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ELICITORS IN VITICULTURE AND THEIR EFFECT IN WINEMAKING: A SUSTAINABLE APPROACH TO CLIMATE RESILIENCE

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Abstract

Climate change exerts an increasingly pronounced impact on the viticultural sector, requiring sustainable solutions for adaptation and maintaining production quality. The use of elicitors, natural or synthetic compounds that stimulate the grapevine`s defense mechanisms, represents an innovative approach to reducing pesticide dependency and optimizing the biochemical and organoleptic properties of grapes and wines. Elicitors such as chitosan and salicylic acid significantly enhance the grapevine`s resistance to pathogens, including to Plasmopara viticola and Botrytis cinerea, while promoting the accumulation of secondary metabolites with enological value, such as polyphenols. Their use in vine growin can influence fermentation during winemaking or can lead to more stable wines or with enhanced aromatic profile. This review synthesizes recent advancements in the use of elicitors, highlighting their mechanisms of action, practical applications, and impact on wine quality, while exploring opportunities for their integration into climate-smart agricultural systems to enhance the resilience and sustainability of viticulture and winemaking.

Key words: *chitosan, climate-smart viticulture, polyphenols, sustainability, grape oenology.*

INTRODUCTION

Modern viticulture faces significant challenges, primarily driven by climate change, which affects both crop productivity and final product quality. These challenges are amplified by abiotic and biotic stress, as well as the strict requirements for reducing chemical use in agriculture (Delaunois et al., 2014). In this context, adopting sustainable practices becomes imperative for ensuring the long-term viability of the viticulture sector. The use of elicitors, compounds that stimulate the vine's defence mechanisms, offers an innovative and effective solution (Pieterse et al., 2012). These elicitors, whether natural or synthetic, enhance plant resistance against pathogens and stress without negatively impacting the environment.
Elicitors like chitosan and salicylic acid have been extensively studied for their ability to induce physiological and biochemical responses in grapevines (Aziz et al., 2006; Iriti & Faoro, 2009). These responses mimic stress effects, but without compromising plant health. For example, chitosan has shown significant efficiency in enhancing grapevine resistance to infections caused by pathogens such as *Plasmopara viticola* and *Botrytis cinerea*, which can lead to substantial crop losses (Romanazzi & Mlikota Gabler, 2021; Verhagen et al., 2010). Moreover, the application of these elicitors stimulates the biosynthesis of valuable secondary metabolites, including polyphenols, essential for the organoleptic and nutritional quality of grapes and wine (Chitarrini et al., 2017; Garde-Cerdán & Pérez-Álvarez, 2022). Integrating elicitors into viticultural practices not only reduces pesticide dependency but also positively influences winemaking processes. Elicitor treatments can improve must fermentation, wine stability, and aromatic profile - critical aspects for consumer satisfaction and the commercial success of the final product (Gómez-Plaza & Martínez-Cutillas, 2022). This approach contributes to developing climate-smart viticultural systems capable of effectively addressing climate challenges while maintaining market-quality standards (Buonassisi et al., 2023). The objective of this paper is to synthesize recent advances in the use of elicitors in viticulture and winemaking, analysing their

mechanisms of action, practical applicability, and impact on wine quality. Furthermore, the paper explores opportunities for integrating these compounds into sustainable agricultural systems, thereby contributing to the long-term resilience and viability of the viticulture sector. This approach becomes increasingly relevant given the complexity of current challenges and the necessity of adopting innovative solutions for sustainable viticulture.

ELICITORS: CLASSIFICATION, MECHANISMS OF ACTION, AND IMPACT ON PLANTS

Elicitors are substances or stimuli that induce physiological and biochemical responses in plants, which are fundamental in enhancing plant resilience to biotic and abiotic stressors. These plant responses can be classified into two main categories: biotic and abiotic elicitors. According to Bhatt & Mathpal (2022), biotic elicitors originate from living organisms and include compounds such as chitosan, which is derived from crustacean shells, polysaccharides, microorganisms, microbial proteins and extracts, while abiotic elicitors include molecules with hormonal effect (salicylic acid methyl jasmonate), chemical agents (heavy metals, mineral salts, gaseous toxins) and physical agents (UV radiation, osmotic stress, salinity, drought). Understanding the classification and functionality of these elicitors is crucial for leveraging them in agricultural practices to improve plant health and productivity (Kantayos et al., 2021).

Biotic elicitors, particularly chitosan, have attracted considerable attention for their role in stimulating the production of secondary metabolites, which are critical for plant defence (Kahromi & Khara, 2021). These metabolites include phenolic compounds and alkaloids, which play vital roles in protecting plants against pathogens and pests. Studies have shown that chitosan application can lead to the upregulation of various defence-related genes, ultimately enhancing the plant's intrinsic resistance mechanisms. When plants are exposed to chitin-derived compounds like chitosan, they activate specific signalling pathways that enhance their defence responses. Moreover, the interaction of biotic elicitors with environmental factors, such as nutrient availability and microbial symbiosis, appears to significantly influence the biosynthetic pathways that lead to secondary metabolite accumulation (Özkurt & Bektaş, 2022).

Abiotic elicitors also have profound effects on plant physiology, particularly under stress conditions. Salicylic acid is one of the most well-studied abiotic elicitors, known for its pivotal role in mediating plant defence mechanisms (Suksawat & Panichayupakaranant, 2024). It functions by activating defence pathways and promoting the accumulation of not just protein-based defences, but also secondary metabolite production, vital for stress tolerance. This compound has been documented to enhance tolerance to abiotic stresses such as drought, salinity, and extreme temperatures by regulating osmotic balance and improving nutrient uptake (Abdi et al., 2022). The mechanism by which salicylic acid functions includes the modulation of ion channels, which could be crucial for generating a physiological response that leads to increased stress tolerance (Nofal & Attia, 2023).

The interactions between biotic and abiotic elicitors further complicate our understanding of plant-environment interactions. For instance, exogenous application of salicylic acid specifically has been found to synergistically interact with other signalling molecules and elicitors to trigger more robust defence responses in plants (Deshmukh et al., 2023). A study highlighted that the co-application of salicylic acid with chitosan not only improved disease resistance, but also augmented the levels of bioactive compounds in treated plants, showing the necessity of a multi-faceted approach to elicitor application (Vishala et al., 2023). Additionally, distinct concentrations and application timings of these elicitors have been shown to modulate the efficacy of the stress response, illustrating the importance of precision in biotechnological applications (Miclea et al., 2020).

Recent advancements in elicitor research have elucidated the specific biochemical pathways involved in plant responses to biotic and abiotic stressors. For instance, oxidative stress mitigation through the accumulation of antioxidants such as flavonoids and phenolics has been a significant focus area (Nazir et al., 2020). Chitosan and salicylic acid have both been recognized as potent initiators of these pathways, providing a dual benefit of stress tolerance and enhanced nutritional value for crops (Kantayos et al., 2021). Furthermore, salicylic acid's ability to influence the phenolic profile of fruits underscores the potential of elicitors in improving crop quality beyond mere stress resistance (Gačnik et al., 2021).

Another vital aspect of elicitors is their impact on the secondary metabolism of plants, which can influence flavour, colour, and the nutritional quality of produce (Alwakil et al., 2022). For example, the application of various biotic and abiotic elicitors has resulted in increased levels of bioactive compounds in plants like garlic and certain medicinal herbs, where both growth parameters and metabolic profiles were significantly enhanced (Andrade et al., 2020). This relationship emphasizes the commercial significance of elicitors, particularly in the production of nutraceuticals and functional foods.

Moreover, recent studies have indicated that the timing and frequency of elicitor application are crucial for maximizing their beneficial effects on plant resilience and secondary metabolite production. The integration of elicitation protocols with traditional agricultural techniques is gaining traction, as farmers assess the benefits of improved crop yields and quality (Ahmad et al., 2019). Understanding these interactions is crucial for the development of sustainable agricultural practices that rely on natural elicitors to boost plant defences and reduce reliance on chemical pesticides (Rusadi et al., 2023).

Emerging research also suggests that elicitors have the potential to enhance the efficacy of other agricultural inputs, like fertilizers and biocontrol agents, leading to synergistic effects that maximize growth and resistance (Gačnik et al., 2021).

APPLICATION OF ELICITORS IN VITICULTURE

The application of elicitors in viticulture has gained notable attention, primarily due to their effects on grapevine growth and their ability to confer resilience against abiotic stresses such as drought and extreme temperatures. Elicitors, such as salicylic acid and chitosan, have been studied for their role in enhancing grapevine physiological responses under adverse conditions, which has critical implications for maintaining grape quality and productivity in the face of environmental challenges. For instance, the use of salicylic acid in grapevines is associated with significant increases in antioxidant enzyme activity, which serves as a protective mechanism against oxidative stress that can arise during unfavourable environmental conditions (Alwakil et al., 2022; Abd-Elall, 2019). This increase in antioxidant capacity not only mitigates potential damage, but also supports overall plant health and growth during periods of stress (Oraei et al., 2019). Moreover, the enhancement in defence mechanisms elicited by these compounds translates not only to improved stress tolerance, but also promotes overall plant growth metrics, including increased biomass and root development. Such growth improvements are essential for ensuring that grapevines can effectively uptake water and nutrients, leading to healthier plants that produce better yields and higher quality grapes. Elicitors such as salicylic acid and chitosan have been shown to facilitate these physiological enhancements, including greater root biomass, which is crucial for absorption efficiency. Research indicates that the use of elicitors can potentiate the development of primary and secondary metabolites within the grapevine, thereby enhancing not just the plant's defensive capabilities, but also the qualitative aspects of the grapes produced (Martín et al., 2023). For example, salicylic acid has been found to promote the biosynthesis of anthocyanins, leading to grapes with more vibrant colours and potentially enhanced market value. Similarly, the increased levels of phenolic compounds due to elicitor treatment can contribute positively to the flavour profiles of wines made from these grapes, demonstrating the utility of elicitor application not only from a plant health perspective, but also from an economic standpoint (Oraei et al., 2019; García-Pastor et al., 2020).

Table 1. Elicitors and their mode of action in enhancing plant defence mechanisms

Elicitor type	Mode of action	Recommended dosage	References
Chitosan	Enhances disease resistance by triggering plant defense pathways and stimulating phenolic compound synthesis.	0.1-1% solution (foliar)	Salifu et al. (2022), Romanazzi et al. (2013)
Methyl Jasmonate (MeJA)	Induces synthesis of secondary metabolites (like phenolics) and boosts resistance to abiotic stress.	100-200 µM (foliar)	Garde-Cerdán et al. (2022); Martínez-Lapuente et al. (2023)
Salicylic acid	Modulates gene expression related to pathogen resistance, enhances systemic acquired resistance (SAR).	0.1-0.5% solution (foliar)	Adrian et al. (2017)

The interplay between elicitors and other environmental stressors is another area where significant findings have emerged. Elicitors such as salicylic acid enhance the grapevine's ability to cope with combined stress conditions, including heat and drought (Jalili et al., 2023; Zhao et al., 2023). Studies have elucidated how salicylic acid interacts with plant regulatory pathways, leading to enhanced expression of genes associated with stress tolerance and antioxidant defence mechanisms, allowing grapevines to manage oxidative challenges during intense sunlight and heat periods (Pálfi et al., 2021). The implications for vineyard management practices are thus profound, as strategic timing and application of elicitors could be pivotal in ensuring grapevine health and productivity in changing climates (Pálfi et al., 2021; Oraei et al., 2019).

The impact of elicitors extends beyond individual plant physiology; they can enhance the overall vineyard ecosystem resilience. For instance, the application of chitosan has been shown to reduce pathogen incidence while bolstering the plant's immune responses, which contributes to less reliance on chemical fungicides (Martín et al., 2023; Wang et al., 2023). This promotes a healthier vineyard environment and also aligns with increasing consumer demand for sustainably produced wines (García-Pastor et al., 2020; Zhang et al., 2019). By adopting these sustainable practices involving the use of elicitors, viticulturists can cultivate grapes that are resilient to stressors while also enhancing flavour profiles, opening avenues for premium wine production (Martín et al., 2023; García-Pastor et al., 2020). A summary of the main elicitors used in viticulture, their mode of action in enhancing plant defence mechanisms and recommended dosage is presented in Table 1.

The application of elicitors in viticulture significantly enhances grape quality, particularly regarding aroma, polyphenol content, and antioxidant levels. Research findings indicate that the use of elicitors such as methyl jasmonate (MeJA) elevates the concentrations of anthocyanins and other phenolic compounds in grapes, thereby improving both the organoleptic qualities of the wine produced and its nutritional profile. For instance, Paladines-Quezada et al. (2022) reported that MeJA application during the veraison stage led to a notable increase in anthocyanin levels in Monastrell grapes, significantly enhancing the sensory characteristics of the resulting wine .This study underscores the critical role of timing in elicitor application to maximize the phenolic profile of grapes (Paladines-Quezada et al., 2022 ; Qu et al., 2022).

Moreover, elicitors such as chitosan have been shown to promote higher production of polyphenols, which boast significant antioxidant properties. These polyphenols serve a dual role: they protect plants against biotic and abiotic stresses while also contributing to enhanced wine quality by improving flavor and health benefits. For example, studies have documented that chitosan-treated grapes exhibit increased polyphenol concentrations compared to untreated controls, highlighting the potential for using elicitors to elevate grape and wine quality (Miliordos et al., 2021; Nardello et al., 2021). In addition to their influences on phenolic accumulation, elicitors also play a crucial role in enhancing the aromatic profile of grapes. The biosynthesis of volatile compounds responsible for wine aroma can be stimulated through elicitor application, making these compounds pivotal for consumer acceptance and preference (Paladines-Quezada et al., 2019; Garde-Cerdán et al., 2023). Specifically, MeJA application has been correlated with increased terpene concentrations in Muscat Hamburg grapes, resulting in a more intense and complex aromatic profile in the final wine product (Yue et al., 2020). This ability to modulate wine aroma emphasizes the multifaceted benefits of using elicitors in viticultural practices, reinforcing the notion that they serve as valuable tools for flavor enhancement.

Furthermore, certain studies emphasize how elicitor treatment can significantly alter the chemical composition of grape skins, which in turn affects the winemaking process. Research shows that MeJA can enhance the cell wall composition of Monastrell grape skins, potentially contributing to better extraction of phenolic compounds during winemaking (Giménez-Bañón et al., 2023). This interaction improves the organoleptic properties of the wine and underlines the potential of elicitors to influence the structure and quality of the grape itself.

The impact of elicitors is not limited to enhancing aroma and phenolic content; they also substantially influence the antioxidant properties of grapes. Elicitors such as MeJA promote the plant's natural defense mechanisms, leading to an accumulation of secondary metabolites with antioxidant properties (Miliordos et al., 2021; Gutiérrez-Gamboa et al., 2019). The increased antioxidant capacity of treated grapes can enhance the health benefits associated with wine consumption, further justifying the use of elicitors as a strategy to improve grape quality from multiple angles (Nardello et al., 2021; Yang et al., 2019).

Additionally, elicitors may have synergistic effects when applied in combination with other treatments, like pre-fermentation cold maceration, enhancing overall polyphenol extraction from grapes during winemaking (Pastore et al., 2019). Elicitors enhance grape composition directly and optimize the winemaking process itself, ensuring that more bioactive components are captured from the fruit.

As viticulturists seek to improve grape quality sustainably, the evidence supporting the use of elicitors continues to grow. Employing these natural compounds can help reduce reliance on synthetic chemicals while simultaneously enhancing grape and wine quality (Cunha et al., 2021; Shricharan et al., 2024). This aligns with current trends in agriculture towards more sustainable and environmentally friendly practices, making the exploration and application of elicitors in viticulture increasingly relevant.

INFLUENCE OF ELICITORS ON TASTE, AROMA, CLARITY, FERMENTATION AND WINE MATURATION

The sensory profile of wine encompasses essential attributes, including taste, aroma, and clarity, all of which can be significantly influenced by the application of elicitors. Elicitors, such as methyl jasmonate (MeJA) and chitosan, have been shown to enhance various organoleptic qualities of wine, making them critical tools in modern viticulture and winemaking practices (Sherman et al., 2020; Martínez-Lapuente et al., 2023).

Aroma is one of the most vital aspects of the sensory profile that can be profoundly affected by elicitor treatments. Elicitors induce the biosynthesis of aromatic compounds, leading to a richer and more complex aromatic profile in wines. For example, the application of MeJA has been linked to an increase in terpene concentrations in Muscat grapes, which resulted in wines exhibiting more pronounced floral aromas. This enhancement improves the sensory appeal of wines and contributes significantly to consumer satisfaction and market success (Martínez-Lapuente et al., 2023; Bilko et al., 2022). The complexity provided by these aromatic compounds is crucial for achieving a high-quality wine experience, where the integration of various volatile substances interacts with the olfactory system to produce distinct and pleasurable sensory perceptions (Sáenz-Navajas et al., 2021; Armstrong et al., 2020). Aside of the function of elicitor, it was demonstrated in a study on the use of chitosan in winemaking, that the application of 1 g/L of fungoid chitosan for fining an aromatic white wine lead to significant improvements in wine stability and composition. Specifically, chitosan effectively removed chitinases while causing only a negligible depletion of thaumatins. Moreover, the heat stability of the treated wine samples was significantly enhanced. Additionally, reductions in tartaric and malic acids, potassium, and iron were observed, along with a decrease in free terpenols. However, the glycosylated terpenols and fermentative aroma compounds remained unaffected, preserving the wine's aromatic profile (Colangelo et al., 2023). The effects of elicitors extend beyond aroma to significantly influence the taste of wine. Elicitors can elevate sweetness perception and balance acidity and tannins in wine, aligning with consumer trends favoring sweeter varietals, especially in the context of climate change-induced fluctuations in grape sugar levels (Marín et al., 2020; Kazumyan et al., 2023). This modulation of taste is essential for winemakers aiming to adapt their products to evolving consumer preferences while ensuring consistency across varying environmental conditions. The interaction between taste and aroma is noteworthy, as sweetness can enhance the perception of aromatic compounds, illustrating the interdependent nature of these sensory attributes (González-Lázaro et al., 2020).

Table 2. Elicitors for improving wine quality and grapevine resistance

Elicitor type	Mode of action	Dosage	References
Chitosan	Induces the production of secondary metabolites (e.g., terpenes, resveratrol) and enhances resistance against pathogens; as fining agent improves wine quality characteristics.	0.1-1% (foliar)	Salifu et al., 2022; Bavaresco et al., 2023; Singh et al., 2022
Methyl Jasmonate (MeJA)	Stimulates phenolic and aromatic compound synthesis, enhancing flavor complexity and resistance to stress; effective in improving overall wine composition.	100-200 µM (foliar)	Martínez-Lapuente et al. (2023)
Salicylic acid	Promotes systemic acquired resistance (SAR) and enhances the biosynthesis of phenolic compounds, influencing wine flavor and stability.	0.1-0.5% (foliar)	Delaunois et al., 2013; Cataldo et al., 2022

Also, the characteristics of clarity are not solely dependent on microbiological stability but also on the molecular interactions facilitated by polysaccharides produced in response to elicitors. For example, MeJA treatments have been linked to changes in polysaccharide composition in wines, affecting mouthfeel and the overall sensory experience (Martínez-Lapuente et al., 2023; Bilko et al., 2022). This aspect is particularly important, as polysaccharides contribute to the structure and body of the wine, influencing both taste and texture.

Furthermore, the comprehensive evaluation of the sensory profile, utilizing advanced analytical methods, allows winemakers to predict and tailor wine characteristics based on elicitors' effects on grape composition (Phan et al., 2021; Wang et al., 2021). This precision in winemaking enhances the potential for producing high-quality wines consistently, ensuring that the sensory attributes align with consumer expectations while adapting to environmental changes and market trends. Recent research has delved into the effects of elicitors on fermentation and wine maturation processes, revealing their significant impact on the final quality of wines. Elicitors can influence enzymatic activity during fermentation, thereby enhancing fermentation efficiency and leading to an increased production of aromatic compounds essential for high-quality wine production. For instance, the application of elicitors can optimize the enzymatic reactions that occur during fermentation, resulting in a more effective transformation of grape must into wine while promoting the enhancement of desirable aromatic profiles (Paladines-Quezada et al., 2019).

The main elicitors used for improving wine quality and grapevine resistance are presented in Table 2.

CLIMATE CHANGE MITIGATION AND SUSTAINABLE VITICULTURE ADAPTATION: REDUCING WATER STRESS AND TEMPERATURE RESILIENCE

In the context of climate change, elicitors have emerged as essential tools to mitigate water stress and enhance grapevine resilience to extreme temperatures. The application of elicitors, such as salicylic acid and chitosan, has shown promising results in improving plant tolerance to drought and high heat conditions (Tscholl & Vigl 2024 ; Alsafadi et al., 2023). Salicylic acid has been documented to increase antioxidant enzyme activity, thereby shielding plants from oxidative stress induced by adverse environmental factors like drought and elevated temperatures, which is crucial for maintaining grapevine health, particularly during periods of water deficiency, increasingly common in many viticultural regions as climate change progresses (Irimia et al., 2024).

Chitosan has demonstrated efficacy in enhancing water and nutrient uptake during drought stress. The ability of chitosan to improve physiological responses relating to hydration and nutrient acquisition is integral to sustaining vine vitality under challenging climatic conditions. Leveraging elicitors like chitosan supports crop health and also enhance fruit quality, a crucial consideration for sustainable wine production (Hall & Blackman, 2019; Lemaître-Guillier et al., 2021).

The integration of elicitors into precision viticulture practices can further optimize vineyard resilience to climate challenges. By applying elicitors alongside established water management practices, grape growers can develop effective strategies to address the impacts of climate change, thus ensuring long-term sustainability in viticulture. This approach involves a comprehensive understanding of the physiological responses induced by elicitors and the environmental conditions affecting grapevine performance (Monteiro et al., 2024).

Recent studies have highlighted significant spatial shifts in viticulture potential due to climate change, necessitating adaptation strategies that consider both bioclimatic indices and crop varieties (Irimia et al., 2024; Biasi et al., 2019). As traditional grape-growing regions may become unsuitable for certain cultivars, the importance of adapting management practices, including the use of elicitors, is underscored. These shifts in climate necessitate selecting more heat-tolerant grape varieties, alongside innovative agricultural strategies to foster resilience against changing weather patterns (Alsafadi et al., 2023; Naigeon et al., 2023).

Additionally, advancements in understanding the genetic and phenotypic responses of grapevines are essential. Considering local genetic variations and adopting indigenous cultivars can enhance grapevine adaptability to increasingly erratic climate conditions (Molitor & Junk, 2019). By integrating these genetic strategies with elicitor applications, wine producers can cultivate varieties that withstand environmental stressors while maintaining desirable quality traits essential for high-quality wine production (Blanco-Ward et al., 2019; Candiago et al., 2022).

Collaboration across scientific disciplines is also essential in developing adaptive strategies for viticulture. The use of data analytics to monitor climate impacts can inform growers about the optimal application of elicitors and other management practices tailored to local conditions. Recognizing the interplay between climate models and viticultural responses allows for more precise decision-making in vineyard management (Naigeon et al., 2023; Martins et al., 2021).

MITIGATION: REDUCING CHEMICAL INPUTS AND CARBON FOOTPRINT

Elicitors, such as chitosan and salicylic acid, are increasingly recognized for their potential to mitigate climate change impacts in viticulture by reducing chemical inputs and minimizing carbon footprints. By effectively controlling grapevine diseases like downy and powdery mildew, these natural alternatives to synthetic pesticides help enhance both environmental health and biodiversity within vineyard ecosystems (Naigeon et al. 2023 ; Nerva et al., 2019). The use of elicitors not only decreases chemical dependency but also aligns with sustainable practices that support cultivation methods aimed at preserving ecological balance (Héloir et al., 2019).

The use of elicitors can optimize production processes, thereby lowering carbon emissions associated with agricultural inputs. For instance, research has shown that elicitor applications enhance grapevine health and fruit quality, reducing the need for frequent pesticide and fertilizer applications (Candiago et al., 2022; Pérez-Álvarez et al., 2020). This reduction in input frequency lowers the overall carbon footprint of grape production and contributes to a more sustainable approach to vineyard management, particularly as agriculture becomes a significant contributor to global greenhouse gas emissions (Thiollet-Scholtus et al., 2020). The interplay of improved plant resilience and reduced chemical application fosters environmentally friendly viticultural practices that benefit both producers and consumers.

Combining elicitors with advanced water management practices represents a promising avenue for developing climate-smart viticulture approaches. Integrating elicitors into precision viticulture systems empowers grape growers to formulate effective strategies that can handle the multitude of climate-related challenges presented by rising temperatures and water scarcity (Madouas et al., 2023). This synergy ensures the long-term viability of vineyards and promotes economic benefits while preserving environmental resources. Such holistic strategies encompass a wide range of practices aimed at enhancing both the resilience of grapevines and the sustainability of the broader agricultural system. In addition to their direct effects on plant health, elicitors are also associated with optimizing soil health and promoting sustainability. By encouraging beneficial microbial communities in the phyllosphere, elicitor applications can enhance the overall health of grapevines, facilitating nutrient exchanges and improving soil structure (Nerva et al., 2019). This focus on soil management is paramount in sustainable viticulture, as healthy soils contribute significantly to grape quality while playing a critical role in carbon sequestration efforts (Gaiotti et al., 2021).

Furthermore, the adoption of elicitors aligns with the growing body of research advocating for reduced chemical use in agriculture. The environmental and health risks associated with synthetic pesticides have led to increased scrutiny of traditional viticulture practices, making elicitor application an attractive alternative. By minimizing reliance on chemical inputs, grape growers can enhance their ecological footprint while meeting consumer demands for sustainably produced wines that resonate with modern environmental consciousness (Candiago et al., 2022; Héloir et al., 2019).

CONCLUSIONS

The application of elicitors in viticulture and winemaking has proven to be a transformative strategy, offering significant benefits to both plant health and wine quality. Elicitors such as salicylic acid, chitosan and methyl jasmonate have been directly linked to the enhancement of polyphenol and anthocyanin content within grapes, which are critical determinants of wine colour, flavour profile, and antioxidant capacity. By boosting these vital compounds, elicitors not only elevate the overall quality of wine but also contribute to the resilience of grapevines in the face of diseases and abiotic stressors like drought and high temperatures, thereby ensuring sustainable production practices. Also, the integration of elicitors throughout the winemaking process - including during fermentation and aging - has demonstrated positive effects on sensory characteristics, resulting in wines that are more complex and aligned with consumer preferences. This capability to enhance wine quality positions elicitors as essential components for sustainable viticulture, especially in the context of adapting to climate change by promoting resilience and reducing dependency on synthetic inputs.

For effective implementation, it is crucial that specialists foster the development of standardized protocols for the use of elicitors in viticulture. Such protocols should encompass optimal dosages, appropriate application timing, and the specific environmental conditions required to maximize the efficacy of elicitors.

Research in this field must continue to evolve, focusing on elucidating the mechanisms through which elicitors operate and their interactions with various environmental factors. Future studies should aim to explore how different types of elicitors influence grape composition, wine quality, and the broader vineyard ecosystem, ensuring that findings benefit practitioners within the industry. Additionally, conducting cost-benefit analyses that compare the economic viability of elicitor use versus conventional agricultural practices will yield valuable insights for growers, empowering them to make informed decisions regarding their implementation.

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