Following the Smoke Signals: Elucidating the Future of US Smoke Exposure Research

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Introduction

Smoke Exposure in Vineyards and Smoke Taint in Wine

Wildfires have increasingly become a significant threat to agriculture, particularly in regions such as the western United States that are prone to such events. One of the most pressing challenges for grape growers is the impact of wildfire smoke on their vineyards, and more critically, the effect this smoke has on the quality of the wine produced from those grapes. As wildfires become more frequent and intense, the risk of smoke exposure to vineyards grows, threatening both the health of the vines and the financial stability of the wine industry.

When grapes are exposed to wildfire smoke, they absorb volatile phenolic compounds that are released during the combustion of plant material. These compounds are metabolized by the grapes as part of their detoxification response, resulting in an accumulation of compounds associated with smoke exposure. This is further complicated when the grapes are processed into wine, where fermentation and aging release the aroma-active compounds that contribute to the characteristic smoky flavors. The presence of these compounds—such as volatile phenols, thiophenols (a subset of volatile phenols), and their glycoconjugates—can lead to "smoke taint," a defect in wine that imparts undesirable smoky and ashy flavors, severely affecting wine quality.

The phenomenon of smoke taint has sparked a growing body of scientific research aimed at understanding how wildfire smoke affects both grapevines and the wines they produce. Assessing smoke impact in grapes and wine relies on identifying specific chemical markers, such as volatile phenols, thiophenols, and their glycoconjugates. Specialized analytical instruments are used to assess the extent of smoke contamination, helping winemakers make informed decisions about harvest timing and fruit selection. Given the potential for smoke taint to compromise wine quality, this issue has far-reaching implications for the economic stability of the wine industry, which relies on consistent, high-quality grape production. As a result, addressing smoke exposure and taint has become a key focus of ongoing research and industry discussions, underscoring the need for innovative solutions to safeguard both wine quality and the livelihoods of growers.
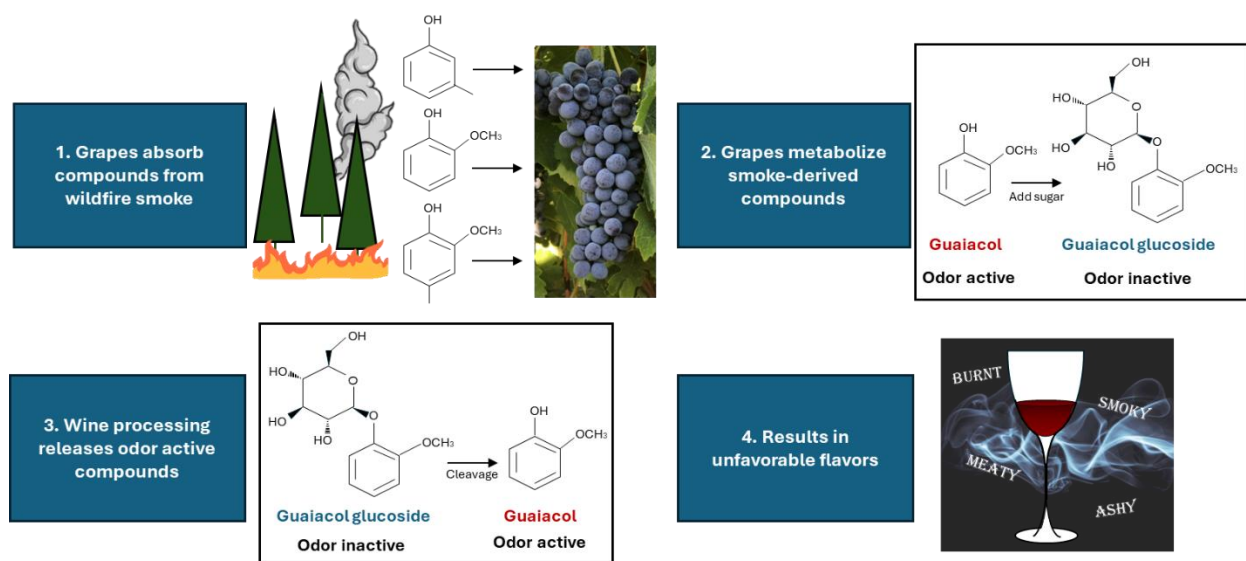
Figure 1. Diagram depicting the fate of smoke marker compounds in grapes and through wine processing.

Definitions: Smoke Exposure, Impact, and Taint

- **Smoke Exposure** specifically refers to the duration and intensity of smoke that grapevines experience during a wildfire event. Factors such as the proximity of the fire, the type of fuel, and environmental conditions (e.g., wind, humidity) influence the level of exposure.

- **Smoke Impact** refers to the various effects of wildfire smoke on grapevines and wine quality. These impacts could range from changes in grapevine physiology to alterations in grape metabolism.

- **Smoke Taint** is the term used to describe the undesirable sensory characteristics imparted to wine due to the chemical compounds found in wildfire smoke. These compounds can alter the aroma and flavor of wine, leading to "off-flavors" described as smoky, ashy, or medicinal.

Purpose and Goal of the Workshop

The primary purpose of this workshop was to bring together researchers and stakeholders to discuss the impact of wildfire smoke on grapevines and wine quality, with the aim of advancing knowledge and targeting key areas of research. Participants focused on key challenges related to detecting, predicting, and managing smoke exposure in vineyards. Central topics included improving detection methods, understanding the chemical processes behind smoke taint, and exploring mitigation strategies to reduce the risk of smoke affecting wine quality. The workshop also emphasized the importance of collaboration between researchers and the industry

members to bridge knowledge gaps and develop tools that can help growers assess and manage smoke exposure in real-time.

The workshop's objectives included **fostering collaborative research efforts between researchers and industry members** by addressing specific focus points such as risk assessment, mitigation, and prevention strategies. Another key goal was to produce this **comprehensive report that outlines the current state of the science, identifies knowledge gaps, and future research priorities** needed to create smoke-resilient vineyards. Additionally, the event aimed to disseminate the findings both domestic and international to push research beyond its current scope and foster a global conversation about wildfire smoke's impact on viticulture and enology.

Overall, the workshop aimed to move toward **the development of actionable, science-based solutions** that could be implemented in vineyards to manage smoke exposure, as well as to refine models and methodologies for predicting smoke taint in wine making. These efforts are critical to ensuring the sustainability of vineyards and the quality of wines in regions affected by frequent wildfires.

Unification of Research and Industry Efforts

Top Industry Concerns

The grape and wine industry faces significant challenges related to smoke exposure, which can severely impact grape quality and wine characteristics. A primary concern is the difficulty in measuring and monitoring the compounds responsible for smoke taint, particularly volatile phenols and thiophenols. These compounds are associated with the undesirable "ashy" flavor in wine, and understanding their metabolism in grapes is crucial for managing their impact. While new methods for detecting these compounds are emerging, the industry struggles with developing reliable, cost-effective, and real-time detection tools, such as portable sensors, to assess smoke exposure in the vineyard and during winemaking. Additionally, the complex chemistry of smoke-related compounds complicates the task of establishing specific thresholds for sensory detection, as phenols and thiophenols often interact synergistically to intensify the smoky flavor.

In response to these challenges, the industry is focused on improving prevention and mitigation strategies. Barrier sprays and other treatments are being explored to protect grapes from smoke exposure, but practical issues such as the timing of application and their varying effectiveness need further investigation. Research into preventative measures, such as the use of cultivar selection, barrier sprays, and environmental adjustments, is crucial to reducing smoke exposure before harvest. There is also a strong need for rapid, accurate methods to assess risk in vineyards, including predictive models that consider factors like fire proximity and the type of fuel burned. With the increasing frequency and severity of wildfires, these concerns

are becoming more urgent, highlighting the need for coordinated efforts between researchers, producers, and regulators to develop strategies that safeguard grape and wine quality.
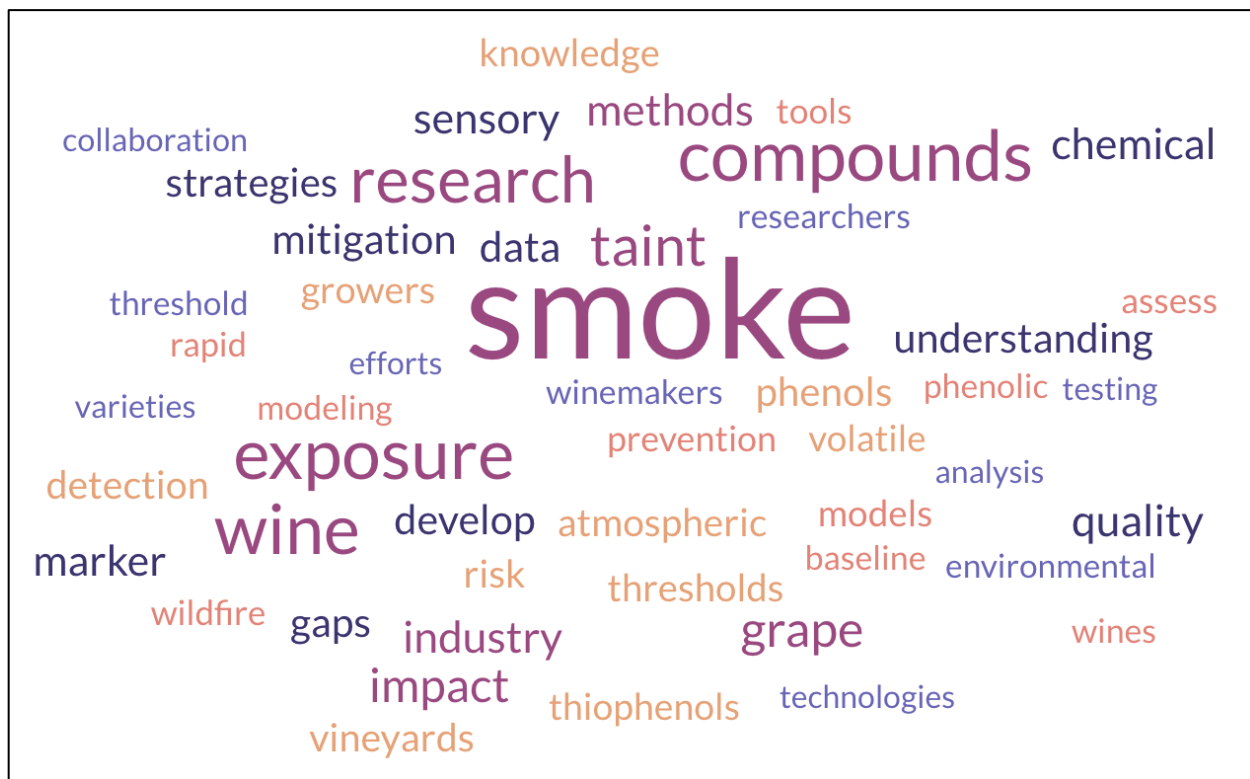
Figure 2. Word cloud of top industry concerns discussed during the first day of the workshop.

US Research Programs

USDA-ARS Programs

ARS researchers in Davis, CA are focusing efforts in developing an inexpensive and rapid detection tool to monitor levels of smoke-derived compounds in grapes. In addition, they are generating a database of endogenous and exogenous levels of smoke marker compounds across genotypic and environmental factors, investigating the mechanism of smoke absorption into grapes, and probing into the grape metabolism to understand the fate of smoke marker compounds after absorption. In Albany, CA, ARS scientists are utilizing genomics, transcriptomics, biotechnology and gene editing approaches to better understand the phenomenon of smoke taint in wine grapes and to generate plants with modified metabolic pathways that alter the accumulation of smoke-derived phenolic compounds. ARS researchers are also exploiting microorganisms' diverse metabolic capabilities to develop microbial-based tools for the quick detection of smoke-derived volatile phenols and their remediation from grapes. Finally, in Corvallis, OR, ARS scientists are investigating ways to predict smoke exposure within vineyards through atmospheric forecasting tools for industry stakeholders that facilitate quicker implementation of vineyard mitigation efforts and/or adjust harvest dates.

California University Programs

California's research is extensive, with a strong emphasis on both vineyard management and winery interventions. Key studies include the development of a vineyard sensor network incorporating satellite imagery to assess smoke risks, and predictive models for air quality that aim to improve decision-making in both vineyards and wineries. California researchers are also exploring the use of oak and oak products to mitigate smoke impacts on wine, as well as developing advanced treatments for smoke-affected wine, such as unique phenol glycosidases and resins. On the prevention side, studies focus on barrier sprays and canopy management practices to reduce smoke compound uptake. Additionally, California is investigating the role of ash in vineyards and its potential impact on grape composition and wine quality. University researchers are also testing small-scale fermentation protocols to predict how smoke exposure will affect commercial wine production. Finally, California is working on decision-making tools to help growers and wineries make informed harvest and winemaking choices based on smoke exposure risks.

Oregon University Programs

Oregon is involved in a variety of research projects aimed at understanding and mitigating the impacts of smoke exposure on vineyards and wine. Key studies include the development of a vineyard sensor network to assess smoke density and composition in real time, which is crucial for predicting smoke-related risks. Researchers are also working on improving methods to measure smoke compounds in grapes and wine, including developing analytical tools to measure both free and bound compounds. Sensory research in Oregon is focused on establishing sensory thresholds for smoke compounds, developing standard sensory evaluation methodologies, and exploring interactions between wine compounds that could influence the perception of smoke taint. Additionally, Oregon is investigating mitigation strategies like the use of enzymatic hydrolysis, reverse osmosis, and yeast to reduce the impact of smoke compounds during fermentation.

Washington University Programs

Washington's research efforts are similar to those in Oregon, with a focus on understanding the effects of smoke on grapes and wine, particularly through the use of vineyard sensor networks and air quality models. Researchers are evaluating field-based sensors to assess smoke exposure and integrate data from various sources, including satellite imagery. Analytical research is also underway to refine methods for measuring smoke compounds, such as using LC/QTOF-MS technology to compare results from smoke-affected and control wines. Washington is also exploring the potential of oxidative methods and microbial metabolism to mitigate smoke taint. Moreover, work is being done on vineyard prevention techniques, such as

barrier sprays and canopy management practices to reduce smoke uptake. Lastly, Washington researchers are focused on understanding grapevine responses to smoke exposure through RNA transcriptomics and chemical profiling.

State of the Science

Risk Assessment

Overview

Measuring and monitoring smoke marker compounds in grapes and wines is a critical area of research due to the growing impact of wildfire smoke on viticulture. Smoke from wildfires releases volatile compounds, such as phenols, which can penetrate grapes and affect the final taste of wine, potentially leading to smoke taint. Compounds such as volatile phenols, thiophenols, and their glycosylated markers impart undesirable smoky and ashy flavors, often compromising wine quality. These compounds, while naturally present in grapes and wines in trace amounts (parts per billion to parts per trillion), are significantly elevated after smoke exposure and contribute to undesirable taste in wine.

Early and accurate detection of these compounds is essential for winemakers to assess the extent of smoke contamination and make informed decisions about fruit selection, harvesting, and processing. However, conducting reliable risk assessments is challenging due to the complexity of smoke exposure and the diverse chemical compounds involved. Sensitivity and selectivity of detection methods vary, and there is currently no universally applicable approach to assess smoke exposure across different vineyard conditions. Moreover, additional research is needed to fully understand the range of compounds responsible for smoke taint and establish clear correlations between chemical markers and sensory characteristics in wine. Developing efficient, scalable detection methods will allow growers and winemakers to assess risk more accurately, streamlining the identification process. This will help focus resources where they're needed most, reducing both the costs and lab congestion typically associated with comprehensive testing of obvious cases. Ultimately, this approach will help mitigate the economic impact of smoke taint and support the long-term sustainability of vineyards in fire-prone regions.

Smoke Marker Compound Analysis

Over the past decade, researchers have identified a set of compounds that are correlated to smoke exposure and smoke taint. The select volatile phenols (Figure 3) and their glycoconjugates (Figure 5) are now routinely analyzed in grapes and wines to determine the level of smoke impact, while methods to quantify thiophenols (Figure 4) are still being developed.
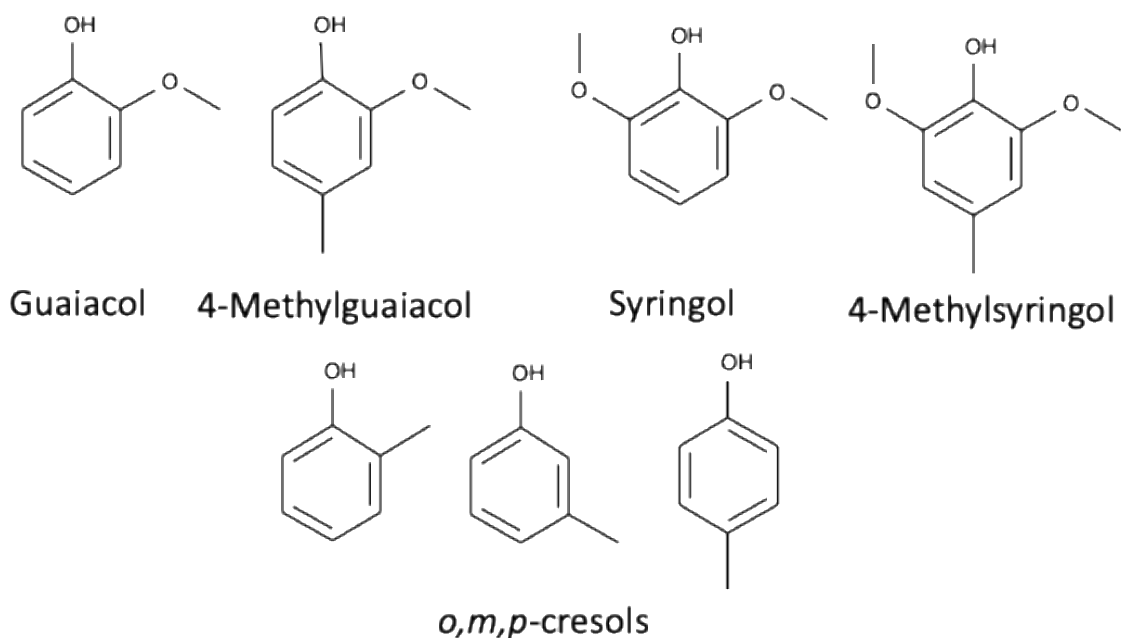
Figure 3. Chemical structures of volatile phenols associated with smoke exposure in grapes and wines.
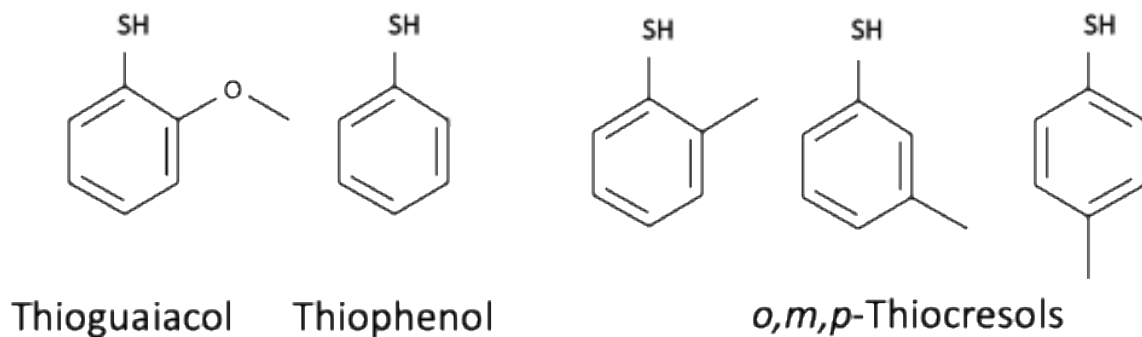
Figure 4. Chemical structures of recently reported thiophenols associated with smoke exposure in grapes and wines.
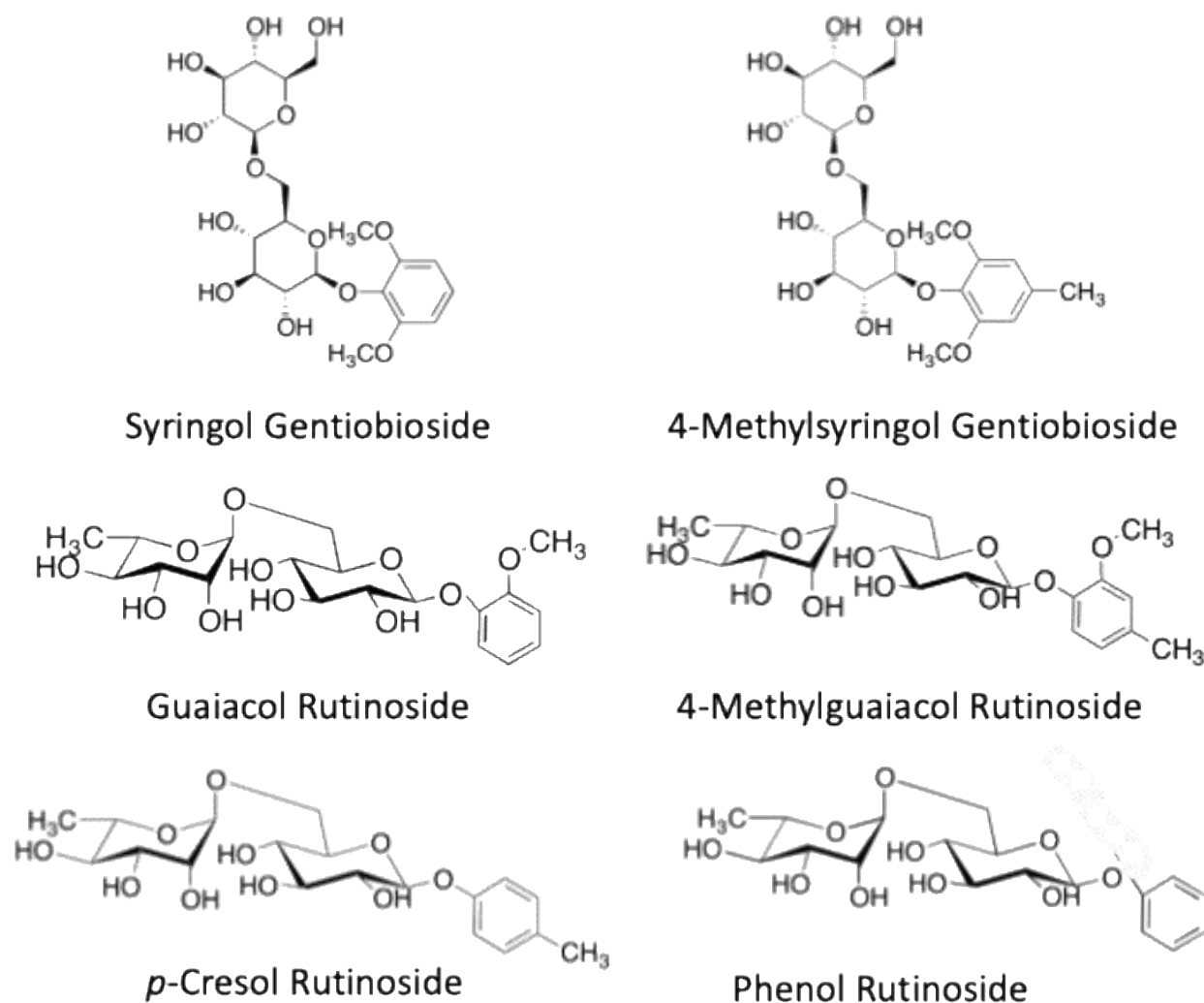
Figure 5. Chemical structures of the six main glycosylated volatile phenols associated with smoke exposure in grapes and wines.

Chromatographic techniques, such as liquid chromatography (LC) and gas chromatography (GC), are the most established methods for detecting smoke marker compounds in both grapes and wine. These techniques are highly sensitive and capable of identifying and quantifying trace levels of volatile phenols, thiophenols, and glycoconjugates that are linked to smoke exposure. However, they are generally expensive, require specialized equipment and trained personnel, and have long turnaround times, making them impractical for routine field use. Despite these limitations, LC and GC remain the gold standard for confirming the presence of smoke marker compounds and are used primarily in research and laboratory settings.

Nanofermentation is a technique that simulates the winemaking process at a smaller scale and is being explored for rapid detection of smoke taint in grapes. By mimicking fermentation in a controlled setting, nanoferments allow researchers to evaluate how smoke marker compounds evolve during fermentation, offering insight into the potential impact of smoke exposure on the

final wine. This method has shown promise for moderately quick, low-cost evaluations, enabling rapid screening of grapes for smoke-related compounds. It is a valuable tool for growers who need to make timely decisions, as it provides a faster alternative to traditional laboratory analyses, which can be prone to delays due to backlogs when large volumes of samples are sent in at once, potentially taking weeks to process. However, this technique requires sufficient time for growers to 1) collect a composite fruit sample from impact vineyard, 2) complete fermentation, and 3) analyze the sensorial characteristics of the wine.

Threshold Levels and Baseline Analysis

Establishing threshold levels of smoke marker compounds in grapes that are correlated with altered sensory perceptions in wine is essential for growers to assess the risk of smoke taint early in the growing season, thereby informing decisions on whether to accept or reject grapes. These thresholds are likely to vary depending on factors such as grape cultivar, wine style, and the inherent concentrations of smoke marker compounds. Several laboratories have already collected baseline data on the natural levels of volatile phenols and their glycoconjugates, revealing minor variations across vintages and vineyard locations, with concentrations primarily influenced by grapevine cultivar. However, a standardized methodology is needed to establish a comprehensive database of baseline concentrations across different cultivars and environmental conditions. This baseline information, built over multiple years and regions, will help distinguish typical concentrations of smoke marker compounds in grapes from concentration ranges associated with smoke impact and potential for smoke taint, thus facilitating more predictable and scientifically supported management of smoke exposure.

Additionally, determining sensory odor thresholds for smoke marker compounds in wine is essential for understanding consumer acceptance. These thresholds can vary by wine variety, wine style, and market as consumer sensitivity to smoke taint is not universal. Sensory evaluation is crucial in defining these thresholds; however, it must be integrated with chemical analysis to ensure the accuracy and consistency of results. Current research has identified concentration ranges of volatile phenols, thiophenols, and glycoconjugates in wine that are linked to smoke taint, revealing significant variation in odor thresholds based on factors such as grape cultivar, wine style, and consumer sensitivity. By identifying the specific concentrations at which smoke-related compounds impact wine flavor, the industry can better understand potential consumer dissatisfaction and improve its ability to manage and mitigate the effects of smoke exposure on wine quality.

Atmospheric Modeling

Atmospheric modeling plays a crucial role in evaluating the impact of wildfire smoke on vineyards by tracking the movement, deposition, and transformation of airborne compounds, such as volatile organic compounds (VOCs) and particulate matter (PM), that contribute to smoke taint in wine. These models integrate environmental factors like wind, temperature, humidity, and elevation, along with data from vineyard sensors, to forecast smoke exposure in real-time. Yet, one of the primary challenges is accurately forecasting when and where smoke

exposure will be significant enough to affect grape quality, which is complicated by the complex behavior of smoke compounds. Existing models are not yet fully optimized for viticulture, as they often lack the specificity needed for growers to make timely decisions. Models typically treat VOCs and particles broadly, missing the detailed insights required to assess smoke taint risk. Additionally, while progress has been made, there is a gap between atmospheric modeling and the chemical understanding of how key compounds, like volatile phenols and thiophenols, degrade and interact with the environment. More field data and detailed chemical speciation are needed to refine models for specific vineyard conditions, enabling better predictions of smoke exposure and its potential impact on grape quality.

Knowledge Gaps Identified

Standardization of Testing and Risk Assessment Methods: Inconsistent sampling methods and analytical tools across the industry make it difficult to generate comparable datasets. To establish reliable risk assessment practices, ring testing and standardized laboratory performance are essential.

Thresholds and Variability in Smoke Taint: There are no established baseline or threshold levels for acceptable smoke taint in grapes, and the thresholds likely vary by grape cultivar, smoke exposure intensity, and wine style. Additionally, the sensitivity of different grape varieties to smoke exposure needs further research to refine risk assessments.

Chemical Understanding of Smoke Impact: The degradation and environmental interactions of smoke compounds (e.g., guaiacol, thiophenols) are poorly understood, including how they accumulate and affect grape quality over time. A comprehensive understanding of the full range of volatile compounds responsible for smoke taint and their sensory impacts is still lacking.

Data Gaps and Model Integration: There is a lack of long-term, high-resolution data to validate atmospheric models, making it difficult to accurately predict the impact of smoke exposure on grape quality. Additionally, the integration of sensor data with predictive models remains underdeveloped, limiting the effectiveness of risk assessments.

Prevention and Mitigation

Overview

Prevention

Research on preventing smoke taint in grapes remains limited, primarily focusing on spray-based treatments and genetic improvements, both of which face considerable challenges. Barrier sprays are currently being studied, but their effectiveness remains uncertain due to limited knowledge of how smoke-marker compounds interact with grape tissues, as well as practical challenges like applying the sprays at a commercial scale, ensuring complete coverage,

and possibly needing to remove them after smoke exposure. Genetic approaches to developing smoke-resistant grape varieties show promise as a long-term solution; however, progress is slow, and regulatory issues related to genetically modified organisms (GMOs) may arise. Additionally, there is a significant gap in knowledge regarding how different grapevine genotypes respond to smoke exposure. Collaboration within the research community is hindered by a lack of data sharing between universities, researchers, and the wine industry, impeding the development of integrated solutions. Research remains in its early stages, and a more comprehensive understanding of the chemistry of smoke exposure is essential for creating effective prevention methods.

Mitigation

The current state of science regarding smoke taint mitigation in wineries reveals significant challenges and gaps in knowledge. Efforts to mitigate smoke taint in wine are focused on removing or altering the smoke marker compounds that negatively impact wine quality. Various methods are being explored, including enzyme-based treatments, bio-based removals, and advanced absorbents, though their projected feasibility varies. While individual wineries and growers have developed and tested mitigation strategies based on experience, there is no consensus on key factors such as which methods should be used based on the timing and duration of smoke exposure, what compounds (like thiophenols and phenols) to target for removal, and the thresholds for sensory and chemical detection of smoke taint.

Looking forward, there is a clear call for immediate practical solutions, alongside investments in longer-term strategies. These include removal of smoke markers via microbial enzymes, zeolites, and molecularly imprinted polymers (MIPs) for smoke marker degradation, although their feasibility remains unknown. A more collaborative approach is needed, including creating a shared database for winemakers and growers to exchange data and the development of tiered mitigation methods based on the severity of smoke exposure. Furthermore, economic and sustainable evaluation of these solutions is essential, as is consumer education and engagement to better manage market perceptions of smoke-tainted wines. Research into alternative markets and the financial viability of mitigation strategies will also play a key role in shaping future approaches.

Knowledge Gaps Identified

Understanding Phenolic Binding and Prevention: A key challenge in preventing smoke taint is understanding how phenolic compounds from smoke bind to grape skins, which is essential for developing effective barrier sprays. The long-term effectiveness of these sprays remains uncertain, especially regarding their interaction with grapevine physiology and whether washing is needed for optimal results.

Genetic Resistance: Research on the genetic variability of grapevines in response to smoke exposure is limited. There is a critical need to identify and develop grapevine cultivars that are genetically resistant to smoke taint to provide a long-term and sustainable solution.

Mitigation Research Gaps: More research is needed to determine the timing and effectiveness of mitigation strategies during winemaking. Further investigation is also required on mitigation tools like zeolites, molecularly imprinted polymers, and genetically engineered yeast to better address smoke taint.

Industry Collaboration and Market Development: Improved communication and data sharing between researchers and the viticulture industry is essential for advancing prevention and mitigation strategies. Additionally, exploring alternative markets for smoke-affected wines and educating consumers about smoke taint will help address market challenges and promote collaborative solutions.

Current and Future Research Directions

Establishing Threshold Levels

Summary

Current research focuses on understanding the impact of chemical composition in grapes, particularly regarding sensory effects such as smoke taint in wine, and the role of marker compounds in predicting these impacts. Future directions include the creation of smoke marker databases and the standardization of grape and wine samples to build comprehensive datasets. There is also an emphasis on developing predictive models that incorporate timing and duration of smoke exposure and grape varietal. Efforts are underway to establish a correlation between sensory thresholds in wines made from smoke exposed grapes and smoke-marker compounds in grapes.

Knowledge Gaps Identified

Several knowledge gaps remain, particularly regarding the precise baseline and threshold levels for smoke taint in wine, as well as the varying sensory thresholds across different consumers and grape varieties. While sensory thresholds for smoke-impacted wines are relatively well understood, much less is known about the threshold levels in the grapes themselves and how these levels affect sensory perceptions in wine. The complexity of compounds involved, such as guaiacol, cresols, and thiophenols, and their varying natural presence in different grape varieties, complicates the establishment of reliable "baseline" values. To define meaningful thresholds, more data and a standardized approach to sampling, testing methods, and data analysis are needed. Additionally, the impact of smoke exposure during various phenological stages of grape development remains underexplored. The industry lacks standardized data, and further research is necessary to bridge the gap between baseline measurements and the consumer's ability to detect taints. Furthermore, the role of predictive models based on chemical composition and sensory impact requires deeper investigation, along with the development of effective strategies for industry-wide data sharing and collaboration.

Research Aim 1: Creating Database of Baseline Levels

Overview

The first step in understanding the impact of smoke exposure on grapes and wine is to establish a comprehensive database of baseline levels for smoke marker compounds. This requires tracking compounds over multiple years to understand their natural variability in different grape cultivars and regions. The database will serve as a foundation for determining when smoke exposure exceeds normal levels and affects the sensory characteristics of wine.

Objectives

- Collect and analyze baseline data for smoke marker compounds in grapes including volatile phenols, thiophenols, and glycoconjugates.

- Standardize sampling methods to ensure consistency in data.

- Track data across multiple vintages and regions to capture variations and establish reliable baseline values.

- Monitor and record the response of different grape varieties to smoke exposure throughout grape development, particularly the presence of glycosylated compounds as markers of exposure.

- Develop a centralized, accessible database of smoke marker compound levels to facilitate further research and decision-making.

Research Aim 2: Establishing Grape Threshold Levels

Overview

While there is progress in understanding the sensory thresholds of smoke exposure in wine, the threshold levels of smoke marker compounds in grapes remain less clear. Establishing these thresholds is essential for determining when smoke exposure in grapes starts to affect wine quality. This research will focus on identifying the levels of smoke marker compounds in grapes that lead to altered sensory characteristics, particularly undesirable "ashy" tastes.

Objectives

- Define the threshold levels of smoke marker compounds in grapes that correlate with changes in wine sensory characteristics, such as "ashy" flavors.

- Investigate the impact of thiophenols and other key smoke-related compounds on wine quality and consumer perception.

- Identify the differences in grape cultivar responses to smoke exposure and how these affect the establishment of thresholds for different varieties.

- Develop methods to monitor and measure both smoke marker compounds in grapes that contribute to smoke taint in wines for a more comprehensive understanding of exposure.

- Explore the relationship between different stages of grapevine growth (e.g., veraison) and the absorption of smoke marker compounds to determine optimal sampling times.

Research Aim 3: Developing Decision Matrix

Overview

To help winemakers and grape growers make informed decisions about grape acceptance and wine quality, a decision matrix is needed that incorporates smoke exposure levels, sensory perceptions, and potential risks to wine quality. This matrix will take into account varying thresholds for different consumer segments, including casual drinkers, sommeliers, wine critics, and high-end consumers. The goal is to provide a practical tool that helps the industry assess the viability of affected grapes and wines.

Objectives

- Develop a decision matrix to guide grape growers and winemakers in assessing smoke exposure risk and wine quality based on threshold levels of smoke marker compounds.

- Include variables such as the level of smoke exposure, grape cultivar, phenological stage of growth, and consumer segment preferences in the matrix.

- Create a tiered approach to categorize smoke exposure into low, moderate, and high-risk categories for both grapes and wines.

- Incorporate sensory evaluations from different wine consumption groups (e.g., consumers, sommeliers, wine critics) to define acceptable thresholds for each group.

- Explore the feasibility of a smoke exposure index, similar to the air quality index, to track and communicate smoke-related risks across the industry.

- Integrate findings into educational materials and training programs for the industry to better understand smoke exposure and its impact on wine quality.

Rapid Detection and Risk Assessment

Summary

Rapid detection of smoke marker compounds in grapes and wine is crucial for winemakers and growers to assess exposure to smoke and mitigate the risk of undesirable flavors in the final product. Traditional methods, such as liquid chromatography (LC) and gas chromatography (GC) coupled to a mass spectrometer, are highly accurate but time-consuming and expensive, making them impractical for field-level testing. As climate change leads to more frequent wildfires, there is an increasing demand for low-cost, portable tools that can provide immediate, actionable results on-site. Methods such as spectroscopic techniques (e.g., UV-Vis, Raman, fluorescence), handheld devices, and microbial sensors are being explored as potential solutions for rapid screening. This approach recognizes the trade-off between speed and precision. While it emphasizes rapid results, it does not match the accuracy of comprehensive laboratory tests. Rather, it serves as an initial screening tool to efficiently identify clear positives and negatives, helping to reduce laboratory congestion and lower costs for growers and wineries when extensive testing is not required. A tiered strategy—beginning with cost-effective methods for initial risk assessment and advancing to more precise analyses for confirmation—has been proposed as an effective and scalable solution.

Knowledge Gaps Identified

Despite progress in measuring and monitoring important smoke marker compounds, several key gaps remain in the field. One major challenge is the lack of uniformity in analytical methods used, making comparisons difficult across studies. The detection of thiophenols, key compounds responsible for smoke taint, remains challenging, particularly with handheld devices that may not have the required sensitivity or specificity. The correlation between atmospheric sensors and chemical analysis is not fully established, and more research is needed to understand how compounds measured by sensors relate to sensory perceptions of the final wine. There is also a need for a more complete list of compounds that impact smoke exposed grape and wine aromas. Finally, the cost of deploying rapid detection systems must be low enough to be accessible for growers, but methods must still maintain an adequate level of sensitivity and specificity.

Research Aim 1: Standardization of Analytical Methodologies

Overview

The development and standardization of reliable and uniform analytical methodologies are essential for accurately detecting smoke taint in vineyards and wineries. While substantial progress has been made in this area, effort is needed refining primary methods such as liquid chromatography (LC) and gas chromatography (GC) to improve sensitivity and selectivity and ensuring consistency across labs and analytical tools. Establishing robust analytical protocols

that correlate chemical analysis to sensory perceptions of wine is critical for both growers and winemakers.

Objectives

- Standardize primary analytical methods (LC, GC) to ensure consistency across different laboratories and instruments through a national ring test. A ring test is a quality assessment method in which blind, spiked samples are distributed to participating laboratories, and a central lab evaluates both individual and inter-laboratory performance to assess methodological accuracy and consistency.

- Institute an annual, **national ring test (i.e., interlaboratory study)** to ensure consistency across different labs.

- Develop methods that balance sensitivity and selectivity, especially for thiophenol detection and other volatile compounds associated with smoke taint.

Research Aim 2: Development of Rapid Screening Methods

Overview

The need for fast, cost-effective, and user-friendly methods for detecting smoke taint at early stages is critical. Rapid screening tests must be accessible to unskilled labor, easy to deploy in the field, and inexpensive. A tiered testing approach is suggested, with an initial low-cost screening tool followed by more expensive, detailed testing for confirmation. The goal is to develop methods that offer quick results while maintaining enough sensitivity to provide accurate risk assessments.

Objectives

- Develop a rapid screening test (30 min-1 hr) for smoke taint detection that costs less than $50.

- Explore various rapid detection technologies, including portable sensors, handheld spectroscopic devices, and colorimetric or enzymatic assays (e.g., nanoparticle sensor or microbial embedded strips).

- Test and refine tiered approaches, starting with low-cost, lower-sensitivity sensors that indicate high, medium, or low levels of concern, followed by more precise analyses (e.g., LC-MS for confirmation).

- Address the challenges of interpreting field-based results and providing actionable recommendations for growers based on the initial detection.

Research Aim 3: Correlation of Smoke Marker Compounds to Sensory

Overview

There is a need to better understand how smoke marker compounds detected in grape, juice, and wine relate to sensory experiences in the finished product. This project will focus on linking chemical markers of smoke exposure with sensory evaluations from winemakers, aiming to refine risk assessments and improve detection strategies. This research will help provide a more comprehensive understanding of smoke taint and its impact on wine quality.

Objectives

- Identify and analyze smoke marker compounds that correlate with sensory attributes such as smoky and ashy flavors that can affect wine quality.

- Develop a list of compounds that impact the aroma of smoke and assess their detection thresholds across different wine types and varietals.

- Explore the relationship between chemical measurements (using methods like LC/GC and spectroscopic techniques) and sensory analysis of the wine.

- Conduct studies to understand how different cultivars react to smoke exposure and whether certain varieties can serve as sentinel plants for smoke detection.

- Use findings to refine thresholds for risk assessment and to develop more effective methods for quantifying smoke taint after fermentation, including during barrel aging.

These research projects aim to create a more reliable, standardized, and cost-effective framework for smoke taint detection, benefiting both growers and winemakers by improving the accuracy of early-stage testing, streamlining analysis, and correlating chemical data with sensory results.

Atmospheric Modeling

Summary

Research into the atmospheric modeling of smoke exposure in vineyards is essential for developing predictive tools that help winegrowers manage the risks of smoke taint. While atmospheric models are progressing rapidly, there remain significant gaps in understanding the specific compounds responsible for smoke exposure, how those compounds travel, and how they affect grapevines. The need for high-quality, real-time data from vineyards, as well as improved models for simulating smoke transport and its chemical effects, is paramount. Collaborative efforts across disciplines—particularly between atmospheric scientists and the wine industry—are needed to refine these models and provide actionable tools for growers.

Knowledge Gaps Identified

Key gaps include the need for comprehensive, long-term data on smoke exposure at the vineyard level, as well as better understanding of the specific compounds responsible for smoke taint and their behavior in the atmosphere. Current atmospheric models lack sufficient detail to predict exposure accurately for vineyards, especially under variable conditions such as complex terrain and weather. The role of different fuel sources and their impact on smoke composition remains poorly understood, and the lack of integration between atmospheric modeling and field data (such as chemical composition of smoke and environmental variables) limits the effectiveness of existing tools. Moreover, there is a need for more accessible data collection tools and clearer guidance on which atmospheric parameters are most critical for winemakers.

Research Aim 1: Vineyard-Level Exposure Characterization

Overview

This project aims to enhance understanding of how smoke affects vineyards by developing a robust data collection system that monitors key atmospheric parameters, including PM, VOCs, and other relevant chemicals. The goal is to provide growers with data that helps predict smoke exposure and understand its potential impact on grape quality.

Objectives

- Develop mobile sensor capabilities to capture real-time smoke exposure data during fire events.

- Expand the existing fixed sensor network to increase spatial coverage.

- Collect data on key atmospheric parameters, including PM2.5, CO (carbon monoxide), CO_2 (carbon dioxide), and volatile phenols, with a focus on grapevine-level interactions.

- Ensure data collection spans different regions to capture variability across topographies and climates.

Research Aim 2: Modeling Smoke Transport and Chemical Composition

Overview

This project focuses on refining atmospheric models to better simulate the transport of smoke and the chemical reactions that occur during wildfire events. It will use improved model inputs, such as data on fuel sources, fire dynamics, and atmospheric conditions, to better predict the compounds most likely to affect vineyards.

- Improve atmospheric models to track the lifecycle of critical smoke compounds (e.g., VOCs, phenols, and other smoke markers).

- Incorporate local topography, wind, other weather conditions, and fuel source to increase model accuracy.

- Use results from controlled burn studies to better parameterize key chemical reactions in atmospheric chemistry models.

- Develop tools for predicting when and where specific compounds will travel, and how long they will persist in the atmosphere.

- Validate models with measurements from field data and controlled burn studies.

Research Aim 3: Chemical Surrogates for Smoke Exposure

Overview

This project explores the potential of using easier-to-measure chemicals as surrogates for predicting smoke taint in vineyards. By focusing on easily accessible compounds like ozone or carbon monoxide, the project aims to simplify the smoke exposure monitoring process and provide winemakers with faster, actionable insights.

Objectives

- Investigate whether compounds like ozone (O_3), CO, or other tracers correlate with harmful smoke compounds (e.g., phenols).

- Develop simple, cost-effective sensors that can measure these surrogate compounds in the vineyard.

- Establish correlation models between surrogate chemical levels and smoke taint severity.

- Validate the use of these surrogates through field testing and comparison to traditional smoke markers.

As the wine industry continues to grapple with the impact of wildfire smoke on grape quality, these research projects provide a path forward in terms of improved monitoring, modeling, and predictive tools. With advances in sensor technology, modeling capabilities, and cross-disciplinary collaboration, the industry can better manage smoke exposure risks and ultimately preserve wine quality during wildfire seasons.

Prevention Strategies in the Vineyard

Summary

Prevention strategies, including sprays, genetic improvements, and barrier methods, hold potential for reducing smoke volatile absorption and retention in vineyards, but they come with significant challenges. While sprays are a quick solution, their effectiveness and practical use at a commercial scale remains uncertain, and they may change grapevine physiology. Genetic improvements, while promising, require time and extensive research. Barrier methods like biofilms offer a novel approach, but their practicality, sustainability, and long-term effectiveness need further investigation. Collaboration between researchers and industry is essential to refine these strategies and close knowledge gaps.

Knowledge Gaps Identified

Several key knowledge gaps hinder the development of effective smoke prevention and mitigation strategies in vineyards. One major gap is the incomplete understanding of how phenols, responsible for smoke taint, bind to grape tissues and migrate through the plant. Researchers are still investigating the mechanisms of absorption, particularly through the stomata, cuticle, or plasmodesmata, which is crucial for developing targeted prevention methods. Additionally, the feasibility of current strategies such as barrier sprays, microbial treatments, and genetically modified or selected smoke-resistant grape varieties remains uncertain, particularly in large-scale vineyards due to cost and scalability challenges. There is also limited understanding of how different fire intensities, smoke compositions, and prescribed burns affect smoke exposure and risk to vineyards. The lack of collaboration between researchers and industry further complicates the progress, and more research is needed to bridge these gaps, especially regarding the genetic variability of grapevines and their interaction with smoke.

Research Aim 1: Understanding Phenolic Binding and Barrier Development

Overview

This research aims to understand how phenolic compounds from smoke bind to grape tissues and explore potential ways to prevent or reduce this binding using barrier strategies.

Objectives

- Study the chemical processes involved in phenolic absorption by grapevines.

- Investigate biofilm or barrier sprays that could prevent phenolic absorption without washing.

- Collaborate with the food industry to adapt existing barrier technologies for use in vineyards.

Research Aim 2: Genetic Approaches for Smoke Resistance

Overview

This project focuses on developing grapevine cultivars that are resistant to smoke taint, either through traditional breeding or gene editing via biotechnology.

Objectives

- Identify and select grapevine varieties that exhibit natural tolerance to smoke exposure and exhibit less taint.

- Use genetic modification, gene editing and/or advanced breeding techniques to develop smoke-resistant cultivars.

- Study the impact of these cultivars on wine quality and their ability to withstand smoke exposure.

Research Aim 3: Environmental and Atmospheric Factors in Smoke Exposure

Overview

This research aims to explore how environmental conditions such as fire intensity, wind patterns, and UV radiation (photooxidative reactions) influence the movement and chemical composition of smoke compounds.

Objectives

- Study the effects of different fire intensities on smoke compound composition.

- Investigate how atmospheric conditions, including UV radiation and wind speed, affect chemical composition and smoke transport.

- Develop predictive models to assess smoke exposure risk based on environmental factors.

These research directions, along with continued collaboration between scientists and the industry, will help build a more comprehensive understanding of smoke exposure, ultimately leading to more effective prevention strategies.

Mitigation Techniques in the Winery

Summary

Mitigation strategies in the winery focus on addressing smoke taint by understanding how phenolic compounds, including thiophenols, interact with grape skins during smoke exposure and throughout winemaking. The development of multi-tiered mitigation approaches, which take into account the diverse sizes of wineries and vineyard conditions, is essential. Future strategies also involve selective adsorbents, microbial or enzymatic degradation technologies, and better sensory thresholds to reduce the impact of smoke exposure on wine quality.

Knowledge Gaps Identified

There are several gaps in the current understanding of smoke taint, particularly in how different grape varieties respond to smoke exposure and how to effectively separate must and skins during winemaking. A standardized approach for sensory thresholds and chemical quantification of phenolic compounds is needed across wineries. Additionally, more research is required to understand the longevity and fate of bound vs. free phenols and how timing and duration of smoke exposure affect wine quality. Collaboration across the industry and research sectors is necessary to create standardized protocols for mitigation and to better assess the impact of various strategies on wine quality.

Research Aim 1: Develop Multi-Tier Mitigation Approach

Overview

The goal of this research aim is to develop a comprehensive multi-tier mitigation approach that considers the size and economic viability of wineries (small, medium, large) and the varying levels of smoke exposure. This approach would address both high- and low-impact strategies and help provide a practical, scalable solution for different types of wineries.

Objectives

- Develop tiered mitigation strategies tailored to different winery sizes.

- Account for economic feasibility, sustainability, and varying levels of smoke exposure.

- Standardize protocols for implementing mitigation techniques across the industry.

Research Aim 2: Selective Adsorbents for Phenols and Thiophenols

Overview

This research aims to explore and develop selective adsorbents to remove phenols and thiophenols from wine, reducing the sensory impact of smoke taint. Adsorbent materials like resins, zeolites, and molecularly imprinted polymers (MIPs) are being considered for their potential to target and eliminate smoke compounds from wine.

Objectives

- Investigate and develop selective adsorbents for removing phenolic compounds.

- Assess the specificity and effectiveness of different adsorbents for various phenols.

- Develop scalable and economically viable adsorbent solutions.

Research Aim 3: Develop Biological Phenol/Thiophenol Degradation Technologies

Overview

This aim focuses on developing microbial or enzymatic technologies that can break down phenols and thiophenols in wine, providing a biological solution to smoke taint. These technologies would help to degrade the compounds responsible for the undesirable flavors and aromas associated with smoke exposure.

Objectives

- Develop microbial or enzymatic solutions for degrading phenolic compounds in wine.

- Explore genetic engineering approaches, such as using engineered yeast, to enhance degradation efficiency.

- Assess the scalability and consumer acceptance of such technologies.

Conclusion

The growing impact of wildfire smoke on viticulture necessitates comprehensive research and collaboration to mitigate its detrimental effects on grape and wine quality. While much has been achieved in understanding the chemical compounds responsible for smoke taint, such as volatile phenols, thiophenols, and glycosylated markers, there remain significant knowledge gaps. The sensory thresholds of these compounds in grapes and wine, especially regarding their impact on the final product, are not fully established. Further research is required to develop a more precise understanding of how different grape varieties respond to smoke exposure and the exact chemical markers that lead to undesirable flavors in wine.

A crucial area of focus is the development of reliable, standardized methods for detecting and monitoring smoke exposure. The advancement of analytical tools, such as liquid and gas

chromatography, alongside the creation of rapid and cost-effective screening technologies, will enable growers and winemakers to assess smoke contamination early, allowing for informed decisions about harvesting and wine processing. Standardizing testing methods and establishing clear thresholds for smoke taint are essential to ensuring that risk assessments are consistent across the industry, enabling timely and effective interventions.

Additionally, research into the prevention and mitigation of smoke taint in vineyards and wineries is imperative. Current efforts, such as the development of barrier sprays and smoke-resistant grape cultivars, face challenges that require deeper investigation. Understanding how smoke compounds bind to grape skins and how environmental conditions affect the absorption and movement of these compounds is crucial for designing more effective prevention strategies. Furthermore, advancing mitigation techniques in the winery, including the use of selective adsorbents and enzymatic degradation technologies, will be key to minimizing the sensory impact of smoke exposure on wine quality.

Atmospheric modeling also plays a significant role in predicting and managing smoke exposure. Improved models that integrate environmental factors, real-time sensor data, and detailed chemical tracking will help growers anticipate smoke events and understand their potential impact on grape quality. By combining predictive modeling with early detection systems and sound vineyard management practices, the wine industry can better prepare for wildfire seasons and safeguard against smoke taint.

Ultimately, collaboration between researchers, winemakers, and grape growers, along with a concerted effort to standardize protocols, will enhance the industry's ability to adapt to the increasing risks posed by wildfire smoke. By establishing robust databases, refining detection methods, and exploring new prevention and mitigation strategies, the grape and wine sector can build resilience against smoke taint, ensuring sustainable wine production in fire-prone regions for the future.