Research Note

Effect of Different Crown Cap Closures on Phenolics and Sensory Attributes of Bottle-Fermented Sparkling Wines

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Accepted for publication: October 2025

Key words: Crown cap closures, sparkling wine, phenolics, sensory attributes

Bottle-fermented sparkling wines closed with crown caps of different O_2 permeabilities while ageing on the yeast lees were investigated for their effect on phenolics and sensory attributes. The crown caps were denoted as reference (least permeable), Crown++ (intermediate permeability) and Crown+ (most permeable) to oxygen. Total phenolics and physiochemical parameters were measured using a spectrophotometric technique and infrared spectrometry, respectively. Individual phenolics were quantified using an HPLC technique. Dissolved oxygen was not significantly different between Crown+ and Crown++ wines. Crown+ wines were approx. 2% higher in flavan-3-ols than Crown++ wines and flavonols were approx. 8% higher in Crown+ wines than Crown++ wines. Total phenolic acids were approx. 3% higher in Crown+ wines than Crown++ wines. Gallic, caftaric, and caffeic acids were not significantly different between Crown+ and Crown++ wines, whereas *p*-coumaric acid was reported to be approx. 6.6% higher in Crown+ wines. Reference wines were associated with short aftertaste, bruised apple, small bubbles, toasty, and more autolysis flavours. Crown+ wines were associated with few bubbles, balanced acidity, fruity, full-bodied, intense aroma, and yeasty, whereas Crown++ wines had varying associations with large and numerous bubbles, less autolysis, thin, shy nose, but persistent aftertaste. Differences in phenolic concentrations and sensory attributes could be ascribed to oxygen variability in the wines as a result of the different closures. Based on the sensory profile, it is concluded that the Crown+ wines had the most favourable sensory attributes and are therefore the most suitable closure for base wine after 43 months on the yeast lees. The use of more or less permeable crown caps during the production of bottle-fermented sparkling wines can be a tool for a desired sensory outcome.

INTRODUCTION

Bottle-fermented sparkling wine has a primary fermentation (first), followed by a second fermentation. In the first fermentation, the base wines are produced in the same manner as still wines, whereafter sugar and additional yeast are added and then bottled. The second fermentation occurs in the bottle which is followed by a mandatory minimum ageing period on the yeast lees. During the second fermentation and ageing, bottles are closed with a metal crown cap with a bidule. After ageing on the lees, the wine is clarified using the hand *remuage* or automated process before removal of the crown cap. The final bottle closure is the customary two-disc or agglomerated sparkling wine cork tied in place with a wire hood (*muselet*).

Crown caps are suitable closures for sparkling wines during production due to their impermeability to fluids but permeability to atmospheric oxygen (O_2) which can result in the polymerisation/degradation of grape derived phenolic compounds, i.e., mainly phenolic acids, anthocyanins, flavonols and flavan-3-ols (Danilewicz *et al*., 2008; Gambuti *et al*., 2013).

Wirth *et al.* (2010) and Guaita *et al.* (2013) reported that moderate exposure of wine to atmospheric O_2 through bottle closures during bottle ageing, resulted in improved mouthfeel (increase in flavan-3-ol concentrations). Oxidation (browning) can occur in sparkling wines during ageing, but bottle pressure because of the presence of carbon dioxide and closure permeability prevent excessive oxidation (Pons-Mercadé *et al.,* 2020). However, gas exchange does take place through the crown cap so that carbon dioxide can exit and O_2 can enter the bottle. During bottle ageing of sparkling

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Acknowledgements: Pieter Ferreira, Cellar Master, and Graham Beck Wines for donating the sparkling wines. Ms Genevieve Peterson and Ms Alicia Coetzee, The House of JC le Roux for the use of their CarboQC system. The Cap Classique Producers Association, the Agricultural Research Council and Winetech (now South Africa Wine) for infrastructure, support, and funding. The authors thank Mss Candice Februarie and Elana Pekeur for assisting in sample analysis

wine, O_2 ingress through the closure is dependent on the sealing effectiveness of the closures, which present different O_2 barrier properties (Furtado *et al.*, 2021). Therefore, post-bottling conditions can lead to the development of different wine characteristics, due to different bottle closure types, which are considered one of the most determinant factors in the process of wine ageing.

Phenolics are reactive compounds, which undergo oxidation, polymerization and degradation through both enzymatic and non-enzymatic reactions (Oliveira *et al.*, 2011; 2015). Wine exposure to O_2 involves a mechanism of induction of the transformation of phenolic compounds through enzymatic reactions (Petrozziello *et al.*, 2018). Enzymes responsible for the oxidation of phenolics are mainly laccase and peroxidase (Tarko *et al.*, 2020). Oxygen exposure also alters the structure of tannins by decreasing the proportion of acid-labile interflavan bonds (McRae *et al*., 2015).

The mechanism for non-enzymatic oxidation causes the depletion of monomeric phenolics, i.e., (+)-catechin, (−)-epicatechin, gallocatechin, gallic acid and their esters, and caffeic acid, among others (Danilewicz *et al.*, 2008) and oligomeric phenolic compounds, i.e., hydroxylation of the *ortho*-position adjacent to an existing hydroxyl group of the phenolic substrate (Oliveira *et al.,* 2015; Oliveira *et al.,* 2017). Over exposure of wine to O_2 can however negatively affect the sensory characteristics of sparkling wines. Crown cap manufacturers supply crown caps with variable levels of O_2 permeability which result in the rate of oxidation. However, limited independent data is available to support the manufacturer's claims.

The aim of this work was to investigate the effect of three different crown cap closures of varying O_2 permeability on sensory attributes and selected phenolics of bottle fermented sparkling wines obtained from a South African commercial wine cellar.

MATERIALS AND METHODS

Wine samples and treatments

Three batches (treatments) of bottle-fermented sparkling wines (seven bottles per batch) from the 2014 vintage (Chardonnay:Pinot noir 50:50 blend) undergoing ageing on yeast lees were sourced from a wine cellar in Robertson, South Africa. The three batches were produced from the same base wine (23.8 g/L sugar, 6.50 g/L total acidity, 10.75% alcohol) and sealed with three different crown cap closures with varying O_2 permeabilities (Table 1). Individual bottles within a batch were considered replicates.

The yeast used for the second fermentation was IOC 18-2007 (Lallemand, South Africa). The bottled sparkling wines were obtained for investigation after 43 months on the yeast lees. Five bottles of each batch were opened using a CBoxQC and SFD filling system (Anton Paar, Graz, Austria) that measured pressure, dissolved O_2 and dissolved CO_2 in a nitrogen gas environment. After opening, the wines were clarified and degassed by centrifugation at 11270 x *g* for 10 min. (Avanti, Beckman-Coulter, Johannesburg, South Africa). Three replicates of clarified wines were used for physicochemical, total phenolics and individual phenolics analysis. The remaining two bottles of each batch underwent mechanical *remuage*, disgorgement and recapping with the standard crown cap closures following standard sparkling wine production protocols (Jeandet *et al.,* 2011). Bottles were not topped up, but the ullages were the same height across all treatments and were therefore not considered a variable. These wines were kept at 15°C until required for sensory analyses.

Physicochemical parameters

Total acidity, alcohol, residual sugar and malic acid were measured in the clarified wines using infra-red spectroscopy (ALPHA II™ FTIR spectrometer, Bruker, South Africa). The ALPHA II™ FTIR spectrometer was calibrated with the manufacturer's supplied internal calibration supplemented with in-house generated data verified by wet chemical methods (Koelenhof Laboratory, Koelenhof Cellar, Stellenbosch, South Africa). Yeast assimilable nitrogen (YAN) was measured using the FORMOL titration method (South African Wine Laboratories Association [SAWLA], 2002).

Spectrophotometric analysis

Absorption spectroscopy was used to estimate total flavan-3-ols, flavonols and phenolic acids (Minnaar *et al.,* 2018). A UV-VIS Aurius Model CE2021 spectrophotometer (Cecil, Cambridge, UK) was used to determine the maximum wavelength absorbance for total phenolic acids (316 nm), total flavonols (360 nm) and total flavan-3-ols (279 nm) using *p*-coumaric acid, quercetin and (+)-catechin as reference standards (Merck KGaA, Darmstadt, Germany), respectively, in the wavelength scan program mode. Calibration curves were established using the reference standards to determine the concentrations in the matrix. Concentrations were expressed as mg quercetin equivalents

TABLE 1
Approximate theoretical O_2 and CO_2 transfer of the three crown cap closures used for bottled fermented sparkling wines during fermentation and ageing on yeast lees.

Closures[1]	Codes used	O_2 transmission (mg/L/year at 15°C)	CO_2 loss (cm^3/24h)
Solcap 80[2]	Reference	0.50	0.17
Solcap Scel++	Crown++	0.66	0.26
Solcap Scel+	Crown+	1.76	0.56

[1]Technical information and crown caps supplied by Africa Cellar Suppliers, Paarl, South Africa. [2]Crown cap normally used by the wine producer.

(mg QUE), mg *p*-coumaric acid equivalents (mg PCAE) and mg (+)-catechin equivalents (mg CAE)/L for total flavonols, total phenolic acids and total flavan-3-ols, respectively. The spectrophotometric technique used is non-specific, however, it does give an indication of the total phenolic status of a given sample.

Liquid chromatographic analysis

The quantification of individual phenolic acids was performed using an Agilent model 1260 high-performance liquid chromatographic (HPLC) system (Agilent Technologies, Santa Clara, California, USA). The system was equipped with an auto-sampler and a photodiode array detector. A polymer reversed-phase column (PLRP-S 100 Å, 5 µm, 250 x 4.6 mm) with polystyrene divinylbenzene as a stationary phase was used to separate the phenolic compounds (Varian, Polymer Laboratories, Palo Alto, California, USA). A gradient elution program was used for compound elution (Minnaar *et al.,* 2015). Eluent A consisted of water/phosphoric acid (985:15 v/v) with pH = 1.35, and eluent B consisted of water/phosphoric acid/acetonitrile (185:15:800 v/v/v) with pH = 1.25. The gradient elution phase programme was: 94% of eluent A initially at 0 min, 94% to 69% of eluent A at 73 min; 69% to 38% of eluent A at 78 min; 38% to 94% of eluent A at 90 min. The system was equilibrated for 20 min after each analysis to reach baseline conditions. The flow rate was 1 mL/min. Separation of the compounds was carried out at 25°C.

Wine samples (2 mL) were filtered through a 0.45 µm nylon membrane syringe filter. The injection volume was 50 µL. Replicate samples (n = 3) were analysed on the same day. Quantification was based on calibration curves of gallic, caffeic, caftaric, and *p*-coumaric acid reference standards (Merck [Pty] Ltd, Johannesburg, South Africa). Individual phenolic acids were quantified using peak areas at 316 nm. The identification of phenolic acids was confirmed by their relative retention times based on reference standards and UV-visible absorption spectra.

Sensory analysis

Sensory analysis was performed using a check-all-that-apply (CATA) method (Jaeger *et al.,* 2015; Alexi *et al.,* 2018). The CATA tasting sheet was compiled and described by Jolly *et al.* (2021) and 25 attributes were used in the evaluation. Small bubbles (S_bubbles), Large bubbles (L_bubbles), Few bubbles (< Bubbles), Many bubbles (> Bubbles), No collar, Collar, Foamy, Bubbly, Intense, Shy, Fruity, Matured, Little or no autolysis character (< Autolysis), Pronounced autolysis character (> Autolysis), Yeasty, Toasty, Bruised apple, Low acidity, High acidity, Balanced acidity, Full bodied, Thin, and Short aftertaste (Short a/taste), Medium aftertaste (Medium a/taste) and Long aftertaste (Long a/taste) were considered as attributes.

The logistics of the evaluation sessions were based on the guidelines of Lawless and Heymann (2010) with further details as described by Jolly *et al*. (2021). Six wines (three crown cap treatments with two repetitions each) were evaluated by a tasting panel consisting of 14 members (males and females, between 20-65 years old) with 5 to 20 years experience in wine evaluation (no collective training). The panel was trained in the terminology and CATA evaluation sheet and instructed to check all attributes relevant to a wine sample. The tasting room was lit by a combination of natural light and daylight-type fluorescent lights. The ambient temperature was approx. 22°C. The wines were stored at 15°C and only opened once the judges were seated to maximise CO_2 content in each glass. Wines were poured by hand in a manner to minimise foaming. The wines were served randomised and marked with three-digit codes in clear ISO wine tasting glasses (approx. 110 mL aliquots) per judge. Treatments were not disclosed to the judges.

Still water and unsalted crackers for palate cleansing, and spittoons for expectoration were provided. The panellists were seated at tables in a manner not to influence or communicate to each other.

Statistical analysis

Physicochemical and phenolic data (completely randomised and continuous) were subjected to analysis of variance (ANOVA) using General Linear Models Procedure (PROC GLM) of SAS software (Version 9.4; SAS Institute Inc, Cary, USA). The Shapiro-Wilk test was performed on the standardised residuals from the model to verify normality (Shapiro & Wilk, 1965). Fisher's least significant difference was calculated at a 5% level to compare treatment means (Ott & Longnecker, 2010). A probability level of 5% was considered significant for all tests. The CATA sensory data were analysed to establish the number of agreeing panellists that are required for 95% confidence level between the treatments (Roessler *et al.*, 1978). Thereafter the data from the CATA questions were analysed by correspondence analysis (CA) to produce a bi-dimensional representation (biplot) of the samples and the relationship between samples and attributes of the CATA question (Jaeger et al., 2015; Alexi et al., 2018). The CA was performed using XLSTAT with the *chi*-square distance (XLSTAT statistical software 2021.4.1213, Addinsoft, Paris). Additionally, phenolic data was subjected to principal component analysis (PCA) to reduce the complexity of the data into a principal component space (XLSTAT statistical software 2021.4.1213, Addinsoft, Paris). Results are reported in biplots illustrating the relative positions and loadings of the variables in relation to treatments.

RESULTS AND DISCUSSION

Physicochemical parameters

The physicochemical parameters measured are listed in Table 2. There was a large degree of variability in the pressure (kPa) among the replicates showing the inherent inconsistencies that can be expected between bottle fermented sparkling wines within the same batch.

Despite this, Crown++ wines had significantly higher bottle pressure than the reference and Crown+ wines (Table 2). This was supported by a similar expected pattern of higher dissolved CO_2 in the Crown++, wines compared to reference and Crown+ wines. However, the lowest pressure was measured for the reference samples which does not agree with the crown cap's technical specifications which indicated that the reference crown cap is the least permeable to CO_2 loss (Table 1) and therefore should have the highest pressure. The

 DOI: https://doi.org/10.21548/46-2-6806

reasons for this are unclear but may be related to variances in bottle neck sizes resulting in crown caps not seated properly.

Dissolved O_2 was not significantly different between the three crown cap treatments. Lowest dissolved O_2 was measured in the reference wines which is in accordance with the technical specifications (Table 2). However, any O_2 ingress would be bound to wine chemical compounds ("oxygen consumption by wine") such as phenolics and would not necessarily be seen as dissolved O_2 (Carrascon *et al.,* 2015).

Total acidity (TA) is mainly determined during the preparation of the base wine and should not be affected by the second fermentation. Results show that they are similar to the base wine at approx. 6 g/L (Table 2). All the wines fermented to dryness (<0.2 g/L residual sugar) with similar alcohol content (from a practical point of view, the measured differences in alcohol content are marginal). The YAN values, as a broad representation of nitrogen content and indication of the progress of yeast autolysis (Feuillat & Charpentier, 1982; Jolly *et al*., 2021), show that autolysis in the reference wines may have progressed further, compared to the other two wines.

Crown cap closure effect on sensory attributes

The correspondence analysis (CA) of the CATA sensory data show that the use of the three different crown caps affected the sensory profile of the wines as per the intentions of the crown cap manufacturer (Fig. 1). However, as already pointed out the differences in pressure did not align with expected technical attributes of the reference crown caps. The reference wine replicates are grouped separately from the Crown+ wine replicates, showing that the effect of the crown cap was consistent across the repetitions for the measured sensory attributes of these two closures (Fig. 1). The same did not apply for the Crown++ wines where sensory differences between the two replicates were evident. As previously discussed, this could be due to manufacturing variances in either the bottle or crown cap dimensions, causing ill-fitting crown caps that led to the sensory differences. A larger number of bottle replicates could improve this data set, but they were not available. Reference wines were associated with short aftertaste, bruised apple, small bubbles, toasty, and more autolysis flavours, which align with the higher YAN values measured (Feuillat & Charpentier, 1982; Jolly *et al*., 2021).

Crown cap closure effect on phenolics

Reference wines were lowest in total phenolic acids (Table 3) but highest in gallic acid (Table 4). Caftaric and caffeic acids were not different between Crown+ and Crown++ wines, including reference wines. Crown+ wines were associated with less visible bubbles (s- bubbles; <bubbles), balanced acidity, fruity, full-bodied, toasty, intense aroma and yeasty, all of which are generally considered favourable attributes for bottled fermented sparkling wines (Fig. 1). Crown+ wines were also highest in total flavan-3-ols (Table 3), hence the "Full-bodied" attribute and highest in total phenolic acids (Table 3). The Crown++ wines had varying associations with large bubbles (a negative attribute for bottled fermented sparkling wines), but many bubbles (>bubbles), less autolysis, thin, shy nose but long aftertaste and lowest in total flavonols and total flavan-3-ols.

Crown+ wines were approx. 2% higher in flavan-3-ols than Crown++ wines and flavonols were 8% higher in Crown+ wines than Crown++ wines, and total phenolic acids were approx. 3% higher in Crown+ wines than in Crown++ wines (Table 3). An increase in total phenolic acids of Crown+ wines was likely due to the hydrolysis of tannins by weak acids or weak bases to produce carbohydrates and phenolic acids. Gallic, caftaric, and caffeic acids were not significantly different between Crown+ and Crown++ wines, whereas *p*-coumaric acid reported to be approx. 6.5% higher in Crown+ wines (Table 4).

TABLE 2

Comparison of physicochemical parameters of bottled fermented sparkling wines (2014 vintage) closed under three crown cap closures of varying O_2 and CO_2 permeability[1].

Parameters	Reference crown (Least permeable)	Crown++ (Intermediate permeability)	Crown+ (Most permeable)
Pressure at 20°C (kPa)	484.98c ± 37.91	626.00a ± 12.98	539.52b ± 44.53
Dissolved CO_2 (g/L)	10.20b ± 0.16	10.58a ± 0.02	9.87c ± 0.05
Dissolved O_2 (mg/L)	0.08ba ± 0.12	0.13a ± 0.08	0.12a ± 0.05
Total acidity (g/L)	6.33a ± 0.06	6.18ab ± 0.18	6.14b ± 0.11
Alcohol (%, $^{v}/_{v}$)	12.40b ± 0.03	12.65a ± 0.26	12.66a ± 0.09
Malic acid (g/L)	BLD[2]	BLD	BLD
Residual sugar (g/L)	0.20a ± 0	0.08a ± 0.11	0.12a ± 0.11
Yeast assimilable nitrogen	121.52a ± 2.50	112.00b ± 5.24	111.44b ± 6.97

[1]Average values of five replicates. Different letters in the same row indicate significant differences in the content of the measured variables among the different closures according to Fischer's least significant difference test (p = 0.05).
For closure permeability refer to Table 1. [2]BLD = Below limit of detection.

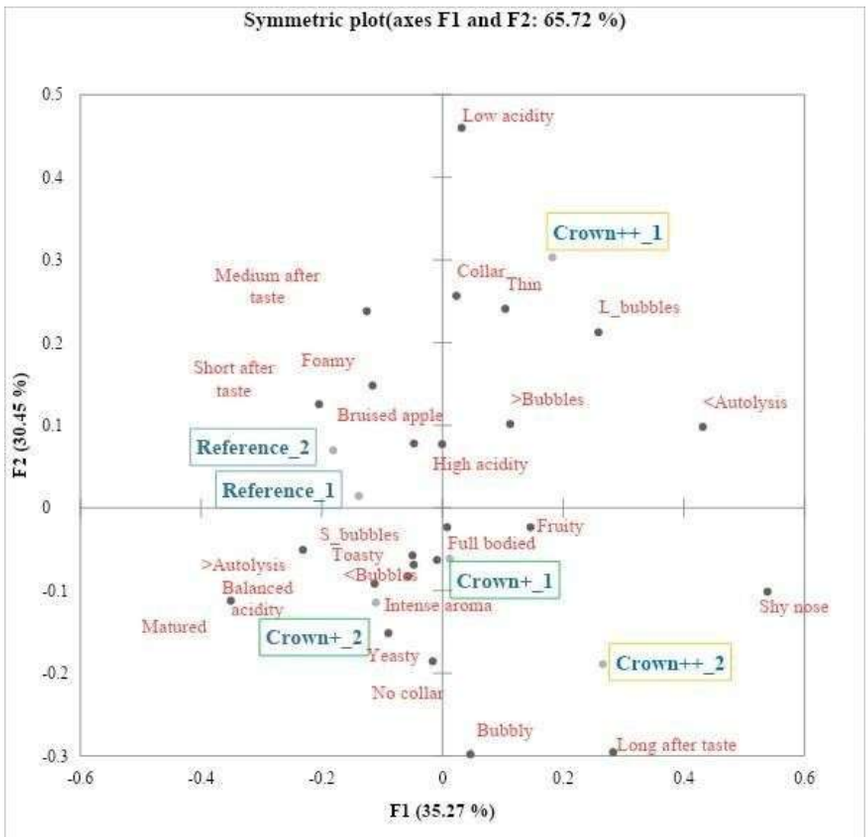

FIGURE 1
Correspondence analysis biplot for CATA sensory data of bottle fermented sparkling wines for three crown cap closures.

TABLE 3
Comparison of total phenolic acids, flavonols and flavan-3-ols in bottle fermented sparkling wines (2014 vintage) closed under three crown cap closures of varying permeability[1].

Phenolics	**Reference crown (Least permeable)**	**Crown++ (Intermediate permeability)**	**Crown+ (Most permeable)**
Total phenolic acids[2]	11.48b ± 0.54	11.76ab ± 43	12.18a ± 0.29
Total flavonols[3]	26.38a ± 0.99	23.17b ± 1.58	25.19a ± 1.16
Total flavan-3-ols[4]	22.04b ± 0.05	21.84c ± 0.15	22.28a ± 0.09

[1]Average values of five replicates. Values within rows followed by the same letter do not differ significantly ($p < 0.05$).
[2]Phenolic acids = mg *p*-coumaric acid equivalents/L (mgCAE/L). [3]Flavonols = mg quercetin equivalents/L (mgQE/L).
[4]Flavan-3-ols = mg (+)-catechin equivalents/L (mgCE/L).
For closure permeability refer to Table 1.

TABLE 4
Comparison of phenolic acids[1] in bottle fermented sparkling wines (2014 vintage) closed under four crown cap closures of varying permeability.

Phenolics (mg/L)	**Reference crown (Least permeable)**	**Crown++ (Intermediate permeability)**	**Crown+ (Most permeable)**
Gallic acid	15.23a ± 0.22	14.27b ± 0.24	14.68ab ± 0.63a
Caftaric acid	7.69a ± 0.02	7.89a ± 0.07	7.79a ± 0.31
Caffeic acid	5.45a ± 0.006	5.51a ± 0.03	5.45a ± 0.15
p-Coumaric acid	4.52ab ± 0.09	4.37b ± 0.09	4.68a ± 0.15

[1]Average values of three replicates. Values within rows followed by the same letter do not differ significantly ($p < 0.05$).
For closure permeability refer to Table 1.

Principal component analysis (PCA) was performed on the phenolic data. The first two principal components illustrate the association of phenolics with the different crown cap closures (Fig. 2), explaining 100% of the total variation in the two dimensions with 68.01% and 31.99% explained by PC1 (F1) and PC2 (F2), respectively. PCA revealed that reference wines were positively associated with total flavonols and gallic acid, whereas Crown+ wines were positively associated with total flavan-3-ols and *p*-coumaric acid and Crown++ wines were positively associated with caffeic acid (Fig. 2). The main cause of variation was therefore total flavan-3-ols, total flavonols and caffeic acid which separates the different crown cap closures.

Measurement of total monomeric phenolics showed that differences occurred which is attributed to the permeability of the closures (Tables 3 and 4). Atmospheric O_2, which enters through a bottle closure, is initially consumed by the yeast, but is also a substrate for chemical transformations in wine during bottle ageing (Wirth *et al*., 2010). This implies that the phenolic profile is modified (oxidised) during bottle ageing using different crown cap closures with different O_2 permeabilities (Wirth *et al.*, 2010; Guaita *et al.,* 2013; Xing *et al.,* 2016). Polymerisation of monomeric phenolic compounds can also occur, which can result in a decrease of these compounds (Gambuti *et al.*, 2013).

The results also show that the different closure types had an ingress and egress effect on the O_2 and CO_2, respectively and the concentrations of certain phenolics. This agrees with Poças *et al.* (2010), who reported that bottle closures with different permeabilities affect the dissolved O_2 and subsequently the phenolic concentration in bottled still wines (Waterhouse & Laurie, 2006). Kallithraka *et al.* (2009) and Wirth *et al*. (2010) reported that during bottle ageing, both O_2 and time on lees initiate the oxidation and polymerization of phenolics in sparkling wines. The Crown+ caps theoretically allow the most O_2 transfer and highest CO_2 loss.

The decrease of flavan-3-ols during bottle ageing of Crown++ wines was likely due to polymerization/ degradation because of O_2 ingress (Oliveira *et al.*, 2011; Oliveira *et al*., 2015). However, these closures resulted in wines with a long aftertaste (Fig. 1). Crown+ wines had the highest *p*-coumaric acid levels and were associated with the "Full-bodied" attribute. A similar association between phenolic acids (*p*-coumaric and ferulic acids) and wine body/ structure (persistence) was reported by Oberholster (2008).

The increase in *p*-coumaric acid and total phenolic acids in Crown+ wines is ascribed to the acid hydrolysis of *trans*-caffeoyltartaric acid (caftaric acid) to caffeic acid, and *p*-coumaric acid cinnamyl ester to *p*-coumaric acid (Monagas *et al*., 2005). A decrease in gallic acid (Crown++ wines) is ascribed to the polymerization of gallic acid due to oxygen ingress (Monagas *et al*., 2005).

Phenolic acids reported in this study represent a small percentage of grape phenolics. Free phenolic acids were quantified, but since their levels are related to phenolic acid esters (Monagas *et al*., 2005), the effect of closures on phenolic acid ester content may be obscured.

Flavonols can undergo autoxidation, i.e., reactions with oxygen which results in the degradation of flavonol glycosides (Csepregi & Hideg, 2017). The decrease in total flavonols in Crown++ wines, compared to the reference and Crown+ wines, may be due to the reaction with O_2 (ingress of O_2) which resulted in the degradation of flavonols (Petrozziello *et al.*, 2018).

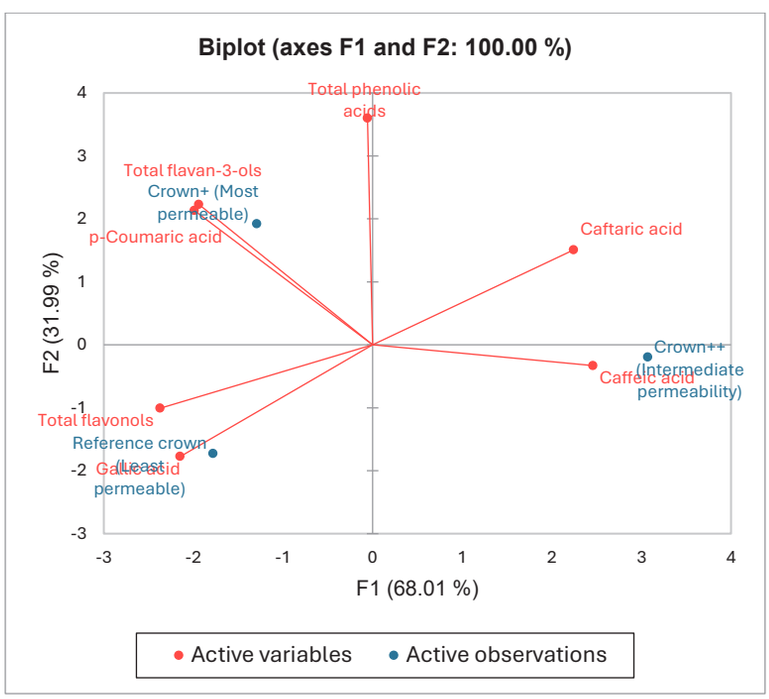

FIGURE 2
PCA biplot illustrating the association of phenolics with treatment, i.e., three different crown cap closures permeabilities.

CONCLUSION

The effect of closure type on selected physicochemical parameters, sensory attributes and phenolics of bottle fermented sparkling wines, after 43 months on lees was studied. As expected, there were differences in pressure, dissolved CO_2, and O_2 among the three closure types due to the inherent technical characteristics of the closures. Although some pressure variability was observed between bottle replicates, dissolved CO_2 content was lower after 43 months of bottle ageing in Crown+, and reference wines, compared to Crown++ wines.

Reference wines were associated with short aftertaste, bruised apple, small bubbles, toasty, and more autolysis flavours. These wines were highest in gallic acid and lowest in total phenolic acids. Crown+ wines were associated with few bubbles, balanced acidity, fruity, full-bodied, intense aroma, and yeasty, which are complementary for bottled fermented sparkling wines and highest in flavan-3-ols and phenolic acids. The Crown++ wines had varying associations with large bubbles, which is a negative attribute for bottled fermented sparkling wines with increased bubbles, less autolysis, a thin and shy nose, but a persistent aftertaste.

It is inferred that the differences in phenolics of reference, Crown+ and Crown++ wines during bottle ageing resulted from polymerization reactions or acid hydrolysis. Differences in phenolic concentrations and sensory attributes could be ascribed to O_2 variability in the wines. The different closures under study can therefore be used to alter monomeric phenolic concentrations of sparkling wines during bottle ageing, subsequently affecting sensory attributes. Stylistic changes can be imparted to the wines, depending on the market segment intended. Based on the sensory profile of this investigation, it can be concluded that the Crown+ wines had the most favourable sensory attributes and were therefore the most suitable closure for the base wine after 43 months on the yeast lees.

The use of more or less permeable crown caps during the production of bottle-fermented sparkling wines can be a tool to use by wine producers to guide a desired sensory outcome. However, the producer is reliant on the technical information supplied by the crown cap manufacturer and his or her own practical experience.

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