Grapevine Smoke Exposure

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Grapevine smoke exposure and the subsequent development of smoke taint in wine has resulted in significant financial losses for grape growers and winemakers throughout the world. Smoke taint is characterized by objectional smoky aromas such as "ashy", "burning rubber", and "smoked meats", resulting in wine that is unpalatable and hence unprofitable.

Keywords: smoke taint ; Grapevine

1. Introduction

Bushfires are a common occurrence globally, in places such as Australia, South Africa, Mediterranean Europe, and North and South America [1][2][3][4][5][6]. Unfortunately, climate change effects, such as increases in temperature, winds, and drought, have led to more favorable bushfire conditions [7][8][9][10][11][12][13]. Recent climate research predicts an increase of 15–70% in the number of days of "very high" or "extreme" fire danger by 2050 and a lengthening of the fire season, resulting in more frequent and intense bushfires [12][13][14][15][16].

Many vineyards are located in regions characterized by Mediterranean-type environments with long, hot, dry summers and where both planned controlled burns and unplanned bushfires are prevalent [17][18][19][20]. While fires may damage vineyards directly, there is also significant indirect damage caused by smoke drifting into vineyards resulting in grapevine smoke exposure [19]. Grapevine smoke exposure alters the chemical composition of grape berries, and the resulting wine produced is characterized by off-putting smoky aromas such as "burnt wood", "ashy", "burning rubber", and "smoked meat" [1][21][22][23]. These smoky characteristics have been attributed to various volatile phenols present in smoke, including guaiacol, 4-methylguaiacol, syringols, and cresols [1][4]. While some of these compounds may be produced naturally in some grapevine cultivars, elevated levels result in objectional smoky-related aromas [3][24][25][26][27]. Unfortunately, the most sensitive period for grapevine smoke exposure also corresponds with the highest risk of bushfires occurring, and with the number of bushfires predicted to rise, the incidence of grapevine smoke exposure and smoke taint development in wine will also most likely increase [28].

Aroma is an important characteristic for wine quality assessment; hence, grapevine smoke exposure and the resulting smoky aromas and flavors associated with smoke taint in wine have led to considerable economic losses due to both discarded fruit that may be contaminated and unsold wine [3][26][29][30]. The financial impact of smoke exposure is estimated by the percentage of grapes and/or wine damaged by smoke, which is influenced by several factors such as the vineyard's distance to the fire and prevalent wind direction [31]. It is estimated that the 2006/2007 bushfires in Victoria resulted in approximately AUD 75–90 billion in lost revenue, and the 2009 Black Saturday bushfires resulted in a loss of approximately AUD 300 million to the local wine industry [19][30][32]. Furthermore, the 2019/2020 bushfires in eastern Australia have been estimated to have cost the wine industry AUD 40 million due to smoke taint, burnt vineyards, and lost sales [33]. Thus, grapevine smoke contamination and smoke taint in wine is a significant economic problem.

2. Effect of Smoke Exposure on Vine Physiology and Fruit Production, and Carry-Over of Smoke Compounds to Following Years

While smoke exposure on plant physiology and growth is not completely understood, comparisons can be made with studies on the effects of air pollutants as many of the chemicals present in smoke are also components of air pollution [21][34]. Smoke contains a complex mixture of gases, including SO_2, CO_2, NO_2, and O_3, which have been shown to inhibit photosynthesis and cause leaf necrosis [21][35][36]. Looking at a mixture of three evergreen and three deciduous conifer tree varieties, Calder et al. [36] found that photosynthesis was reduced by more than 50% following a twenty-minute smoke exposure in five of the six conifer species studied. Evergreen conifers were found to recover faster than deciduous varieties, and no long-term changes were observed in seedling growth or leaf chemistry. Smoke was thought to reduce photosynthetic capacity by reducing stomatal conductance (g_s) and impairing biochemical function. In a similar study, the

g_s CO_2 assimilation rate and intercellular CO_2 levels of Chrysanthemoides monilifera were significantly reduced for 5 h following 1 min smoke exposure [37]. Grapevines are reported to be tolerant to several stressors such as drought, high atmospheric vapor pressure deficit, high irradiance, UV-B radiation, and high temperatures [21]. Consequently, their resilience may allow them to withstand short periods of smoke exposure without damaging leaf function [21]. Bell, Stephens, and Moritz [21] found that short periods of smoke exposure to Cabernet Franc, Cabernet Sauvignon, Chardonnay, Durif, Pinot Noir, and Syrah grapevine cultivars had only short-term physiological effects on leaf functioning. All cultivars returned to pre-smoke levels of photosynthesis, g_s, and transpiration within 48 h.

In other research, Kennison et al. [34] found that exposure to smoke resulted in reduced yields. In the smoke exposure season (year 1), grapevines exposed to smoke produced an average of 11 kg of fruit per vine, compared to control vines, which produced an average of 15 kg per vine. In the following season (i.e., year 2), no further smoke exposure occurred; however, yields in grapevines originally exposed to smoke yielded approximately 6.4 kg less fruit than control. The reduced fruit yield in the year following smoke exposure was thought to result from reduced photosynthetic capacity [34]. In a previous study, Kennison et al. [38] found that smoke exposure reduced sugar accumulation in berries and caused necrotic lesions in leaves, which reduced the photosynthetically active leaf area. It was proposed that smoke exposure led to a reduction in photosynthetic capacity, which inhibits berry maturation and ripening [38]. Therefore, the reduction in fruit yield may result from altered physiological functioning in the grapevine brought about by smoke exposure [34].

Conversely, Ristic et al. [39] found few significant differences in berry growth, maturation, and yield between control and smoke-exposed grapevines. Smoke was applied to seven different grapevine cultivars (Chardonnay, Sauvignon Blanc, Pinot Gris, Pinot Noir, Shiraz, Cabernet Sauvignon, and Merlot) for 1 h at approximately 7 days post-veraison. Measurements were then conducted to assess the effects on yield, vegetative growth, and vine physiology. Yield was not affected by smoke exposure, and few significant differences were observed between control and smoke-exposed grapes for berry weight and sugar accumulation. Only Shiraz and Pinot Noir grapevines exposed to smoke had lower TSS than control [39]. One factor that did appear to be affected by smoke exposure was stomatal conductance, and responses varied for the different grape varieties [39]. Cabernet Sauvignon, Merlot, Shiraz, Pinot Noir, and Chardonnay displayed significant reductions in g_s immediately after smoke exposure. Except in Pinot Noir, the initial reduction in g_s was close to 50% of the controls. There was also variation in the time it took the g_s for each grapevine variety to recover. Pinot Noir grapevines recovered the fastest, followed by Chardonnay (within 1–3 days), Shiraz (<6 days), Cabernet Sauvignon (6–10 days), and finally Merlot, which was the most sensitive and took the longest to recover (10–15 days). While Shiraz grapevines regained stomatal control after 6 days, measurements taken 17 days later demonstrated that g_s was higher in smoked vines than control. This variation in response may be due to Shiraz vines’ anisohydric behavior, which allows them to be less responsive to environmental changes [39]. Furthermore, Sauvignon Blanc and Pinot Gris appeared to be unaffected by smoke exposure.

It was not surprising that there was variation in g_s between grapevine varieties following smoke exposure, as previous studies have also found varietal differences in response to other stressors such as heat stress and/or water deficit [39][40][41]. Calder et al. (2010) also found differences in g_s recovery time between conifer species following smoke exposure and noted that plant species could develop tolerance to pollutants that affect photosynthesis. Different plant species may employ various fire resistance strategies and develop tolerance mechanisms to avoid smoke exposure’s detrimental effects [36]. Fuel type may also influence the physiological response of grapevines to smoke [21]. As smoke composition can differ depending on the fuel sources present, the varying emissions produced may result in different leaf-level responses amongst plants [21]. Bell, Stephens, and Moritz (2013) found grapevines were more sensitive to smoke generated from burning leaf litter from Coast Live Oak compared with Tasmanian Bluegum. This research only used single fuel types; however, results may vary if a mixture of fuel sources are used as occurs in bushfires [21]. Furthermore, the duration of smoke exposure, the concentration of smoke components, and other plant stressors such as nutrient status, drought, and high temperatures may also affect the physiological response and recovery of grapevines following smoke exposure [21][42]. For example, research by Summerson et al. [5] found that the intensity of smoke exposure affected the extent of stomatal closure and hence g_s in Cabernet Sauvignon grapevines. Further studies should, therefore, take all variables into account [21].

Smoke taint compounds do not appear to carry over to the following season [32][43]. Grapevines repeatedly exposed to smoke in one year have been shown not to carry over volatile phenols and their metabolites into subsequent years, when no further smoke exposure occurred [43][34].

3. Conclusions

Smoke contains a complex mixture of gases and volatile phenols that may affect grape berries' chemical composition and result in smoke-tainted wine. Uptake of smoke-derived volatile phenols may occur through grapevine leaves and berries, with the most sensitive period for berry uptake occurring between 7 days post-veraison and harvest. These volatile phenols are rapidly glycosylated and stored primarily in the skins of grape berries and the pulp. Traditional methods for smoke taint analysis are time-consuming, destructive, and require trained personnel to conduct them. Significant research into the use of spectroscopic techniques coupled with machine learning (ML) based on artificial neural networks (ANN) has been conducted to offer rapid, accurate, and non-destructive tools that can be used in-field to assess for grapevine smoke contamination and provide insight into the levels of volatile phenols and their glycoconjugates in grapes and wine. In addition to this, the use of e-noses has demonstrated promising results for smoke taint detection in wine and berries. These techniques may allow growers and winemakers to make timely decisions around berry sampling, winemaking practices such as reducing skin contact time during fermentation and potentially applying smoke taint mitigation techniques such as activated carbon treatment. Further research is required to assess the accuracy of ANNs developed on different grape and wine varieties as well as different winemaking techniques such as different yeast strains and fermentation time on skins and the use of other ML techniques to assess whether they provide more accurate results than ANNs.

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