts towards cleaner industrial practices, as supported by the work of Hennink et al. (2011).

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Consequently, raising public awareness and educating consumers are crucial in this context. Research by D'Alessandro and Pecotich (2013) has shown that well-designed information campaigns can substantially boost consumers' willingness to pay for eco-friendly wines. These initiatives utilize various channels such as social media platforms, educational gatherings, and partnerships with influential figures to spread knowledge. Annunziata et al. (2016) underscored the significance of consumer education, revealing that knowledgeable consumers are more inclined to pay a premium for sustainable wines, especially when they comprehend the multifaceted advantages of sustainable grape cultivation, including its positive impacts on the environment, society, and economy.

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4. Society's confidence in vitivinicultural companies

Sustainability is increasingly viewed as an evolving concept. Organizations are expected to demonstrate responsibility and be held accountable for their actions concerning environmental, social, and economic matters (Hayati, 2017). Despite the challenges and the initial skepticism, the global wine industry is now acknowledging the advantages of embracing a more sustainable approach (Golicic, 2022). Wine producers must not only consider their impact on society and local communities, but it's also been demonstrated that companies with higher rates of implementing social sustainability practices tend to experience improved quality and enhanced market perception (Pullman et al., 2010).

Therefore, it seems that the necessity of promoting more sustainable production methods is now widely accepted (Keichinger and Thiollet-Scholtus, 2017). It is evident that climate change significantly shapes company strategies, influencing both product quality and the availability of essential natural resources like water. The close relationship between the environment and wine production compels vitivinicultural industry managers to adopt adaptive strategies as the only viable means of thriving in a constantly changing environment.

Firms should assess how much value consumers place on sustainable strategic choices to determine if these decisions are worthwhile. It is also important to recognize that climate change has not only increased consumer awareness of sustainability issues but has also affected consumption patterns related to traditional and historical characteristics (Miroslava et al., 2021). Consequently, a significant number of studies on wine sustainability have investigated how firms respond to societal changes by observing consumer purchasing behaviors.

Kelley et al. (2017) conducted an experiment to identify consumer preferences when buying green wine. The primary influence stemmed from basic retail attributes, followed by bunch root control and weed management practices. But these authors found that interest in wines produced using sustainable techniques, such as avoiding pesticides and using cover crops, remains relatively low, highlighting the need for greater consumer education. Examining which sustainability aspects are prioritized by consumers when purchasing wine, through surveys or experimental studies, is a practical approach for producers to identify key variables. This understanding should be linked to company practices, especially since firms often adopt sustainable practices due to conformity rather than addressing the specific needs of their direct stakeholders (Alessandri et al., 2024).

An interesting study combines consumer sensory preferences with environmentally friendly canopy management to examine how the purchasing process changes when different variables are introduced (Schmit et al., 2013). Studying the Chinese consumer market, Chi et al. (2021) highlighted that the factors

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motivating green wine purchases include social trust, health consciousness, and positive emotions, but the strength of their influence varies depending on familiarity with the product.

Newman et al. (2014) discovered that consumers are less likely to purchase a green product if they believe a company intentionally improved it for environmental reasons, compared to when the environmental benefit is an unintentional consequence. Magnusson et al. (2001) found that quality and other personal advantages were the most important purchasing criteria for organic products, outweighing environmental considerations. However, recent research suggests that organic wine production practices present an opportunity for grape growers and winemakers to leverage local biodiversity and create high-quality wines that reflect their unique terroir, distinguishing them from conventional wines (Provost and Pedneault, 2016).

Flores and Medeiros (2019) developed a notable framework called *Baccus*, structured as a matrix. This framework connects the five dimensions of sustainable development (Social, Economic, Environmental, Political/Institutional, and Territorial) with 18 thematic guidelines, organized into four key dimensions (Management, Articulation and Cooperation, Innovation, Learning, and Sustainability). Likewise, Moggi et al. (2021) created a framework where sustainability is not the primary element, but rather the pathway to addressing systemic threats at the ecosystem level. Business models that prioritize regenerative resource use, instead of recycling or extraction, are the only ones that truly foster long-term success and fulfillment, ultimately enhancing prosperity. This process can be streamlined by a central organization, such as a local wine consortium, provided it is seen as a credible and authoritative source of knowledge.

According to some authors, choosing a sustainable strategy from both social and environmental perspectives has become the only viable response to consumer demands, as consumers have gained considerable knowledge on this subject (Duarte Alonso, 2010).

Research indicates that the benefits for wine businesses maintaining sustainable practices outweigh their costs (Becker et al., 2020). Considering some socio-economic factors, such as rising energy costs, water scarcity, market demands, increasing concerns about exposure to chemicals, and new environmental policies, the wine industry's vulnerable position becomes clear (reviewed by Trigo et al., 2023).

Several significant studies have been conducted in European countries like Italy, Germany, and France to explore the role of environmentally friendly certifications (Stranieri et al., 2021) and ecolabelling (Delmas and Gergaud, 2021), examining the perceptions of both internal and external stakeholders. Some

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innovative analyses have also sought to establish a link between the implementation of environmentally certified management standards and the understanding and application of sustainability within wineries (Lahneman, 2015).

Furthermore, research has explored how information flows in tele-coupling systems to promote wine certifications (Marola et al., 2020). Consumers tend to purchase wine only when they perceive a personal benefit. The concept of creating a link between current and future generations within wineries can be a strong motivator for adopting sustainable certifications (Delmas and Gergaud, 2014).

Analyzing consumer perception is strategically valuable because company decisions can be misinterpreted, leading to adjustments in marketing strategies. Companies should concentrate on consumer understanding of ecolabels, selecting those that emphasize both the environmental and personal benefits of the product.

The wine industry exhibits significant uncertainty regarding the value of ecolabels among scientists, winemakers, and consumers. Furthermore, the wine industry is particularly well-suited for studying the relationship between eco-certification and quality. Unlike many agricultural products, wine is highly differentiated, with readily available quality ratings from experts (Storchmann, 2018).

Sustainable wine practices can be framed as a novel wine "category," representing a contemporary approach using traditional methods. Some argue this is a "failed category" due to slow adoption (Jones and Grandjean, 2018). However, wine experts don't seem to impede the establishment of sustainable wine practices. More recently, the emergence of specialized wine publications focusing on organic and biodynamic wines can be observed.

Ecolabels currently don't offer consumers information about wine quality. Experts familiar with the practices can evaluate quality independently of labels. This raises questions about the actual effectiveness of ecolabels in the wine market. Storytelling, or detailing the practices of each winemaker, might be more effective at communicating wine quality than relying solely on an ecolabel (Delmas and Gergaud, 2021).

But the entire system could be compromised by labels that fail to live up to their claims. Policymakers need to be aware of the potential for "greenwashing" when using eco-labels (Delmas and Gergaud, 2021).Finally, it can be highlighted that several research efforts have explored various potential scenarios for delivering wine to consumers through the most eco-friendly routes possible (Cholette and Venkat, 2009). These studies aimed to identify optimal distribution strategies that would minimize the carbon footprint associated with wine transportation, considering factors such as distance, mode of transport, and packaging methods to determine the most sustainable supply chain configurations

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5. Climate change and its effects on viticulture

Climate change is having a significant impact on global viticulture, altering growing conditions in many traditional wine-growing regions and creating new opportunities in areas previously considered unsuitable for grape cultivation. The main effects of global warming are significantly altering grape cultivation conditions worldwide. They pose significant challenges for the wine industry, but also offer opportunities for innovation and adaptation

European temperatures rose over twice the global average, as per the World Meteorological Organization (WMO, 2022). The WMO's report noted that 2016–2020 marked Europe's hottest five-year span, averaging 1.6 °C above pre-industrial levels (reviewed by Reta et al., 2025).

According to Straffelini et al. (2024), European vineyards experienced an average increase of 9% increase in land surface temperature, a decrease of 47% in precipitation and 30% in soil moisture in comparison with their respective historical averages for the same month.

An increase in temperature over the last three decades has been suffered by several regions in the Mediterranean area. This fact has altered grape metabolism, significantly affecting the vine phenotype and consequently the berry and wine composition (Reta et al., 2025), as well as the date of grape ripening. In fact, in several countries grape harvest was notably anticipated. Certain emergency practices could compromise the quality of wines. For example, pruning to reduce water use during heat waves can delay ripening of red varieties, altering pH levels in these wines (Riedo, 2019).

Aspects linked to climate change imply a significant challenge to the fundamental characteristics of a site (Rogiers et al., 2022). Winegrowers must apply challenging emergency measures to fight drought and heat, even in regions with tolerant grapevine varieties (such as Grenache in southern France (Straffelini et al., 2024) or Monastrell in southeast Spain (Apolinar-Valiente et al., 2017). Increasing temperatures can damage the plants, alter physiological processes, and affect the resilience of vineyards (Costa et al., 2019).

This overview has led to uncertainties and doubts concerning the management of wine systems. The use of irrigation enhanced in several areas, but this practice could not be sustainable during severe droughts. For instance, extraordinary irrigation measures were approved for some Bordeaux areas, giving recently high water-use vintages (Mercer, 2022).

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The main effects of climate change on viticulture include:

- Alterations in vine phenology
- Changes in grape composition
- Displacement in cultivation zones
- Increased frequency of extreme weather events
- Impact on pests of vineyards

5.1. Alterations in vine phenology

Phenology appears as the key biological indicator of climate change (Menzel et al., 2006). The advancement of phenological stages can lead to a desynchronization with the optimal climatic conditions for each phase of development. For example, early budding can expose young shoots to a higher risk of late frosts. Due to climate change, grapevine phenology and, therefore, harvest dates have advanced worldwide in response to enhancing temperatures (Petrie and Sadras, 2008; Webb et al., 2012).

Both surface temperature and solar irradiation and surface temperature are necessary for grapevine metabolism. They have been shown to affect berry size and composition (Brandt et al., 2019). For instance, solar irradiation can contribute to growth and development through photosynthesis. It can regulate the timing of bud break, flowering, and fruit set, all critical stages in the grapevine life cycle.

Phenologic response depends on the changes in climate conditions and grape variety, as demonstrated by Cameron et al. (2020) studying 23 different grape varieties between 1999 and 2018: some varieties might show some delay, whereas others showed advancements of maturity. Hall et al. (2016) observed that, in a warming climate, the post-harvest phase is lengthening and becoming warmer, evidenced through studies in wine regions worldwide that have correlated recent air temperature increases with changing grapevine phenology. Budbreak, flowering, veraison, and harvest take place earlier than in previous decades. Warming and water deficit cause acceleration of berry shriveling and also the death of mesocarp cell (Bonada et al.,2013). Moreover, leaf-fall occurs later. With earlier ripening, higher sugar concentrations have been reported at harvest and compressed harvests, as well as at early harvests to maintain target sugar concentrations (van Leeuwen and Darriet, 2016).

Variations in synchrony between several metabolites and fruit development occur because of advances in phenology and sugar accumulation (Sadras and Moran, 2012). This can induce an imbalance in berry composition (van Leeuwen et al., 2019), notably changing wine style.

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Researchers such as Parker et al. (2020) are working on developing phenology models that incorporate multiple climatic variables to improve the prediction of grapevine developmental stages under changing conditions.

5.2. Changes in grape and wine composition

Temperature significantly influences wine grape composition, affecting different compounds. Higher temperatures can lead to changes in the grape sugar content. Grapes can suffer considerable damage during heatwaves, thus impacting on their overall quality (Martínez-Lüscher et al., 2020).

Berry sugar dynamics is related with two different processes: sugar accumulation (mg/berry) and sugar concentration. Water loss can imply a concentration effect, enhancing sugar content relative to berry mass (Deloire et al., 2021). Investment in phloem and increasing sucrose accumulation is induced by higher temperature (Wolberg et al., 2024).

The implications of this increase in sugars can be several:

- **Higher alcohol content in wines:** Wines with higher alcohol levels may be perceived as unbalanced and less fresh. Mira de Orduña (2010) highlighted the rise alcohol content as one of the main challenges for the vitivinicultural industry.
- **Fermentation challenges:** Musts with high sugar content can cause problematic or incomplete fermentation.
- **Legal and market aspects:** Some wines may exceed the legal alcohol content limits established for certain appellations of origin.

Lower titratable acidity is also directly linked to higher temperatures (Brandt et al., 2019). The consequences of this decrease in acidity include:

- Wines that are less fresh and have lower aging potential.
- Increased risk of microbiological instability in wines.
- Need for oenological adjustments, such as the addition of tartaric acid, to compensate for the lack of natural acidity.

Higher temperatures can also produce the buildup of color to reduce (Caravia et al., 2016), and the aroma profile to be altered (Ŝuklje et al., 2016).

Berries can also suffer from sunburn, which would affect the taste of the berry. The enhancing temperature of berry surface could favor the oxidation of aroma precursors. The high temperature could also induce other significant metabolic changes in exposed grapes. Sunburned berries lose flavor when the berry

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temperature reaches 40–46 °C for over five hours (Park et al., 2023). The severity of this phenomena depends on how long the berry is exposed to heat and how quickly it can be cooled down (Deloire et al., 2021). The rise in the frequency and severity of heat waves due to climate change (IPCC, 2021) could strengthen this situation.

Solar irradiation can also be a critical factor in berry development. An excess of solar irradiation occurs when the intensity and duration of sunlight exposure exceed the threshold for optimal berry development (Martínez-Lu et al., 2017). The high temperatures related with extreme solar irradiation can lead to sunburn, causing a loss of berry flavor, composition, and quality (Ŝuklje et al., 2016).

Phenolic compounds, responsible for the color, structure, and part of the aromatic profile of wines, are also affected by climate change. Polyphenols in grapes are also sensitive to temperatures. High temperatures can induce anthocyanin degradation (Chassy et al., 2015) and inhibit their accumulation (Ceballos-Casals and Cisneros Zeballos, 2004). Moreover, climate changes significantly impact the phenylpropanoid pathway, which is responsible for the biosynthesis of polyphenols. These changes can disrupt the synthesis and accumulation of these metabolites and also influence the induction of enzymes and genes related to their production (Marchica et al., 2020).

These changes in phenolic compounds can result in:

- Red wines with less color and structure.
- Alterations in the aromatic profile of wines.
- Changes in the perception of wine astringency and body

Moreover, the impact of water deficit on berry composition (Intrigliolo et al., 2012) and wine phenolic substances (Casassa et al., 2013) has been also shown.

The aromatic profile of grapes and, therefore, of wines, is also affected by climate change. Pons et al. (2017) published a very interesting work about this subject. Drappier et al. (2019) shown that thermal stress during grape ripening can reduce the concentration of aromatic precursors, particularly affecting varietal aromas.

These changes in aromatic precursors can lead to:

- Wines with altered aromatic profiles, potentially with less complexity.
- Loss of typical aromatic characteristics of certain varieties or regions.

Summarizing, an increase in fruit injuries related to temperature, radiation and water deficit might be on the horizon (Gambetta et al., 2021), causing financial losses (Mira de Orduña, 2010). For all that, climate adaptation measures are critical for mitigating the negative impacts of high temperatures and extreme solar irradiation on grape and wine quality.

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5.3. Displacement of cultivation zones

As temperatures rise, regions traditionally suitable for grape cultivation are changing. It is predicted that some currently productive areas may become too warm for certain varieties, while other areas, previously considered too cold, could become suitable for grape cultivation.

The displacement of vineyard cultivation zones is a significant consequence of climate change that is transforming the global wine landscape. This phenomenon is characterized by the movement of areas suitable for grape cultivation towards higher latitudes and greater altitudes, in search of more favorable climatic conditions.

According to Hannah et al. (2013), area suitable for viticulture decreases 19% to 62% in the most optimistic model and 25% to 73% in the less optimistic model in major wine producing regions by 2050. Even more than 20 years ago, Kenny and Harrison (1992) estimated that the upper limit of European vineyard would have moved to the north at 10–30 km per decade because of global warming, and that this speed would have doubled between 2020 and 2050. Moreover, Fraga et al. (2016) note an extension of the climatic suitability for grapevines up to 55ºN in Nord Hemisphere, which may represent the obvious emergence of new winemaking areas.

Concerning altitude above sea level, it has been reported that mountain terroirs above 1000 m. a.s.l. could be suitable for viticulture by the end of this century (Caffarra & Eccel, 2011). Recent research has highlighted the significant benefits of high-altitude grape cultivation. These findings could revolutionize traditional winemaking methods for commercial use and offer a new approach to verifying wine authenticity (Kalogiouri et al., 2024).

Mountainous wine-growing regions boast distinctive environmental characteristics. The cooler temperatures in these areas decelerate grape maturation, extending the growing season. This prolonged process allows grapes to maintain high acidity levels, resulting in harvests with optimal titratable acidity and pH. Consequently, winemakers may not need to artificially adjust acidity. The cooler climate of high-altitude regions often leads to later harvests, allowing grapes to develop more complex flavor profiles. Furthermore, the thinner atmosphere at higher elevations results in increased UV exposure. This intensified sunlight stimulates greater production of phenolic compounds in grape skins (Darnal et al., 2024).

It is important to note that this displacement not only affects wine production but also has significant implications for biodiversity and local ecosystems. The expansion of vineyards into new areas could conflict with other land uses and natural ecosystems.

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We must also consider the cultural and the socio-economic aspects that this displacement would entail, relating it to risky issues such as rural depopulation, lack of generational replacement, and the abandonment of agriculture. Cultural landscapes could be therefore also targeted. In spite of their historical adaptation, extreme events can put them at risk, because of higher susceptibility to climate change compared to modern vineyards, as noted by Straffelini et al. (2024). These authors indicate that the combination of extreme agricultural drought and high land surface temperature involved 18% of European vineyards and 10 cultural landscapes. The sustainability of European vineyards and related cultural landscapes is increasingly at risk due to climate change (Tarolli et al., 2023).

Ashenfelter and Storchmann (2016) concluded that climate change is likely to produce winners and losers, with the winners being those closer to the North and South Poles. Moriondo et al. (2013) concluded a dramatic change in the landscape for winegrape production in Europe due to changes in climate. For example, these authors noted that the wine elaboration is becoming of economic interest even in the south of England, whereas wine regions with climatic conditions from the Mediterranean basin today were shown to potentially shift the most over time.

In conclusion, the displacement of vineyard cultivation zones is a complex phenomenon that is redefining the global wine map. While some traditional regions face growing challenges, new opportunities are emerging in areas previously considered marginal for viticulture. Adapting to these changes will require a combination of innovation in viticultural practices, ongoing research, and careful planning to balance production needs with ecosystem conservation and socio-economic aspects.

5.4. Increasing frequency of extreme weather events

Climate change is associated with an increase in the frequency and intensity of extreme weather events, such as heat waves, droughts, late frosts, and intense storms. These phenomena can cause significant damage to vineyards and affect wine production and quality. For instance, Martínez-Lüscher et al. (2020) reported that grapes can suffer considerable damage during heatwaves, thus impacting on their overall quality.

Heavy rains damages may also include soil erosion and flooding (Ramos and Martínez-Casasnovas, 2010). In this regard, steep-slope agricultural areas are especially challenged by climate change (Wang et al., 2022). Ensuring the long-term viability of European wine production necessitates investigating and enhancing vineyard management techniques. This includes minimizing water waste, boosting irrigation system effectiveness and implementing water collection methods. The scientific community bears a significant responsibility in guiding this evolution.

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Moreover, and to maintain Europe's winemaking tradition in the face of changing conditions, it's essential to innovate in water conservation and management. Scientists must lead the way in developing and refining these strategies, providing evidence-based solutions to help vintners adapt to new challenges. Their findings will be instrumental in crafting practical, effective methods for sustainable viticulture in a changing climate. Therefore, viticulture appears as a field which strongly depends on stable climate conditions.

Seasonal predictions have gained attention as a possible mitigation tool to these extreme weather events (Porras et al., 2021). But despite of the recent researches in seasonal climate predictions linked to grape production (Santos et al., 2020, Droulia and Charalampopoulos, 2021), the integration of these practices into existing decision-making processes remains limited.

Several initiatives funded by the European Union have focused on enhancing the adoption of climate predictions in viticulture through the development of specialized climate services. These projects include MED-GOLD (Turning climate-related information into added value for traditional Mediterranean Grape, Olive and Durum wheat food systems), VISCA (Vineyards Integrated Smart Climate Application) or VitiGEOSS (Vineyard Innovative Tool based on the Integration of Earth Observation Services and in-field Sensors). This initiative developed innovative tools integrating satellite data and ground-based sensors for vineyard management. These projects have worked to create tailored climate services that enable viticulturists to make informed decisions and implement effective strategies for adapting to changing climate conditions (reviewed by Vigo et al., 2023).

5.5. Climate change and moth pests of vineyards

Climate change poses significant threats, including the spread of non-native species into new environments. These invasions often occur through accidental introductions, with species adapting and proliferating due to weakened ecosystem resilience caused by climate change (Ioratti et al., 2023).

Rising average temperatures are the primary climate change factor directly affecting plant-eating insects. However, researchers are increasingly studying how changes in relative humidity, CO2 levels, high temperatures and UVB radiation impact various invasive species (Chu et al., 2012; Fisher et al., 2021; Zeni et al., 2022). The risk of diseases and pests can also be improved by high temperatures (Bois et al., 2017).

Generally, warming trends cause most insect species to migrate northward (Roques et al., 2015). Climate change affects agricultural pests both directly, by

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influencing their physiology and behavior, and indirectly, through changes in host plant characteristics and farming practices adapted to new climate conditions (Iltis et al., 2021).

Climate shifts may have favored one moth species over another, with increased aridity disadvantaging the more moisture-loving *E. ambiguella* and allowing *L. botrana* to dominate. This suggests that warmer, drier conditions created an ideal environment for *L. botrana* to thrive and outcompete other species, even in northern vineyards.

As temperatures continue to rise and new invasive species arrive, the composition of grapevine pests is likely to change further. Currently dominant species may be gradually replaced, varying by latitude and altitude across Italian wine regions. Higher average temperatures are already accelerating the life cycles of existing grapevine moths, potentially increasing their annual generations (Reineke and Thiery, 2016).

Phenological models have simulated the complex interactions between pests, pathogens, and plants under climate change. While northern European vineyards may face increased risk near harvest time, southern regions might see reduced pest damage due to various factors, including misalignment between pest and plant life cycles and increased pest mortality (Iltis et al., 2020; Reis et al., 2022; Castex et al., 2023).

The impact of new climate scenarios on pest relevance is still debated. However, previously minor pests are increasingly becoming significant threats. This applies to both resident species and new invasive species that target grapes (Nieri et al., 2022). Climate change may also affect natural enemies of grapevine pests, impacting biological control strategies (Reineke and Thiery, 2016). While some beneficial organisms might thrive in warmer conditions, extreme weather events could harm their populations.

Continued research into the biology and ecology of these species, their complex relationships with host plants and antagonists, and the development of sustainable pest management strategies for warmer Mediterranean agricultural settings remains crucial (Lucchi and Benelli, 2018). Sustainable farming practices are increasingly adopting alternative methods to traditional agrochemicals. One such approach gaining widespread recognition in viticulture is the use of elicitors. These substances are proving to be effective tools in managing vineyard diseases. Elicitors serve as a more environmentally friendly option compared to conventional chemical treatments. Their application in grape cultivation extends beyond mere disease control; they also significantly influence the quality attributes of the grape (Apolinar-Valiente et al. 2018; Salifu et al., 2022).

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Aspect such as previously mentioned displacement of cultivation zones can also impact on the risk of diseases. For instance, vineyards situated in mountainous regions often benefit from improved air circulation. This natural ventilation helps mitigate the risk of common grape diseases like mildew and rot. As a result, these elevated vineyards can more easily adopt organic and sustainable farming methods, leading to the production of healthier grapes. The unique environmental conditions found in high-altitude vineyards offer several advantages, such as reduced need for chemical interventions: or enhanced grape balance. This approach aligns well with the growing consumer demand for more natural and environmentally friendly wine production methods (Darnal et al., 2024).

Finally, and as Ashenfelter and Storchmann (2016) optimistically concluded, "*wine making has survived through thousands of years of recorded history, a history that includes large climate changes*".

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6. Conclusion

The question of sustainability in the viticulture sector has ceased to be a utopian and unattainable point on the horizon to become a well-defined reality. However, this reality is not only still cementing its foundations, but it must also be self-aware that its construction must always be dynamic and flexible, in accordance with local and global circumstances.

Sustainable viticulture must focus on environmental, social, economic, and cultural aspects. However, it would be a mistake to overlook that the paths interconnecting these aspects internally and externally are paved with tiles of communication.

All of this involves working with an eye on the great challenge of not only facing the effects of climate change but also many others (rural depopulation, investment costs in applied technologies, research and development). The objective is to blur possible doubts, uncertainties, mistrust, and problems to give solidity and extend sustainability in viticulture worldwide and to all corners. To achieve this, the participation of both private companies and public organizations must occur.

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