OENO One
VINE AND WINE
OPEN ACCESS JOURNAL
By IVES International Viticulture & Enology Society

DOI: https://doi.org/10.20870/oeno-one.2023.57.2.7261

OPEN ACCESS

ORIGINAL RESEARCH ARTICLE

Consumer response to wine made from smoke-affected grapes

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Associate editor:
Maurizio Ugliano

Received:
16 November 2022

Accepted:
26 May 2023

Published:
16 June 2023

ABSTRACT

When vineyards and grapes are exposed to smoke from wildfires or controlled burns, this can result in wines with smoky, burnt or ashy attributes that have been linked to the presence of elevated concentrations of volatile phenols and phenolic glycosides. These smoky flavours are considered undesirable by winemakers, but there is little information about how consumers respond to smoke-affected wines.

To investigate whether consumers respond negatively to smoky attributes when wine is tasted blind, three studies assessing sets of Pinot noir rosé, Chardonnay and unoaked Shiraz wines with varied smoke flavour were conducted. Overall, wines rated high in smoke flavour were less liked compared to non-smoke-affected wines. Independent of wine type, there was a strong negative correlation between smoky flavour and overall consumer liking. Detailed data analysis revealed that consumers who are wine drinkers fell into one of three categories: highly responsive to smoke, moderately responsive, or a smaller group of non-responders.

This consumer-based information is essential for guiding the assessment of risk from smoke exposure of grapes and potential for quality defects in wine, as well as identifying and benchmarking management options for wine producers, not only in Australia, but globally.

KEYWORDS: wine, grape, smoke flavour, consumer liking

INTRODUCTION

The increasing frequency of wildfires and total area burned globally, has been linked to climate change as the main driver (Canadell *et al*., 2021; Richardson *et al*., 2022). Wine produced from grapes in vineyards exposed to smoke from nearby grass or forest fires can exhibit strong smoky aromas and flavours due to orthonasal and retronasal smoky odours (Parker *et al*., 2012). Commonly referred to as 'smoke taint', these characters are considered highly undesirable by winemakers. The losses to the Australian wine sector due to smoke from wildfires and prescribed burns have been estimated at $1.4 billion AUD since 2003 (Krstic *et al*., 2021). The issue is also a challenge for the global wine industry and has caused significant quality defects and economic impacts in recent years throughout Europe, California and South America (Mirabelli-Montan *et al*., 2021).

There are a broad range of descriptors attributed to smoke taint in wine, such as smoky, medicinal, campfire ash, plastic and burnt aromas; and ash tray, drying and bitter and a lingering ashy aftertaste on palate (Krstic *et al*., 2015; Parker *et al*., 2012; Ristic *et al*., 2011). Some smoky flavour can also be found in wines that have not been exposed to smoke, due to other processing and maturation steps, notably the use of oak barrels that have been toasted or charred using a flame (Francis and Williamson, 2015; Koussissi *et al*., 2009; Prida and Chatonnet, 2010). Toasted oak can impart volatile phenols to a wine, particularly guaiacol, 4-methylguaiacol, and syringol (Chatonnet *et al*., 1999), which are produced during oak toasting from the same lignin degradation process that occurs when wood smoke is generated (Pollnitz *et al*., 2004; Spillman *et al*., 2004). Other common wine flavours that can be present in non-smoke-affected wines and can be confused with smoke taint have been described as medicinal, burnt rubber and leather, which are generally considered negative attributes (Lattey *et al*., 2010; Wedral *et al*., 2010).

The chemical basis for the smoky characters in wildfire smoke-affected wines is complex, with a large number of compounds implicated. The compounds most associated with smoke-affected wines are volatile phenols (originating from smoke) and phenolic glycosides (produced in grapes by the addition of sugar units to the volatile phenols). These volatile phenols impart smoky aroma and flavour, and include guaiacol, 4-methylguaiacol, *o*-cresol, *m*-cresol, *p*-cresol, syringol and 4-methylsyringol (Parker *et al*., 2012). A large number of phenolic glycosides have been identified in smoke exposed wines (Caffrey *et al*., 2019; Hayasaka *et al*., 2010), and routine markers for smoke exposure of grapes include syringol gentiobioside (SyGG), methylsyringol gentiobioside (MSyGG), phenol rutinoside (PhRG), guaiacol rutinoside (GuRG), cresol rutinosides (rutinosides of *o*-cresol, *m*-cresol and *p*-cresol) (CrRG), and methylguaiacol rutinoside (MGuRG) (Hayasaka *et al*., 2013). Beyond their role as biomarkers indicating smoke exposure, the phenolic glycosides can also contribute to the flavour and lingering aftertaste of smoke-affected wines, by releasing odorants in-mouth during consumption or during extended periods of storage (Mayr *et al*., 2014; Parker *et al*., 2020).

While the concentrations of volatile phenols and phenolic glycosides are regularly compared to concentrations found in non-smoke exposed wines to determine whether there is evidence of smoke exposure (Coulter *et al*., 2022), the exact relationship between chemical composition and concentration, and the intensity of smoky flavours in wine is complex (Parker *et al*., 2023). Highly smoke-affected grapes can result in wines with strong smoky flavours and high concentrations of volatile phenols and/or glycosides. For wine made from mildly smoke-affected grapes, smoky flavours are not always evident. A recent study based on over 60 unique smoke-affected Chardonnay, Pinot noir and Shiraz wines found that statistical models based on guaiacol, *o*-cresol, *m*-cresol, *p*-cresol, and some glycosides gave good predictions of smoke flavour intensity, with a slightly different optimal model for each cultivar (Parker *et al*., 2023). In the absence of robust chemical models for predicting smoky flavours in other cultivars and wine styles, sensory analysis remains a critical tool to determine whether a wine has quality defects or is acceptable.

To inform critical business decisions it is imperative that sensory assessment is carefully conducted using recognised protocols (Lawless and Heymann, 2010). However, sensory evaluation of potentially smoky wines is challenging: the response of individuals to smoke volatile compounds such as guaiacol is known to be variable, due to genotypic and phenotypic differences among individuals (Mainland *et al*., 2014). Previous work has shown a large degree of interindividual variation in sensitivity to guaiacol and also guaiacol glucoside (Parker *et al*., 2020). Many individuals perceive a long-lasting smoky sensation from guaiacol glucoside, when the glucoside is hydrolysed in the mouth, and the volatile odorant is released which is perceived retronasally (Parker *et al*., 2012; Mayr *et al*., 2014). The variation in response to phenolic glycosides was found to be related to volatile odour sensitivity rather than the ability to cleave volatile odorants from the precursors (Parker *et al*., 2020). Therefore, individuals who are sensitive to these volatile phenols and glycosides experience a lengthy smoky aftertaste, and as a consequence, carry-over effects are a concern in smoke sensory assessments (Fryer *et al*., 2021).

Very little is known about the levels of smoke aroma and flavour that are acceptable to consumers. For some off-flavours, such as cork taint (Prescott *et al*., 2005), consumer preference data has found that the presence of any degree of perceptible taint can be considered unacceptable. For other wine flavours where consumers respond negatively, such as oxidation, 'Brett', or sulfur characters, a low intensity as determined by a trained sensory panel can potentially have no effect on consumer acceptance (Francis and Williamson, 2015). A previous study assessing consumers' acceptance of guaiacol added to a Merlot wine found an addition of 25 µg/L lowered liking scores (although not significantly) compared to the score for the base wine, but 50 µg/L added resulted in a significantly lower liking response (Herderich *et al*., 2012).

In addition, cluster analysis indicated a relatively small group of consumers (30 %) responded negatively to the 25 µg/L addition. The sensory characters in wildfire smoke-affected wines are likely more complex, with other compounds involved and the potential for matrix effects (Parker *et al.*, 2012), and there is no research to our knowledge that has assessed the acceptance of smoke-affected wines by wine consumers.

For determining whether a wine may be unacceptable due to grapevine exposure to smoke from nearby fires, consumer liking data are required to complement the interpretation of trained sensory panel measures. If acceptability limits can be established with the help of consumer responses (Manzocco, 2016), trained panel results or potentially chemical analytical data can be used for better informed decision-making in the wine industry.

This study aimed to test whether consumers respond negatively to wines made from smoke-affected grapes, and if so to provide guidance regarding the level of wildfire smoke flavour that might be acceptable. As numerous volatile and non-volatile compounds can contribute to smoky flavour, sets of smoke-affected wines were used rather than chemical additions to a base wine. The first study involved red wines made under controlled conditions from grapes sourced from vineyards with varied degrees of wildfire smoke exposure. This experiment was complemented by studies with two heavily smoke-affected wines, a rosé and a white wine, blended with different proportions of an unaffected wine. A secondary aim of this research was to assess the applicability of a streamlined smoke-specific panel rating procedure in comparison to a full quantitative descriptive analysis (QDA) approach.

MATERIALS AND METHODS

1. Wines

1.1. Shiraz

Eight Adelaide Hills (South Australia) Shiraz wines from vintage 2020 were selected from a study investigating the chemical composition of wine after a single early season smoke event (Jiang *et al.*, 2022). Each of the wines were made in an identical fashion from vineyards with a different degree of smoke exposure during the grape ripening season, which resulted in a range of volatile phenol and phenolic glycoside concentrations as well as some variation in basic composition (Supplementary Table 1 and 2). The wines had a range of smoke flavour ratings, including control wines with low smoke flavour ratings produced from grapes with no known smoke exposure (SHZ A and SHZ B). Full details of the grape and wine composition and sensory ratings can be found in the referenced manuscript (Jiang *et al.*, 2022). Following trained panel sensory assessments, a subset of wines was selected for the consumer liking study.

1.2. Pinot noir rosé

Pinot noir grapes, on the vine before harvest, were exposed to wildfire smoke from the Huon Valley, Tasmania, forest fire in January 2019 were selected and processed into a rosé style juice in Tasmania then transferred to WIC winemaking services at the Hickinbotham Roseworthy Wine Science Laboratory in Adelaide, SA. Grape selection, processing and composition results are described in Culbert *et al*. (2021). Free run Pinot noir juice was made into rosé style wine using standard small-scale winemaking protocol. Wine was bottled into 375 mL bottles and stored at 15 °C for three months before sensory analysis.

A similar style commercial rosé wine from a region where no wildfires were present, sourced from the same vintage (bottled 2019 Pinot noir rosé, Adelaide Hills, South Australia) was selected after a preliminary sensory assessment of several candidate Pinot noir rosé wines, together with consideration of basic chemical composition as well as the concentration of smoke and oak-derived compounds (Supplementary Table 1 and 2).

The smoke-affected Pinot noir rosé was blended by volume with the non-smoke-affected rosé to make wines with different degrees of smoke aroma and flavour intensities as follows: 0 % smoke-affected wine (PNR 0 %); 6.25 % smoke-affected wine with 93.75 % unaffected wine (PNR 6.25 %), 12.5 % smoke-affected wine with 87.5 % unaffected wine (PNR 12.5 %), 25 % smoke-affected wine with 75 % unaffected wine (PNR 25 %), 50 % smoke-affected wine with 50 % unaffected wine (PNR 50 %) and 100 % smoke-affected wine (PNR 100 %). After the trained panel assessment, a subset of the blends were prepared for the consumer liking test (PNR 0 %, PNR 6.25 %, PNR 12.5 %, PNR 25 %, PNR 100 %). New bottles of both smoke-affected and non-smoke-affected were freshly opened for each day of the assessments, and fresh blends prepared immediately prior to assessment.

1.3. Chardonnay

A 2020 smoke-affected Chardonnay wine was made from grapes from North-East Victoria which had been exposed to smoke from fires while ripening on the vine before harvest during the 2019-2020 season. Grapes were frozen in Victoria to follow the biosecurity requirements and transferred to the WIC winery for the winemaking process. The winemaking followed the same protocol as for the Pinot noir rosé. For this study, the smoke-affected Chardonnay wine had an alcohol content of 15.2 % v/v (Supplementary Table 2), which is high compared to typical table wines. A non-smoke-affected Chardonnay of a similar style was sourced from the same vintage (2020 Chardonnay, Barossa Valley) after a preliminary sensory assessment of several candidate Chardonnay wines. The non-smoke-affected wine was selected with consideration of basic chemical composition as well as the concentration of smoke and oak related compounds (Supplementary Table 1), but for this study the wine selected had a lower alcohol concentration which was adjusted prior to presenting to the consumers as detailed below.

The blends were prepared to make wines with different degrees of smoke aroma and flavour intensities as follows: 0 % smoke-affected wine (CHA 0 %), 6.25 % smoke-affected wine with 93.75 % unaffected wine (CHA 6.25 %), 12.5 % smoke-affected wine with 87.5 % unaffected wine (CHA 12.5 %), 25 % smoke-affected wine with 75 % unaffected wine (CHA 25 %), 50 % smoke-affected wine with 50 % unaffected wine (CHA 50 %) and 100 % smoke-affected wine (CHA 100 %). Similar to the Pinot noir rosé, after the trained panel assessment, a subset of five samples was prepared for the consumer liking test (CHA 0 %, CHA 12.5 %, CHA 25 %, CHA 50 %, and CHA 100 %). On the day of the consumer test, 18 mL of food grade ethanol (Tarac Neutral grape spirit, ≥ 96 % v/v) was added to each bottle (750 mL) of the non-smoke-affected Chardonnay to achieve a similar final alcohol concentration, between 15.2 % and 15.5 % v/v for all treatments.

2. Trained panel assessments

2.1. Screening, selection and training

A large pool of screened, qualified and experienced assessors with previous experience in wine smoke sensory evaluation (n > 30) were additionally screened for their sensitivity to assess specific smoke compounds. The assessors, who were all AWRI staff members, were screened for their ability to perceive smoke flavour from phenolic glycosides (guaiacol glucoside and *m*-cresol glucoside) dissolved in MilliQ water, and correctly identified guaiacol glucoside and *m*-cresol glucoside at concentrations of 0.5 g/L by duplicate 3- alternative forced choice difference testing (3-AFC). For these difference tests, 2-minute breaks were imposed between each sample. All selected assessors correctly identified the glycoside sample in at least 75 % of the tests and provided comments indicating smoke related flavours.

Prior to formal sensory assessments, all panellists were extensively trained for smoke aroma and flavour in wine. A process of familiarisation of smoke aroma and flavour across different varieties was used during training. Examples of real smoke-affected wines, as well as mixtures of volatile compounds and reference standards were presented to the panel. From this, the panel came to a consensus for the definition of smoke aroma and flavour. Examples of other possible faults and taints in wines were also presented, to provide context and clarity to smoke characters and avoid confusion with other off-flavour compounds. All panellists also completed an informal smoke evaluation (as described below), under the same conditions that they would experience during formal evaluations, but the results and feedback were discussed immediately after the evaluations. Panellists were told which were the clean controls and which were smoke-affected samples, and then discussed any confusable attributes. The panellists were given individual performance feedback regarding their repeatability (standard deviation), agreement with the rest of the panel (distance from the panel mean) and ability to discriminate between the wines (one way ANOVA). These performance measures were calculated and given to panellists after every smoke study for ongoing evaluation, motivation and skill development.

From this ‘smoke sensitive’ group, smaller panels were convened to evaluate each of the wines sets, using a consistent cohort where possible, but with some changes between the panels due to availability of the panellists. The assessors (10 for the Shiraz set, 11 for the Pinot noir rosé set,8 for the Chardonnay and 12 for the Shiraz descriptive analysis) were then selected based on availability and performance on smoke attributes.

2.2. Quantitative Descriptive Analysis of Shiraz wines

A panel of twelve assessors (ten females, two males, average age of 53 years (SD = 8.2)) was convened to assess the Shiraz wines. All panellists were part of the Australian Wine Research Institute (AWRI) trained descriptive analysis panel with previous experience in wine sensory descriptive analysis (minimum 40 hours) in addition to their ability to perceive the phenolic glycosides mentioned above.

Generic descriptive analysis (Heymann *et al*., 2016) was used. Assessors attended three two-hour training sessions to determine appropriate descriptors for the set of wines. All the wines from the study were progressively used during training sessions to generate and refine appropriate descriptive attributes and definitions through a consensus-based approach. In the second session, standards for aroma, taste and mouthfeel attributes were presented and discussed and these standards were also available during the subsequent training sessions, the booth practice session and the formal assessment sessions. As a warmup exercise, assessors revisited these aroma and palate standards at the beginning of each formal assessment session.

Following the third training session, assessors participated in a practice session in the sensory booths under the same conditions as those for the formal sessions. After the practice session, any terms which needed adjustment were discussed and the final list consisted of 23 attributes. (Table 1). Samples were presented to panellists in 30 mL aliquots in 3-digit-coded, covered, ISO standard wine glasses at 22–24 °C, in isolated booths under daylight fluorescent lighting. Randomised presentation order was followed except in the practice sessions when there was a constant presentation order. All samples were expectorated. In the practice booth sessions, the assessors were presented with twelve wines across four trays, with three wines per tray. In the formal evaluation sessions, the eight Shiraz wines were presented to assessors in triplicate, in an incomplete Williams Latin Square random block design. In total, the assessors were presented with twenty-four wines, split across two days, with four trays of three wines presented on both days of formal sensory assessment.

The assessors were required to wait for one-minute before they could finalise the palate ratings for their assessments, to account for any lingering attributes and aftertastes. There was a forced two-minute rest between samples and filtered water was used for rinsing between samples. A minimum ten-minute rest was required between sets of three samples, during which the assessors left the booths. A new bottle was used for each of the presentation replicates.

The intensity of each attribute (listed in Table 1) was rated using an unstructured 15 cm line scale (0 to 10), with indented anchor points of 'low' and 'high' placed at 10 % and 90 %, respectively. All sensory data was collected by Compusense20 sensory evaluation software (Compusense Inc., Guelph, Canada).

2.3. Smoke Rating Panel (SRP) Assessment

The assessors rated smoke aroma (orthonasal assessment defined as any type of smoke aroma, including hickory smoke

TABLE 1. Shiraz QDA wine sensory attributes, definitions and composition of reference standards.

Attribute	Definition/Synonyms	Standard
Appearance		
Purple	The degree of purple colour intensity in the sample	
Opaque	The degree to which light cannot pass through the sample (colour intensity).	
Aroma		
Dark Fruit A	Intensity of the aroma of blackberries, blueberries and dark cherries	4 whole blueberries (Welch's) and 3 whole blackberries (Welch's)
Blackcurrant A	Intensity of the aroma of blackcurrant and Ribena	5 mL Blackcurrant syrup (Ribena) in 30 mL water
Red Fruit A	Intensity of the aroma of strawberry and raspberry	2 whole strawberries (Welch's)
Eucalypt A	Intensity of the aroma of eucalyptus leaves	20 μL 1,8-cineole at 1 g/L
Smoke A	Intensity of the aroma of smoke, burnt ash, smoked meats and Band-Aids.	70 μL Guaiacol at 605.3 mg/L, 20 μL o-cresol at 519 mg/L, 35 μL m-cresol at 238 mg/L and 21 μL p-cresol at 505 mg/L
Earthy A	Intensity of the aroma of dust and dry earth	10 g soil
Spices A	Intensity of the aroma of pepper and sweet spices: cinnamon, nutmeg and cloves	2 whole cloves (Masterfood's), < 0.01 g ground black pepper (Saxa) and < 0.01 g ground cinnamon (Masterfood's)
Jammy A	Intensity of the aroma of jam and cooked/dried fruits	10 g blackberry jam (Beerenberg) and 5 g satsuma plum jam (Beerenberg) in 50 mL water – not in wine
Vinegar A	Intensity of the aroma of vinegar and pickled vegetables	5 mL pickle juice/brine (Fehlbergs) and 2 mL white vinegar (Black and Gold)
Eggy/Drain A	Intensity of the aroma of rotten eggs and dirty drains	Std 1. 1 scrambled egg Std 2. 40 μL 2-mercaptoethanol at 2 % and a pinch of wood ash
Pungency	Intensity of the aroma and effect of alcohol	4 mL of 95 % food grade ethanol (Tarac Technologies)
Palate		
Overall Fruit F	Intensity of the overall fruit flavours	
Earthy F	Intensity of the flavour of dust and dry earth	
Smoke F	Intensity of the flavour of smoke, burnt ash, smoked meats and Band-Aids.	
Acidity	Intensity of acid taste in the mouth including aftertaste	1 g/L L-(+)-tartaric acid (Chem-Supply) in water
Astringency	The drying and mouth-puckering sensation in the mouth. Low = coating teeth; Medium = mouth coating & drying; High = puckering, lasting astringency	0.5 g/L aluminium sulfate (Ajax fine Chem Supply Pty Ltd in water
Hotness	The intensity of alcohol hotness perceived in the mouth, after expectoration and the associated burning sensation. Low = warm; High = hot, burning	10 % food grade alcohol (Tarac Technologies) in water
Bitterness	The intensity of bitter taste perceived in the mouth, or after expectoration	0.15 g/L quinine sulfate (Sigma Aldrich) in water
Viscosity	The perception of the body, weight or thickness of the wine in the mouth. Low = watery, thin mouth feel. High = oily, thick mouth feel	1.5 g/L carboxymethylcellulose sodium salt (Sigma Aldrich) in water

All wine standards were added to 100 mL of 2019 Winesmiths premium bag-in-box Shiraz (2L) unless otherwise noted. Aroma standards were sniffed, and palate standards were tasted.

or artificial smoke, phenolic, burnt aroma associated with ashes, ashtray, fire ash, including also medicinal, band aid), smoke flavour (in-mouth assessment defined as including bacon, smoked meat and ashy aftertaste), overall fruit aroma (orthonasal assessment defined as including red fruit, red berry, strawberry, raspberry and cherry for the Pinot noir rosé and Shiraz, and defined as any type of citrus fruit, stone fruit, and tropical fruits including pineapple for the Chardonnay) and overall fruit flavour (in-mouth assessment) for each of the three wine sets. A term of 'other' was available for both aroma and flavour to capture any additional noteworthy characteristics in the wines. The intensity of each attribute was rated using an unstructured 15 cm line scale (0 to 10), with indented anchor points of 'low' and 'high' placed at 10 % and 90 % respectively.

All wines were presented in duplicate, 30 mL aliquots, in 3-digit-coded, covered, ISO XL5 standard wine glasses at 22–24 °C, in isolated booths under colour-masking lighting, with randomised presentation order in a modified Williams Latin Square design generated by Compusense20 sensory evaluation software (Compusense Inc., Guelph, Canada). A minimum 30-second delay was enforced before assessors could finalise the palate ratings for their assessments, to account for any lingering attributes and aftertastes and then a 2-minute break was enforced between each wine do reduce carryover effects. Assessors were encouraged to rinse with water.

3. Consumer hedonic assessments

Following the trained panel evaluations, a subset of wines was selected for assessment by regular wine consumers. For each set, consumers (aged 18-65) were recruited using the selection criteria as detailed below and were not linked to any marketing or wine industry organisation. All testing was conducted in isolated sensory booths with spittoons and water provided, where consumers rated each wine within each respective study for overall liking on the nine-point hedonic scale from 'like extremely' to 'dislike extremely' (Peryam and Pilgrim, 1957). For each assessment, expectoration and rinsing with water between wines was encouraged. All wines were assessed under daylight-type lighting. Prior to each test, consumers were asked to complete an entrance questionnaire to obtain demographic information, and on completion, an exit survey exploring spending behaviour and attitudes to food and wine occasions. All consumers were required to provide informed consent prior to commencing the study and were reminded that their participation was voluntary, and they could withdraw from the study at any point. All consumers were compensated for their time with a gift voucher at the completion of each appointment. All wines were presented with balanced randomised presentation order as provided by Compusense20 (Compusense Inc., Guelph, Canada).

3.1 Shiraz

Consumers (n = 111, 54 % females, 18-60 years old) were recruited from the consumer database of the Australian Wine Research Institute and selected if they consumed 'red wine at least once per fortnight'. Testing was undertaken between 20 and 27 September 2021, in Adelaide, South Australia, with samples presented at 22–24 °C in 25 mL aliquots in 3-digit-coded ISO standard wine glasses. Participants were required to take a five-minute rest between each wine.

3.2. Pinot noir rosé

A central location test was conducted with eighty-two consumers (31 males, 51 females, 18-65 years old), recruited from the consumer database of the Australian Wine Research Institute on the basis of 'drinking rosé wine at least 1 to 2 times per year'. Testing took place between 16 to 19 December 2019 in Adelaide, South Australia. Wines were presented in black wine glasses (30 mL), at room temperature (22-24 °C) with minimum 2-minute break between samples.

3.3. Chardonnay

White wine consumers (n = 124, 52 % female, 18-65 years old) from Melbourne, Victoria were selected on the basis of 'drinking white wine at least once per week', recruited from a database of a professional recruitment company. All participants attended sessions at private research facilities between 29 June and 1 July 2021. Samples were presented chilled (3°-7° C), in 25 mL aliquots. Participants were required to take a five-minute rest between wines.

3.4. Data Analysis

The trained panel performance was assessed using Compusense20 software and R with the SensomineR (sensominer.free.fr/) and FactomineR (factominer.free.fr/) packages. The performance assessment included analysis of variance for the effect of assessor, wine and presentation replicate and their two-way interactions, degree of agreement with the panel mean, degree of discrimination across samples and the residual standard deviation of each assessor by attribute. All assessors were found to be performing to an acceptable standard according to values based on long standing measures developed over time.

The trained panel data were analysed by analysis of variance (ANOVA) using XLSTAT (Addinsoft, 2020, Paris, France). The effects of the wine, assessor, assessor by wine, presentation replicate, assessor by presentation replicate and wine by presentation replicate were assessed, treating assessor as a random effect. Following ANOVA, Fisher's least significant difference (LSD) value was calculated ($P = 0.05$) for the wine effect. An additional principal component analysis (PCA) was conducted for the QDA data of the means of the wines of the significant ($P < 0.05$) and close to significant ($P < 0.10$) attributes using XLSTAT.

For the consumer liking data, ANOVA was carried out using Minitab 20 (Minitab Inc., Sydney, NSW) and XLSTAT for each cultivar separately. The effects of the wine and assessor were assessed. Following ANOVA, Fisher's LSD value was calculated ($P = 0.05$) for the wine effect. Agglomerative Hierarchical Clustering (AHC) was run using Wards method in XLSTAT, and a one-way ANOVA model involving liking scores of the wines as a fixed factor was performed on the groups generated by AHC, with additional LSD on subsequent clusters. A correlation matrix was produced using XLSTAT for the Shiraz wines to determine if there were any other drivers of liking amongst the consumer clusters.

RESULTS

1. Shiraz wines

For the Shiraz sample set, a full QDA was completed. In addition, the QDA data were compared with results from SRP assessments. The QDA data demonstrated that thirteen attributes differed significantly among the eight wines (Supplementary Table 3). These were ‘opacity’, ‘purple’, ‘dark fruit aroma’, ‘blackcurrant aroma’, ‘eucalypt aroma’, ‘smoke aroma’, ‘spices aroma’, ‘eggy/drain (reductive) aroma’, ‘astringency’, ‘hotness’, ‘viscosity’, ‘overall fruit flavour’ and ‘smoke flavour’. Only ‘smoke flavour’ was significantly different for the presentation replicate effect. There were significant ($P < 0.05$) assessor-by-wine-interaction effects for several attributes (Supplementary Table 4).

The sensory attributes of the Shiraz wines that were significantly different were visualised using PCA, shown in Figure 1, with the mean data in Supplementary Table 3. The first two principal components explained 51.4 % and 31.5 % of the variance. The ‘smoke aroma’ and ‘smoke flavour’ attributes were closely correlated ($r = 0.93$, $P < 0.001$), with SHZ G and SHZ C wines rated highest in these attributes, situated in the bottom left quadrant of the PCA (Figure 1), and these wines were rated low in most other attributes, suggesting the ‘smoke flavour’ suppressed other aroma and flavour attributes. Conversely, the wines made from grapes grown from vineyards with no smoke exposure, SHZ A and SHZ B, were rated lowest in the smoky attributes, plotted in the top right quadrant of Figure 1. Wines SHZ A, SHZ B and SHZ D were highest in ‘dark fruit aroma’, with SHZ D and SHZ B and SHZ I high in ‘opacity’, ‘astringency’, ‘overall fruit flavour’ and ‘spices aroma’. SHZ K was rated moderately in smoke and most other attributes and was plotted towards the centre of the PCA. One wine, SHZ F, had relatively high smoke intensity, but was also high in ‘eggy/drain aroma’ (sulfur related off-odour), while SHZ I rated highly in ‘smoke aroma’ and ‘smoke flavour’ and notably high in ‘eucalypt aroma’, ‘blackcurrant aroma’ and ‘hotness (alcohol burn)’.

The SRP procedure also demonstrated that there were significant differences ($P < 0.001$) among the wines for each attribute: ‘overall fruit aroma’, ‘smoke aroma’, ‘overall fruit flavour’ and ‘smoke flavour’. SRP assessors were a significant source of variation ($P < 0.05$) for ‘overall fruit aroma’ and ‘overall fruit flavour’. Assessor-by-wine interaction was a significant source of variation for ‘smoke aroma’ ($P < 0.05$) and ‘overall fruit flavour’ ($P < 0.01$) (data not shown).

There was a strong correlation between the ‘smoke aroma’ and ‘smoke flavour’ ratings from the QDA assessment and the specific SRP procedure: ‘smoke aroma’ (QDA) vs ‘smoke

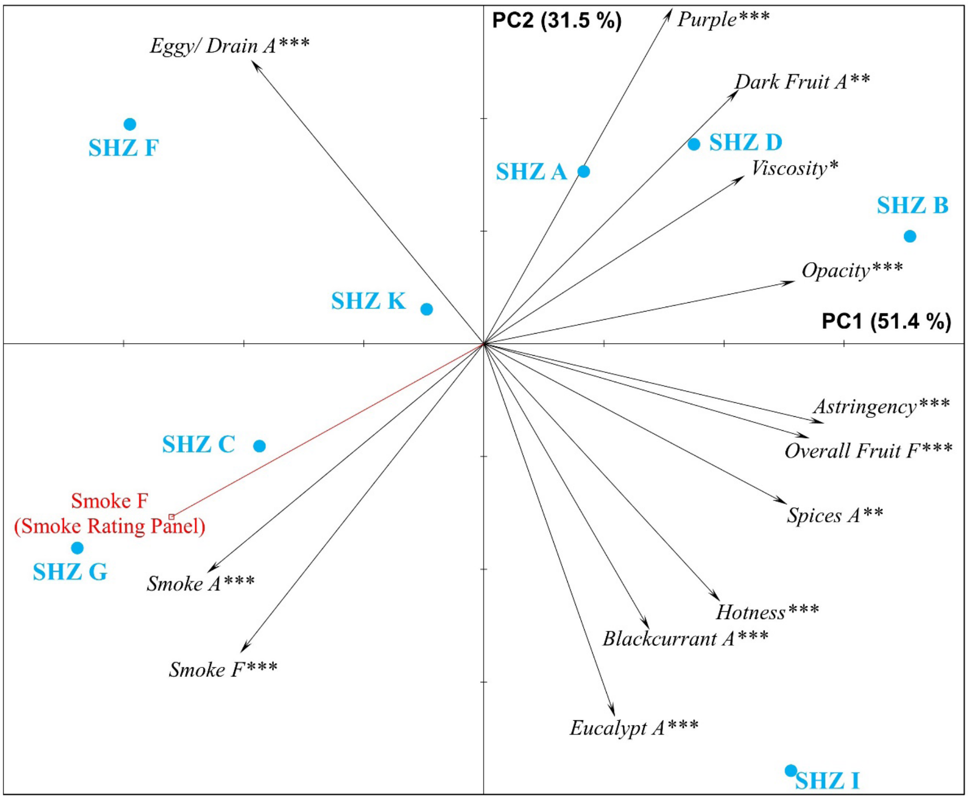

FIGURE 1. Principal Component (PC) biplots of significant sensory attribute means from the Shiraz wines for PC1 and PC2. Significance levels are as follows: * $P \leq 0.05$; ** $P \leq 0.01$; *** $P \leq 0.001$.

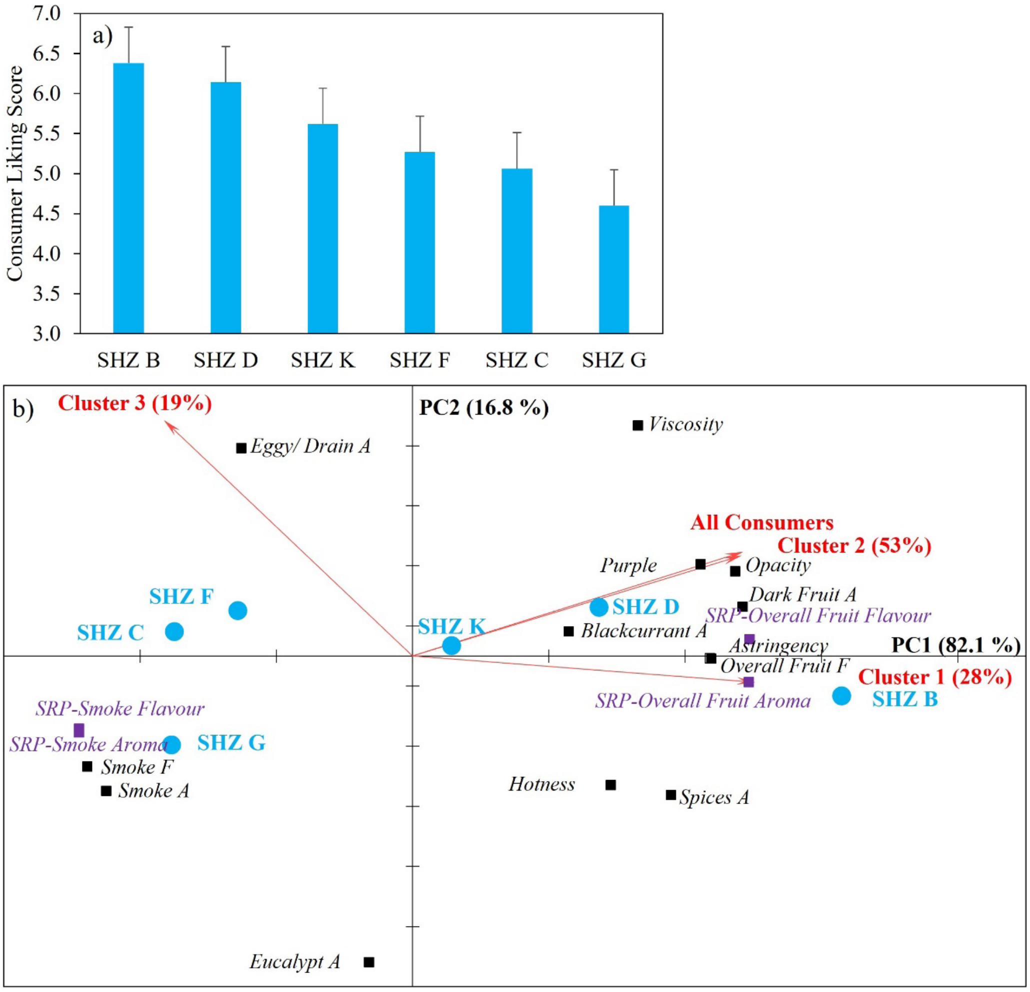

FIGURE 2. Consumer response to wines with various smoke exposed vineyards. (a) Consumer liking mean scores. (b) Shiraz Principal Component Analysis biplot of the mean liking scores of three identified clusters and the total sample shown as vectors. The six wines are shown in blue. The sensory attributes from the QDA are indicated in black, as well as the smoke rating assessment attributes shown in purple. PC = Principal Component, A = Aroma, F = Flavour, SRP = Smoke Rating Panel.

aroma' (SRP), $r = 0.97$ ($P < 0.001$); 'smoke flavour' (QDA) and 'smoke flavour' (SRP), $r = 0.91$ ($P < 0.01$), as illustrated in Figure 1 with smoke flavour ratings from the SRP plotted as a supplementary variable.

With both methodologies, SRP and QDA, the wines SHZ C, SHZ F, SHZ G, SHZ I, SHZ K were significantly higher ($P < 0.05$) in 'smoke flavour' than the control wines (SHZ A and SHZ B). The smoke-affected wines were rated low for 'overall fruit aroma' and 'overall fruit flavour' (Supplementary Table 5). Wines SHZ A and SHZ B were significantly different from one another for 'overall fruit aroma' and 'overall fruit flavour'. For both studies only the wines SHZ C, SHZ F, and SHZ G were significantly higher than the controls for 'smoke aroma'. As expected, the control wines had non-zero scores for smoke attributes for both studies, notwithstanding the extent of panel training. For the SRP methodology, wines SHZ A and SHZ B had relatively low 'smoke flavour' mean scores of 0.74 and 0.39 respectively, while for the QDA approach the values were 1.92 and 1.70.

To complement the expert panel sensory data, a subset of six Shiraz wines spanning the range of smoke flavour intensities from low to high was tasted by 111 red wine consumers, with the liking data shown in Figure 2a. Wines SHZ B and wine SHZ D, which were chosen as controls for the consumer study, were well accepted (as indicated by liking scores above 6.0), with all other wines rated significantly lower in liking. The least liked wine SHZ G (Figure 3a) had the highest 'smoke flavour' intensity (Supplementary Table 5) and the wines with smoke flavour rated above 1.95 from the SRP procedure were significantly less liked than the control wine.

Agglomerative hierarchical clustering analysis was performed to explore if clusters of consumers existed amongst the 111 participants. Three clusters were identified with significantly different liking scores ($P < 0.05$) within

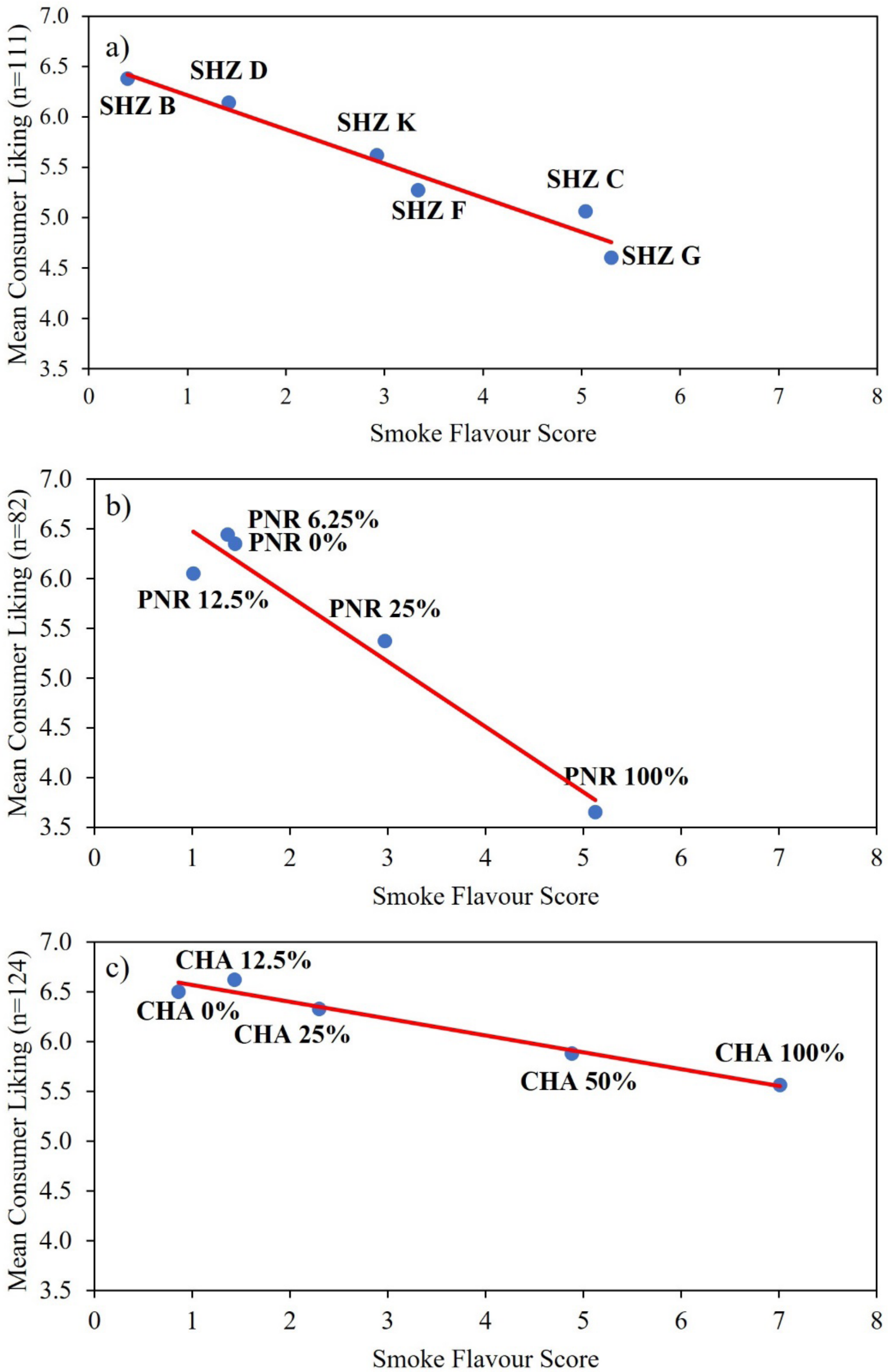

FIGURE 3. The relationship between the mean sensory smoke flavour intensity and the mean consumer liking for a) SH = Shiraz ($R^2 = 0.954^{**}$; $y = -0.34x + 6.55$), b) PNR = Pinot noir rosé ($R^2 = 0.945^{**}$; $y = -0.66x + 7.14$) and c) CHA = Chardonnay ($R^2 = 0.968^{**}$; $y = -0.17x + 6.74$). ** $P \leq 0.01$.

each cluster. The consumer liking data for each cluster and for the total consumer group tested was related to the sensory data by internal preference mapping (Figure 2b) using the mean liking scores of each cluster and of the total sample. The mean liking scores for the total consumer group were strongly negatively correlated with the intensity of the smoke attributes from the two procedures ($r < -0.96$). The total consumer group liking score versus ‘smoke flavour’ rating from the SRP methodology is presented in Figure 3a. The mean liking scores were significantly positively correlated with the QDA attributes ‘opacity’, ‘purple’, ‘dark fruit aroma’, ‘astringency’, ‘viscosity’ and ‘overall fruit flavour’ (r values from 0.81 – 0.96), and the SRP attributes ‘overall fruit aroma’ and ‘overall fruit flavour’ ($r = 0.99$).

Clusters 1 (28 % of consumer) and 2 (53 %) showed similar patterns of liking as the overall group of consumers

(Figure 2b and Supplementary Figure 1), with each showing a strong negative correlation with the smoke attributes (for example, cluster 1 mean scores vs smoky flavour, SRP, r = -0.92, P < 0.01) and strong positive correlation with the attribute 'dark fruit aroma' (r > 0.91, *P* < 0.05), with moderate correlations (r > 0.75, P < 0.1) of liking scores for 'opacity', 'purple', 'viscosity', and 'overall fruit flavour'. The responses of clusters 1 and 2 were similar, although cluster 1 liking scores were lower overall than those of cluster 2; the SHZ D wine was significantly less liked than the control wine SHZ B; and there were notably low liking scores of approximately 3.0 for SHZ F, SHZ C and SHZ G (Supplementary Figure 1). Cluster 3 (19 % of consumers) had a different pattern of liking compared to the other two clusters, with SHZ B, a control wine with no known history of smoke exposure, scored lowest. No strong correlations of the liking scores of this cluster were found for any of the sensory attributes. This was a small cluster, and there was a significant presentation order effect which might explain the differences in liking for this cluster compared to the others, with wines presented earlier generally receiving higher scores for liking, as reported previously (Hottenstein *et al*., 2008).

Consumers in Cluster 1 (28 % of consumers) showed significantly lower liking scores of each of the smoke exposed wines compared to the control wine (SHZ B), which was scored above 6.0, with all other wines having mean values less than 5.0. Wines SHZ C, SHZ F, SHZ G and SHZ K received similar low hedonic scores (below 4.0). Similar to the total group of consumers, the attributes 'opacity', 'dark fruit aroma', 'astringency' and 'overall fruit flavour', were positively correlated with liking for this cluster. 'Spices aroma' was also significantly positively correlated.

2. Pinot noir rosé

For the Pinot noir rosé wine set, all wines were assessed using the specific SRP methodology. There were significant differences (*P* < 0.05) among wine blends for the four attributes rated by the panel, namely 'overall fruit aroma', 'smoke aroma', 'overall fruit flavour' and 'smoke flavour' (Supplementary Table 5). The PNR 100 % smoke-affected wine, the PNR 50 % blend, and the PNR 25 % blend were rated significantly higher (*P* < 0.05) in 'smoke aroma' and 'smoke flavour' than PNR 0 % and were rated low for 'overall fruit aroma' and 'overall fruit flavour' (Supplementary Table 5). PNR 12.5 % and PNR 6.25 % were not rated significantly different from the unaffected PNR 0 % wine for any of the attributes. The PNR 6.25 % had slightly higher 'overall fruit aroma' and 'overall fruit flavour' scores than PNR 0 %, although not by a statistically significant margin. The 'smoke aroma' and 'smoke flavour' scores were highly correlated (r = 0.998, *P* < 0.001). As the PNR 50% wine had similar high smoke flavour rating to the 100 % blend, it was decided that this wine could be excluded from the consumer study to reduce number of samples presented to the consumers in attempt to avoid fatigue.

From the consumer test, the least liked wine was the PNR 100 % wine (Figure 3b). The blend of 25 % of the smoke-affected wine with 75 % of the unaffected PNR wine was liked significantly more than the PNR 100 % wine. There were similar liking scores for the PNR 0 %, PNR 6.25 % and PNR 12.5 % wine.

As observed for the Shiraz wines, the liking scores for PNR wines showed a strong negative linear relationship ($R^2 = 0.95$, P < 0.01) with the smoke flavour ratings. There was also a linear relationship between smoke flavour intensity and proportion of smoke-affected wine (Supplementary Figure 2). There was some evidence that clusters of consumers existed amongst the 82 participants in the PNR consumer study (Supplementary Figure 3). The data indicated that there was a group less accepting of smoke flavour, a moderately negatively responsive group and group of non-responders. Considering the relatively small number of consumers in each cluster, the PNR clustering data were not analysed in greater detail.

3. Chardonnay

For the smoky Chardonnay wine blended with increasing proportions of an unaffected Chardonnay, there were significant differences (*P* < 0.05) among the wines for 'smoke aroma', 'overall fruit flavour' and 'smoke flavour' (Supplementary Table 5). Assessors were a significant source of variation (*P* < 0.001) for 'overall fruit aroma' and 'overall fruit flavour'. Assessor-by-wine interaction was also a significant source of variation for 'overall fruit aroma' (*P* < 0.05) and 'smoke aroma' (*P* < 0.01) (data not shown).

The CHA 100 % smoke-affected wine was rated significantly higher (*P* < 0.05) in 'smoke aroma' and 'smoke flavour' than the CHA 0 % wine by the smoke rating panel and was lowest for 'overall fruit flavour' (Supplementary Table 5). The blend with 50 % smoke-affected wine was rated significantly higher than the unaffected wine for 'smoke aroma' and 'smoke flavour'. Wine CHA 25 % was significantly higher but only in 'smoke flavour' than the unaffected wine. The blends with less than 25 % smoke-affected wine had 'smoke flavour' ratings of 1.01 and 1.36 were not significantly different from the unaffected wine for any of the attributes. The unaffected wine had 'smoke aroma' and 'smoke flavour' values of 1.16 and 1.44 respectively. As observed for the Shiraz and Pinot noir rosé wines, the 'smoke aroma' and 'smoke flavour' attributes of Chardonnay wines were highly correlated (r = 0.97). As no difference was found between CHA 0 %, CHA 6.25 % and CHA 12.5 %, it was decided that CHA 6.25 % would be excluded from the consumer study to avoid fatiguing consumers and collecting superfluous data.

From the consumer test, the least liked Chardonnay wine was the smoke-affected wine, CHA 100 %, with the blend of 50 % of the smoke-affected wine also less liked than the unaffected wine (Figure 3c). There were similar liking scores for the CHA 0 % (0 % smoke-affected) wine, CHA 12.5 % and CHA 25 % wines. The liking scores showed a strong negative linear relationship ($R^2 = 0.97$, P < 0.01) with the smoke flavour rating. The Chardonnay wines with smoke flavour rated above 2.47 were significantly less liked than the control wine.

There was strong evidence that clusters of consumers existed amongst the 124 participants of the Chardonnay study. Cluster analysis identified three groups of consumers with significantly different liking scores ($P < 0.05$) within each of the clusters (Supplementary Figure 4). Cluster 1 (21 % of consumers) most liked the clean control wine, and this cluster had progressively lower liking scores for the wines blended with increasing proportion of smoke-affected wine. There was no significant difference between the CHA 0 % and CHA 12.5 % wines in liking by cluster 1, although CHA 25 % was liked significantly less than the clean wine. The CHA 50 % and CHA 100 % blends had very low liking scores.

For Cluster 2 (38 % of consumers) all the wines were well accepted (mean liking scores above 6.0) with only the CHA 100 % wine significantly less liked than the other wines. For the largest cluster (Cluster 3 – 40 % of consumers) there were no significant differences between any of the wines. This suggests that they were either not sensitive to the smoke flavour or accepted the characteristics it provided. Still, this cluster reported significantly lower purchase intent for the wines with a higher proportion of smoke-affected wine in the blended product (data not shown). As found with Pinot noir rosé, there was a linear relationship between smoke flavour intensity and proportion of smoke-affected Chardonnay wine, however the R^2 value was lower (Supplementary Figure 2).

DISCUSSION

The results clearly show that smoke flavour was a strong negative driver of consumer liking in all three wine styles. The Shiraz wine sample set, which comprised a range of wines all produced using the same winemaking procedure from grapes with varied exposure to smoke from nearby forest fires, were evaluated using a QDA approach and a specific smoke rating methodology. The smoke attribute results were very similar with both methodologies. The correlation between the SRP data and the QDA panel's smoke aroma and flavour ratings was very strong ($r > 0.94$), which is not surprising considering both panels were selected based on successful smoke sensitivity screening procedures and had received training prior to formal evaluations. There were lower mean ratings for the controls from the specific SRP method, indicating fewer 'false positive' non-zero scores given by assessors for unaffected wines compared to a generic QDA panel approach. It is expected that even with a highly trained, screened and experienced sensory panel, 'false-positives' can occur. This can be due to an expectation effect by the assessors (Meilgaard *et al*., 2016), and the presence of confusable characters in the wines. To effectively allow an assessment of the magnitude of a smoke rating that can be considered significant in industrial application, an unaffected control wine should always be included in the sample set. Overall, the time required for one SRP assessment (2 hours total) compared very favourably to that required for one QDA (12 hours), given the almost identical results.

Both the SRP assessments and QDA (with smoke sensitive assessors) for the Shiraz wines showed very strong predictive ability when comparing consumer liking to smoke flavour intensity ratings from trained expert panels. As smoke aroma and smoke flavour were highly correlated in each study, but smoke flavour showed greater discrimination, it was a better overall predictor of consumer liking. The results of the QDA indicated that wines with smoke aroma and flavour were less intense in fruity attributes such as dark fruit or blackcurrant, suggesting a suppressive effect of the smoke flavour as previously indicated (Parker *et al*., 2012).

Consumer liking was highly negatively correlated with smoke flavour intensity for each wine type (Figure 1), independent of the varietal, winemaking and matrix differences between Shiraz red wines, Pinot noir rosé wines and Chardonnay white wines. The mean smoke flavour score that significantly affected consumer liking was different between the three different wine styles, with different slopes of the regression fitted lines across the wine types. This suggests the involvement of matrix effects influencing the absolute magnitude of the smoke flavour rating and therefore consumer liking. The Chardonnay wine set had the shallowest slope, with CHA 100 % affected wine receiving a mean smoke flavour rating of approximately 5.1 on the 10-point scale and a relatively high liking score of 6.5. In contrast, in the Shiraz and Pinot noir rosé sets, the wines rated highest for smoke flavour intensity had liking scores well below 5.0. Higher smoke flavour was thus tolerated in the Chardonnay, possibly because 'toasty/oaky' and 'struck-flint' characters are generally well liked and accepted as part of this wine style (Iland *et al*., 2017), which may be confusable for most consumers.

While a relatively small number of consumers were used in these studies, evidence of clusters of consumers were found for each wine type: a more responsive group of consumers (21-46 %), a moderately responsive group that closely mimicked the total group (33-53 %), and a group that were not responding to smoke flavour (19-40 %). The size of each of these clusters was different between each consumer group and wine style, but the same classifications were found each time.

Blending a heavily smoke-affected wine with a 'clean' wine using a dilution-to-threshold approach was used partly to expand the study, as obtaining a range of smoke-affected grape lots can be difficult given the unpredictable nature of wildfires. The approach also allowed assessment of critical levels of smoke flavour intensity with fewer confounding variables. The approach has the drawback that it is difficult to definitively exclude other confounding sensory attributes that might have contributed to differences in consumer preferences in the blends. The different blends obtained can be considered separate wines with increasing smoke aroma and flavour, but with other possible sensory differences. In this study, careful consideration was applied to select for dilution appropriate 'clean' wines with similar basic chemical composition. The observed linear negative liking response with increasing smoke flavour ratings for each of the three wine sets studied provides reassurance that the smoke flavour caused the negative consumer response, independent of wine style.

Across all three studies, non-zero ratings were observed for the ‘clean’ control wines in the smoke rating SRP and QDA assessments. Smoke flavour values for control wines ranged from 0.74 to 1.92, and we assume that these smoke flavour ratings in ‘clean’ wines reflect their typical wine composition and are not due to experimental artifacts from carry-over effects. For both methods, enforced resting periods were used to allow a) enough time for the flavour to develop and b) avoidance of carryover effects due to long lasting smoky aftertaste, which have been problematic in smoke wine assessments (Fryer *et al*., 2021; Oberholster *et al*., 2022). Both panels had a 2-minute break between samples, and in the SRP assessments, flavour attributes were rated after 30 seconds to ensure that there was sufficient time to allow the flavour to be perceived, rather than for the perception of smoke to be perceived in the break between samples.

One benefit that the SRP methodology has over conventional QDA is the potential to be a much faster and more economical way to assess the risk of smoke taint for industry. Provided robust screening and training procedures are implemented, the SRP process would be a better option for industry to adopt, as sessions can be implemented more rapidly. This methodology was tested with a regional winemaker panel, with good agreement with the results with the data obtained in this study (r = 0.98) and could be adopted more broadly by wine companies or regional organisations (data not shown).

The main benefit of the QDA assessment over the SRP assessment is that the whole range of appearance, aroma and palate attributes is measured, which allows deeper insight into the influence of masking and enhancing sensory characteristics across the wines. The QDA results revealed interactions of smoke aroma and flavour with other elements in the wine, such as alcohol heat, acidity, sweetness and other attributes that can play a role in the intensity of smoke flavour.

An interesting sample was SHZ I, which contained high concentrations of smoke marker compounds, but received moderate ‘smoke aroma’ and ‘smoke flavour’ scores by panellists, both for the QDA and SRP. The QDA revealed that this wine had a ‘eucalyptus aroma’, ‘blackcurrant aroma’ and was high in ‘hotness (alcohol burn)’, which potentially could be suppressing the smoke aroma and flavour in the wine. The SHZ I wine was found to contain a high concentration of the eucalyptus/minty compound 1,8-cineole (19.8 µg/L, well above its sensory threshold of 1.1 µg/L (Herve et al., 2003)), the blackcurrant-like compound dimethyl sulfide, (21.2 µg/L, which has a sensory threshold of 1.74 µg/L) (Lytra *et al*., 2014) and was high in alcohol (16.5 % v/v). More research is warranted to establish and better understand masking effects in wine, which might provide an approach to guide selection of particularly suitable blending wines.

Depending on the commercial considerations of individual wine producers, some companies might prefer not to risk releasing any even slightly smoke-affected products to the market, given the strong relationship between smoke aroma and flavour score, and reduced consumer acceptance. Others may make use of the results of this study to develop a guide regarding limits of smoke flavour above which consumer acceptance is significantly reduced, such as described in Hough *et al*. (2002). Further wine styles will need to be investigated to assess whether the results obtained in this study are applicable more generally. Also, sensory assessment and predictive modelling of combinations of smoke-related compounds need to be established to determine the size of the risk that winemakers and producers will face when smoke events occur. The chemical composition of smoke-affected wines and the relationships with wine flavour are discussed in detail in a separate accompanying manuscript (Parker *et al*., 2023). Reconstitution experiments will need to be specific for individual wine cultivars and winemaking practices. Until then, robust sensory of wine and chemical measures of smoke exposure markers are necessary to identify and gauge a potential risk of quality defects after smoke exposure of vineyards.

CONCLUSION

From all three studies, it is clear that consumers respond negatively to smoke flavour in wine that is caused by vineyard exposure to wildfires and smoke events. The sensitivity of consumers to smoke-affected wines correlated highly with smoke flavour ratings from a screened and trained smoke sensitive panel. While the overall group of consumers in each study showed a strong negative correlation between liking and smoke flavour, there were clusters of consumers that were more sensitive to these characters.

The response to smoke flavour was variable across the different wine styles. However, the wines that showed a negative response from consumers all had concentrations of smoke marker compounds lower than that of the reported sensory thresholds for all individual compounds. With a maximum acceptable concentration of smoke marker compounds not currently known, it will be crucial for the wine industry to incorporate both sensory and chemical analysis for making decisions post-smoke events. Research investigating the way in which these phenolic (and potentially other) flavour compounds interact with one another, and the complexity of the background matrix of the grape cultivars and wine styles, will also be important in solving this issue. Overall, the information from the present study will enable grape-growers and winemakers to make better informed business decisions about reducing or eliminating potential quality defects after smoke events.

FUNDING

This work was performed by the AWRI, a member of the Wine Innovation Cluster in Adelaide, South Australia. Funding was provided by Australian grapegrowers and winemakers through their investment body Wine Australia, with matching funds from the Australian Government. Additional funding and in-kind contributions from PIRSA, the South Australian, Victorian and NSW State Governments, Wine Victoria and NSW Wine, and the Australian Government's Department of Agriculture and Water Resources Rural R&D for Profit program are gratefully acknowledged. External funders were not involved in the study design, collection of data, analysis and interpretation of data, writing the report, or the decision to submit the article for publication.

ACKNOWLEDGEMENTS

The authors would like to acknowledge Affinity Labs for analysis, Kantar Australia for screening consumers for the Chardonnay study, and use of their facilities in Melbourne, Peter Leske and the Adelaide Hills winemakers, and the AWRI sensory panellists for their smoke rating and descriptive evaluations. Additional thanks to Patricia Williamson, Desireé Likos, Damian Espinase Nandorfy, Sheridan Barter, Ella Robinson, Con Simos and Mark Krstic for their assistance. The authors would also like to thank the industry partners who provided access to vineyards and samples for analysis, and finally the numerous staff at the AWRI involved in smoke analysis.

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