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Can silica application enhance vine performance and quality?

Cassandra Collins[1,*], Stuart Bloomfield[1,2], Lauren Hansen[1,3], Matthew Gilliham[1]

[1] School of Agriculture, Food and Wine, Waite Research Institute, The University of Adelaide, Urrbrae, 5064, Australia.
[2] Craft vs Science Boutique Wines, Nuriootpa, 5355, Australia.
[3] Penley Estate, Coonawarra, 5263, Australia.

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*correspondence:
cassandra.collins@adelaide.edu.au

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ABSTRACT

Consumer awareness of environmental sustainability and concern for food safety and quality is driving increased demand for organic and biodynamic (BD) produce. This is coupled with a more physically and economically challenging environment pushing producers to explore more sustainable management techniques. Biodynamic viticulture has both environmental and marketing benefits as drivers and involves the application of a series of nine preparations to soil and plants. Biodynamic preparation 501 is silica-based and has minimum yearly use requirements for certified growers. There are conflicting reports of silicon-based foliar sprays eliciting favourable plant reactions about improvements in quality, yield, and resistance against pests and diseases. Here, vine growth, yield components, berry and wine composition analyses, and sensory evaluations were conducted in two seasons to compare the effects of biodynamic and commercial silica treatments against a water control on Semillon and Cabernet-Sauvignon (*Vitis vinifera* L.) vines. In both seasons differences in yield and vine growth were observed. Generally, yield was greater with the application of biodynamic silica and potassium silicate. Basic berry compositional attributes pH, TA, TSS, and total anthocyanins and phenolics showed little to no differences. Sensory descriptive analysis of berries and wine indicated significant differences in attributes related to skin and seed tannins, implying that these analyses may better detect subtle yet important variations in the vineyard. The results of this study suggest a direct correlation between silicon and polyphenols, potentially influencing sensory mouthfeel characteristics through changes in skin thickness and/or structure. This study indicates that applying silica can positively impact vine performance and quality.

KEYWORDS: Terroir 2024, berry sensory assessment, biodynamics, fruit quality, sustainability, vineyard management

INTRODUCTION

In recent times, there has been an increased exploration into methods of farming that aim to be more environmentally friendly and sustainable such as reducing the dependency upon synthetic fertilisers and chemicals, including the use of organic and biodynamic farming practices (Döring *et al.,* 2019). Biodynamic farming involves using nine key preparations that are applied according to the lunar calendar (Boeringa, 1980; Steiner, 2004; Klett, 2006). The preparations comprise buried cow manure (500), buried ground quartz silica (501), buried animal organ and flower combinations (502, 503, 506), buried wilted stinging nettles (504), wetted and broken down (then dried) oak bark (505), valerian flower extract (507) and concentrated equisetum extract (508) [Boeringa, 1980; Steiner, 2004]. There is anecdotal evidence for the benefits of biodynamic farming, but research has yielded inconsistent results. Reported benefits of biodynamic farming include increased soil microbial diversity and activity compared with conventional (Carpenter-Boggs *et al.*, 2000a; Mäder *et al.,* 2002; Probst *et al.,* 2008; Collins *et al.*, 2015), higher earthworm populations (Zaller and Köpke, 2004; Collins *et al.*, 2015), increased decomposition rates within the soil (Zaller and Köpke, 2004), increased soil organic matter (Carpenter-Boggs *et al.*, 2000a; Gomiero *et al.*, 2011) and reduced weed populations (Carpenter-Boggs *et al.*, 2000b). In grapevines, biodynamic methods have been shown to display ideal vine balance and produce high-quality fruit (Reeve *et al.,* 2005). Wines from biodynamically produced fruit were described as more complex, fresh, and vibrant compared to conventional wines (Collins *et al.*, 2015).

Silicon is the second most abundant element in the soil and a major mineral constituent of plants; however, it is not considered an essential element for plant growth (Marschner, 1988; Epstein, 1994; Epstein, 1999; Epstein, 2001; Ma, 2004; Broadley *et al.*, 2012). Silica has been shown to have numerous benefits for plant growth, including increased growth and yields in rice and cereals, increased disease resistance, reduced uptake of toxic metal ions, increasing crop tolerance to metal toxicity and salinity (Epstein, 1999; Ma *et al.,* 2006; Ma and Yamaji, 2006; Tuna *et al.,* 2008; Song *et al.,* 2009; Soylemezoglu *et al.,* 2009; Song *et al.*, 2014). Silica has been applied to plants through methods such as soil amendments, foliar sprays, hydroponic solutions, seed priming, drip irrigation, silica nanoparticles, and root zone drenches, all aimed at enhancing growth, stress resistance, and yield (Ma and Yamaji, 2015). Silicon fertiliser is predicted to be an important tool for increasing food security (Cooke *et al.,* 2016; de Tombeur *et al.,* 2020; Wang *et al.*, 2021a). Studies indicate that silicon applications can enhance cell wall thickening and improve resistance to abiotic stresses, which may contribute to better overall plant health and productivity (Zagar *et al.,* 2019; Wang *et al.,* 2021b; Zhu and Li, 2021). Anecdotal evidence suggests that the application of atmospheric silica (501) sprays may "strengthen" the plant through the thickening of cell walls and enhanced light assimilation of the plant, leading to better fruit and seed development with improved flavour, aroma, colour, and nutritional quality. Foliar sprays containing silicon have demonstrated the ability to enhance plant responses, including improved quality, yield, and resistance to pests and diseases (Bowen *et al.,* 1992; Reynolds *et al.,* 1996; Soylemezoglu *et al.,* 2009; Laane, 2017). Silica application has been linked with increased cell wall and membrane thickness in leaves and in turn an increase in grapevine disease resistance (Rashad *et al.,* 2021). Foliar application has been observed to increase the total silicon concentrations in leaves and fruit, and the wine produced from the silica-treated grapes was ranked better in sensory evaluations (Schabl *et al.,* 2020). However, to date, there is no definitive link established between silicon use and improved grape and wine quality. This project explored how applying foliar silica, including biodynamic preparation 501 and a commercial equivalent (potassium silicate), affects grapevines and influences the quality of their fruit and resultant wine. All vines used in this experiment were managed conventionally in previous years.

MATERIALS AND METHODS

1. Experimental design, vine management, and treatment application

The experimental trial was performed in the Coombe vineyard at the Waite Campus of the University of Adelaide, South Australia during the 2011/2012 and 2014/2015 growing seasons. Semillon (clone SA32) and Cabernet-Sauvignon (clone 125) vines were planted in 1992 with 3 m row and 1.8 m vine spacing. Vines are grown on their own roots, trained to a bilateral cordon, with vertical shoot positioning, and hand pruned to approximately 30-40 nodes per vine. All treatments received six applications of sulfur and two applications of copper fungicides to manage disease throughout the growing season. Drip irrigation was used throughout the growing season from December to April in both seasons, 0.6 mL/ha in 2011/2012 and 0.9 mL/ha in 2014/2015 to account for seasonal differences (Table S1). The soil type is classified as a Vertic, Red Dermosol, characterised by a thick, non-gravelly, clay loam with high levels of organic matter, nutrient availability, and moisture retention, based on the Australian Soil Classification system (Hall, 2016; Isbell, 2016).

A randomised design comprising three treatments, including a control, was used, with three replicates, six vines per treatment replicate. These were grouped into panels (distance between two vineyard posts), with buffer panels between each treatment to prevent spray drift contamination. Control vines received a foliar application of rainwater, as this was the water base used to prepare the potassium silicate and biodynamic silica treatment applications. The biodynamic preparation was made using a flow form and the rainwater was mixed for 1 hour, according to biodynamic methods (Steiner, 2004). The biodynamic preparation consisted of 1 g of preparation 501 (Biodynamic Australia Pty Ltd, Australia) diluted in 17 L of rainwater (1.2 µM). The potassium silicate (Ferbon, OP-30, Australia) solution was a 1 in 300 dilution in rainwater (18 µM) as per the manufacturer's instructions. Treatments were applied to all replicates in the early morning, using handheld pressure spray equipment (FH220896, Hills, Australia). Application of treatments in the first season was on October 25th, 2011, at the modified E-L stage 19 (beginning of flowering) and December 16th 2011, at E-L Stage 31 (berries pea size). In the second season, application occurred on the 4th of November 2014, at E-L Stage 25 (80 % flowering), and on the 11th of December 2014, at E-L Stage 31 (berries pea size). These dates corresponded to the spray periods for biodynamic silica (501) according to the lunar calendar (Keats, 2010; Keats, 2013), and the phenological stage of development was determined using the modified system developed by Coombe (1995).

2. Vine performance and chemical analysis

2.1. Vine performance assessments

Twenty-five leaf blades were collected at E-L 32 (beginning of bunch closure) from each treatment replicate, after which they were dried at 60 °C for two days, ground to a fine powder, and analysed for elemental composition of iron, manganese, boron, copper, zinc, calcium, magnesium, sodium, potassium, phosphorus, sulfur and aluminium using an inductively coupled plasma optical emission spectrometer (ICP-OES) after using a nitric acid and hydrogen peroxide digestion (Wheal *et al.*, 2011) and the concentration of nitrogen was determined by the combustion technique (Searle, 1984). All analysis was provided by Waite Analytical Services, Adelaide. Silicon concentration of leaf tissues was determined through the colorimetric determination of autoclave-induced digestion of the ground leaf sample, as described by Elliot and Snyder (1991).

In 2011, the total leaf area per shoot was calculated using scanned images of leaves and the total leaf number per shoot. A custom MATLAB script, based on the methods outlined by Fuentes *et al.* (2014), was developed to calculate the total leaf area in each scanned image. The images were captured from a height of 20 cm above the ground, focusing upward with the cordon arm centrally positioned in the frame. These images were then batch-processed in MATLAB (version 2011b) using the specified script from Fuentes *et al.* (2014). Pruning measures included pruning weight per vine (kg) and total shoots, count and non-count shoots per vine, and cordon length. Pruning weight (kg) per m cordon, yield to pruning weight ratio, shoots per m cordon, percent non-count shoots, and mean shoot weight (g) were calculated from these measures (Smart and Robinson, 1991). Several other growth measures were recorded including bunch number per vine, average bunch weight (g), mean berry weight (g), average berries per bunch, seeded and seedless berries per bunch, average seeds per berry, live green ovaries per bunch, and rachis weight (g). Bunch components were assessed on five randomly selected bunches per vine per treatment replicate as described by Collins and Dry (2009). The total bunch number and total yield per vine were measured at harvest for each treatment replicate.

2.2. Chemical analysis and winemaking

A 200-berry sample was collected at harvest from each vine replicate of each treatment strategy for Semillon and Cabernet-Sauvignon. From each sample, a randomised selection of fifty berries was taken and crushed. The juice collected was used for berry compositional analysis. TSS was measured as degrees Brix (ºBrix) using a DMA 35N Density Meter (Anton Paar GmbH, Austria). pH and TA were measured by titration to pH 8.2 (Iland *et al.,* 2004) using a Crison Compact Titrator 08328 Alella (Crison, Spain). A modified spectrophotometry method determined total anthocyanin and phenolic levels (Iland *et al.*, 2004) on an additional fifty berry sample taken at harvest from each treatment replicate. Samples were homogenised using a CAT X620 Homogeniser (Ingenieurbüro M. Sipperer GmbH, Germany). Centrifugation was carried out in a Hettich D-7200 Tuttingen centrifuge (Hettick Universal, Germany) and a Metertech SP-830 Plus spectrophotometer (Metertech, Taiwan) was used to analyse absorbance at 280 and 520 nm. Total grape tannins were measured by the methylcellulose precipitable (MCP) tannin assay (Sarneckis *et al.,* 2006) using the protocol of Mercurio *et al.* (2007). Waite Analytical Services conducted elemental analysis on the juice samples, as previously described.

Wines made in 2015 were from 4 kg ferments taken at harvest. All ferments were conducted in 5 L polypropylene buckets (Amber Plastics Pty Ltd, Australia), with red fermentations open and white fermentations closed with a lid and airlock. Semillon grapes were pressed and then transferred to a 5 L polypropylene bucket for fermentation. A 50 ppm addition of sodium metabisulfite was made before pressing for microbial stabilisation and oxidation protection. Cabernet-Sauvignon must was fermented on skins under controlled conditions at 20 °C ± 2 °C and plunged twice daily with a stainless steel plunger to break and wet the cap. Fruit used for the fermentations was hand de-stemmed and inoculated with 200 ppm of commercial dried yeast (AWRI 796, Laffort, Bordeaux, France) and 200 ppm of nutrient (Dynastart, Laffort, Bordeaux, France). Following an initial drop of 2° Baumé 200 ppm diammonium phosphate (DAP) was added for the Cabernet-Sauvignon ferments malo-lactic bacteria culture (Lalvin VP41, Lallemand, France) at 0.2 ppm to complete primary and secondary fermentation simultaneously. Baumé (measured using a Hydrometer) and temperature were monitored and recorded daily. When Baumé was ≤ 2° or after 5 days of skin contact wines were pressed off using a hand-operated 5 L screw basket press. All the wines were pressed to the same extraction rate to eliminate possible differences associated with varying extraction rates. As ferments approached dryness wines were analysed for residual sugar using the Rebelein method outlined in Iland *et al.* (2004). The malic acid concentration was determined using a Vintessential Laboratories L-Malic Acid Enzymatic Analysis Kit (Vintessential Laboratories, Australia). Following completion of fermentation (including MLF [≤ 0.05 g/L malic acid] for the reds) wines were sulfured to a free level of 30 ppm. Wines were racked and bottled directly, into 750 mL glass claret bottles and sealed under a screwcap. The wines were then stored at a constant 15 °C for future wine sensory and chemical evaluations.

Titratable acidity and pH were measured using an auto-titrator (Crison, CompacT Titrator, Spain). Alcohol was measured with an Anton Parr Alcolyzer (Anton Parr, Alcolyzer, Germany). A modified Sommers method, outlined in Iland *et al.* (2004) and Mercurio *et al.* (2007), was used to determine the anthocyanin concentration (mg/L), degree of anthocyanin ionization, SO_2 resistant pigments (au), colour density (au), SO_2 corrected colour density (au), hue (au), chemical age and total phenolics (mg/L). The model wine used for the modified Sommers procedure had a pH of 3.5, TA of 5 g/L (tartaric acid), and an alcohol of 11.38 %v/v. Epicatechin concentration (g/L) was measured by the methylcellulose precipitable (MCP) tannin assay (Sarneckis *et al.,* 2006) using the protocol of Mercurio *et al.* (2007).

3. Berry and wine sensory analysis

Grape berry and wine sensory evaluation was performed to examine the sensory differences arising from the application of BD 501 and potassium silicate compared to control treatments. At harvest 10 bunches were randomly collected from each treatment replicate for sensory evaluation and stored frozen at –20 ºC and defrosted for 24 h at 4 ºC. Due to time constraints and a busy harvest period, it is not possible to complete the training of panellists and the assessment of the samples without freezing as the berries would deteriorate before completion. All berries from all treatment replicates were collected in the same way on the same day so that any differences observed could be attributed to the treatments applied. All panellists also received the samples in different random orders to eliminate pallet fatigue as an influencing factor. Panels consisted of 8-10 members (21 to 40 years old) all with previous formal sensory evaluation and descriptive analysis experience. The panel underwent sample-specific training in berry and wine assessment and performance evaluation in two to three 2 h sessions and participated in two 2 h formal evaluation sessions. A round table discussion with panellists was conducted to generate sensory descriptors and line scales based on the methods of Lohitnavy *et al*. (2010).

3.1. Training of panel members

Line scales and sensory attributes were agreed upon by panellists during training sessions. The length of the scales was 15 cm with word anchors; end anchors were indented by 1 cm to encourage panellists to use the entire length of the scale (Meilgaard *et al*., 2007). Panellist training sessions consisted of identifying standards, determining variations in sugar, acid, astringency, and bitterness, and generating attributes and descriptors. The solutions and intensity standards for training both berry and wine sensory assessments are summarised in Tables S1, S2 and S3. The first training session involved several trial berry and wine tastings using model line scales to familiarise panellists with the evaluation procedure. Consensus modifications to line scales and sensory attributes were finalised during the training sessions, generating attributes for Semillon (Tables S4 and S5) and attributes for Cabernet-Sauvignon (Tables S6 and S7) with corresponding word anchors. For berry assessments touch standards using different fabrics and materials (satin, suede, felt, velvet, talcum powder, ground pumice, and sandpaper) were used to discuss tannin grain size. Panel performance was assessed in the final training sessions by having each panellist assess different berry and wine samples in duplicate with data generated and analysed using SenPAQ (version 5.0, Qi Statistics, UK). When no significant panellist-by-sample interactions were found, the panel was justified in commencing the final evaluation of the samples.

3.2. Formal evaluations

In the formal sensory evaluation sessions, three randomly selected berries or 50 mL of wines from each replicate of each treatment were presented to panellists and seen in duplicate. The panellists formally assessed samples in the Sensory Laboratory (Plant Research Centre) at the Waite Campus, in individual booths under fluorescent light with a light temperature of 6500 °K. A random three-digit code was given to each replicate and the presentation order was randomised to balance carry-over effects. To avoid palate fatigue, panellists were asked to take a 2-minute break between each sample and a 10-minute break after assessing 6 samples. Panellists were also required to rinse with citrus pectin (2 g/L, Sigma-Aldrich) and water solution between samples. Unsalted water crackers (Arnotts, Australia) were provided to assist in cleansing the palate between samples.

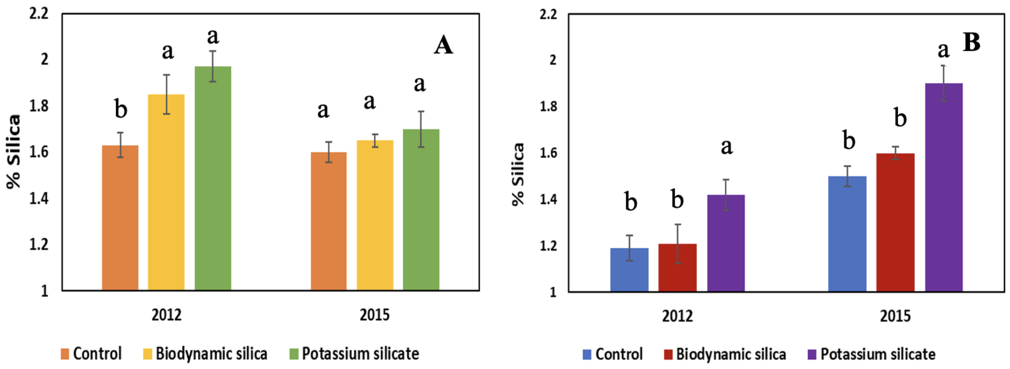

FIGURE 1. Percentage silica in petiole tissues of Semillon (A) and Cabernet-Sauvignon (B) in the 2011/12 and 2014/15 growing seasons, Coombe vineyard, Adelaide, Australia. Different superscript letters indicate statistical differences using LSD at a 5 % level within one growing season.

4. Data analysis

Growth and compositional measures were analysed using analysis of variance (ANOVA) in the statistical software XLSTAT (Addinsoft, XLSTAT, version 2023.1.4). Fisher (LSD) post hoc tests were used with the F probability (*P*-value) set at < 0.05 for statistical significance. Sensory data was analysed using the software package SenPAQ (Qi Statistics, SenPAQ, version 5) using a mixed model with assessors as random and samples as fixed attributes. For sensory analysis, the F probability value was set at < 0.1 for statistical significance, to allow for human influence (Muñoz, 2008). Principal component analysis (PCA) using XLSTAT was also used to display berry and wine sensory attributes that were significantly different between treatments.

RESULTS AND DISCUSSION

1. Elemental analysis and vine performance

Silica concentration in petiole tissues was significantly greater when a foliar application of both biodynamic silica and potassium silicate was applied to Semillon in the first year of the trial and when potassium silicate was applied to Cabernet-Sauvignon in both seasons (Figure 1).

Very few differences were observed in the leaves for other elements (Tables S8 and S9). Minor differences between the elemental content of leaf tissues were detected between silica treatments in the two seasons of experimentation; sodium and phosphorous levels were greater when the potassium silicate and biodynamic 501 treatment were applied to Semillon in 2011/2012 (Table S8), while boron levels were lower in 2014/2015 and phosphorus levels were higher in the biodynamic horn silica (BD) treatment for Cabernet-Sauvignon in 2014/2015 (Table S9). Nitrogen concentration in the leaf was higher for the potassium silicate treatment in Semillon, while lower in Cabernet-Sauvignon compared with the control, however these differences were relatively small. Biodynamic silica was not significantly different from the control in both varieties. Boron concentrations in Semillon leaf tissues in 2014/2015 were found to be lower than the control, which is supported by previous studies that found silicon reduces the uptake and translocation of boron (Gunes *et al.,* 2005; Inal *et al.,* 2009; Soylemezoglu *et al.,* 2009). Ma and Takahashi (1990) studied the effects of silica on phosphorus availability in rice and, although earlier studies suggested silica could increase soil phosphorus availability (Roy *et al.,* 1971; Kundu *et al.,* 1988), concluded that silica application could not affect soil phosphorus availability or the uptake of phosphorus by the plant. It is suggested that interactions with other elements, such as manganese, may be attributable to differences in phosphorus concentrations in plant tissues. Due to the low concentration of silica applied in the sprays, the silicon treatments were not expected to cause a direct effect on elemental content. However, the potential for the interaction between silicon and other elements in changing phosphorus concentration in the BD treatment will be discussed in further detail with berry elemental analysis results.

Silica applications had a greater impact on Semillon (Table 1) than Cabernet-Sauvignon (Table 2). Pruning weight per meter cordon, total shoots, shoots per meter cordon, count shoots, and leaf area index were greater when potassium silicate was applied to Semillon in the 2014/2015 season. Silica application has been found to modify some leaf characteristics in rice plants, including leaf erectness (Yoshida *et al.,* 1969) and leaf angle (Iwata and Baba, 1962). However, Yoshida *et al.* (1969) observed that leaf area was little affected by silica application in rice. Adatia and Besford (1986) saw a larger leaf canopy in cucumber plants supplied with silica, but no significant differences in leaf area. Leaf area has been shown to affect plant growth and fruit composition (Kliewer and Antcliff, 1970; Kliewer and Ough, 1970; Kliewer and Dokoozlian, 2005).

The ratio of fruit weight to pruning weight was not significantly different between treatments in either varietal. Previous studies in grapevine management treatments have consistently seen a reduced ratio of yield to pruning weight in biodynamically managed vines in comparison to organically managed vines, suggesting a more favourable vine balance (Reeve *et al.,* 2005). Although this was not observed in our study, it is suggested that several growing seasons may be required before seeing any effect of the treatments, it may also be that silicon has no individual role in this process, or it is a combination of all biodynamic preparations causing observed differences.

Greater yield was observed when silica was applied with a greater response from potassium silicate application to vines in season 2 for Semillon and in both seasons for Cabernet-Sauvignon (Tables 3 and 4). Yield differences were largely due to greater bunch weights because of greater berry weights observed with silica treatments. Silicon applications have been demonstrated to boost yields in various crops, including rice, sugarcane, and wheat (Abro *et al.,* 2009; Bokhitar *et al.,* 2012; Detmann *et al.,* 2012). Yield differences have also been observed in biodynamic studies of other crops (Reinken, 1986; Carpenter-Boggs *et al.,* 2000b; Heimler *et al.,* 2011; Collins *et al.*, 2015; Döring *et al.,* 2019).

2. Berry and wine chemistry measurements

All treatments were harvested on the same day and no significant differences were observed in harvest parameters pH, TA, TSS, and total phenolic, epicatechin, and anthocyanin levels in both Semillon and Cabernet-Sauvignon apart from TSS of Semillon in the 2014/2015 season (Tables 5 and 6). In the second season, there were high maximum temperatures (> 35 °C) during the harvest period for Semillon, and Brix levels rose rapidly over a few days. The decision was made to harvest all fruit before sugar levels increased further. Minor differences were observed in juice elemental composition between treatments. In Semillon vines, potassium silicate-treated vines had greater potassium and phosphorus (P) in 2011/2012 and lower boron, magnesium, and P in 2014/2015 (Table 5). Whereas in Cabernet-Sauvignon, manganese concentration was significantly reduced in biodynamic silica and potassium silicate treatments and nitrogen and

TABLE 1. The effect of biodynamic silica and potassium silicate on vegetative variables of Semillon in the 2011/2012 and 2014/2015 growing seasons, Coombe vineyard, Adelaide, Australia.

Variable	Season	Treatments			P-value
		Control	Potassium Silicate	Biodynamic Silica	
Pruning weight per m cordon (kg/m)	2011/2012	0.71 a	0.67 a	0.65 a	0.734
	2014/2015	0.49 b	0.71 a	0.57 ab	0.034
Yield to pruning weight ratio	2011/2012	7.4 a	7.6 a	8.4 a	0.453
	2014/2015	9.4 a	11.1 a	9.2 a	0.247
Shoot number per vine	2011/2012	66.3 a	58.0 a	62.8 a	0.102
	2014/2015	31.5 b	41.5 a	35.8 ab	0.030
Shoots per m cordon	2011/2012	37.4 a	29.4 b	32.9 ab	0.014
	2014/2015	17.4 b	25.1 a	20.4 ab	0.003
Count shoots per vine	2011/2012	50.7 a	47.7 a	49.8 a	0.760
	2014/2015	27.0 b	36.5 a	30.8 ab	0.036
Non-count shoots per vine	2011/2012	15.7 b	10.3 a	13.0 ab	0.028
	2014/2015	4.5 a	5.0 a	5.0 a	0.898
% non-count shoots	2011/2012	23.7 a	17.9 a	23.7 a	0.198
	2014/2015	14.5 a	12.0 a	14.1 a	0.762
Mean shoot weight (g)	2011/2012	19.0 a	22.9 a	20.1 a	0.070
	2014/2015	28.4 a	29.1 a	28.1 a	0.973
Leaf Area (cm^2)	2011/2012	36.9 a	38.2 a	34.9 a	0.115
Leaf Area Index	2014/2015	2.5 b	2.9 a	2.6 b	0.046

Different superscript letters within rows indicate statistical differences using LSD at a 5 % level and within one growing season.

sodium concentrations were significantly higher in the control treatment in 2011/2012 while zinc was greater in the potassium silicate treated fruit in 2014/2015 (Table 6). No other elements were significantly different between treatments in either varietal. Increased potassium concentrations in the vines treated with potassium silicate may have been due to the application of potassium silicate. However, this trend was not observed in Cabernet-Sauvignon, and no significant differences in potassium concentrations were observed in the results of petiole analysis to suggest this may be causing any other variation observed. A decrease in manganese uptake due to silica application has been reported in many other studies, with the suggestion that silica may help to alleviate manganese (Mn) toxicity by reducing its uptake by the plant or distributing the element more evenly throughout the plant (Williams and Vlamis, 1957; Ma and Takahashi, 1990; Ma, 2004). Another mechanism by which amelioration of Mn toxicity has been observed is through silica increasing immobilisation of Mn in the cell walls, reducing the amount of Mn available in the apoplast and symplast, thereby mitigating toxicity symptoms (Rogalla and Römheld, 2002). Significant increases in phosphorus concentration were seen in both petiole and juice elemental composition in potassium silicate treatments, this may also be rationalised due to a decrease in manganese, as both phosphorus availability and uptake are not directly affected by silica (Ma and Takahashi, 1990), however, internal phosphorus availability may be enhanced due to its high affinity for manganese (Ma, 2004), and a decrease in Mn concentration was seen in our study with both silica treatments. One claim of biodynamic growers and advocates is that the preparations help to stimulate nutrient cycling (Koepf *et al.,* 1990; Tillet, 2007), hence it is postulated that more interactions such as those above may occur in biodynamic management systems, making nutrients more readily available to the plant. However, this considers the whole plant-soil system, and will refer to nutrient availability in the soil; the effects observed in our study would most likely be limited to direct interactions of silicon in the plant with other nutrients and how this affects uptake and distribution of other nutrients in the plant without affecting nutrient availability from the soil. These results suggest a link worth further consideration, as they may help to provide support to anecdotal claims of altered nutrient use in the plant.

TABLE 2. The effect of biodynamic silica and potassium silicate on vegetative variables of Cabernet-Sauvignon in the 2011/2012 and 2014/2015 growing seasons, Coombe vineyard, Adelaide, Australia.

Variable	Season	Treatments			P-value
		Control	Potassium Silicate	Biodynamic Silica	
Pruning weight per m cordon (kg/m)	2011/2012	0.4 a	0.8 a	0.5 a	0.154
	2014/2015	0.6 a	0.4 a	0.5 a	0.106
Yield to pruning weight ratio	2011/2012	4.3 a	3.9 a	4.1 a	0.776
	2014/2015	2.4 a	1.7 a	2.0 a	0.255
Shoot number per vine	2011/2012	51.3 a	53.3 a	53.2 a	0.910
	2014/2015	43.2 a	36.8 a	39.0 a	0.386
Shoots per m cordon	2011/2012	27.1 a	34.3 a	28.6 a	0.138
	2014/2015	28.1 a	21.7 a	24.4 a	0.112
Count shoots per vine	2011/2012	39.5 a	39.5 a	39.0 a	0.984
	2014/2015	27.2 a	22.5 a	24.8 a	0.344
Non-count shoots per vine	2011/2012	11.8 a	13.8 a	14.2 a	0.701
	2014/2015	16.0 a	14.3 a	14.2 a	0.697
% non-count shoots	2011/2012	22.5 a	25.7 a	26.5 a	0.547
	2014/2015	36.2 a	39.3 a	36.8 a	0.708
Mean shoot weight (g)	2011/2012	13.4 a	21.7 a	19.1 a	0.171
	2014/2015	22.5 a	18.8 a	22.2 a	0.445
Leaf Area (cm^2)	2011/2012	27.36 b	30.41 a	29.27 ab	0.043
Leaf Area Index	2014/2015	2.78 a	1.99 a	2.19 a	0.118

Different superscript letters within rows indicate statistical differences using LSD at a 5 % level and within one growing season.

Juice boron concentrations were lower in Semillon and sodium juice concentrations in Cabernet-Sauvignon with potassium silicate treatment. These results support current observations in the literature regarding silicon application and reducing the effects of metal toxicity. Silica applications have been shown to reduce the translocation of sodium and boron through the root cell membranes in grapevines (Soylemezoglu *et al.,* 2009). This result was not observed for the biodynamic silica treatment which may be due to the differences in the concentration of applied silica. Magnesium was lower in Semillon for the potassium silicate treatment compared with the biodynamic silica and control treatments. The values for magnesium and phosphorous follow a similar trend, however phosphorous does not influence the uptake or translocation of magnesium in grapevines (Skinner and Mathews, 1990). Cabernet-Sauvignon displayed a higher concentration of zinc compared with biodynamic silica and control treatments. Silica application has been shown to decrease the uptake of zinc and prevent toxicity in rice (Gu *et al.,* 2012), however, this was the opposite for potassium silicate with almost double the concentration of zinc compared with the biodynamic silica and control treatments. This suggests that the observed zinc concentrations for Cabernet-Sauvignon may be influenced by other factors.

No differences were observed for wine compositional measures in Semillon, with the only difference observed in Cabernet-Sauvignon being titratable acidity, which was lower for both the silica treatments compared with the control (Tables S10 and S11). Titratable acidity is important in winemaking as it can influence sensory attributes, as well as colour and wine stability (Jackson, 2002). It is known that the concentration of tartaric acid reaches a peak, plateaus, and remains relatively constant during the later stages of berry maturation (Saito and Kasai, 1968). However, the concentration of malic acid varies considerably depending mainly on temperature and the rate of malic acid degradation (Lakso and Kliewer, 1975). As the application of silica decreased titratable acidity compared with the control treatment in Cabernet-Sauvignon this may suggest that skin contact may be lowering the titratable acidity, as this was not seen in Semillon. Silica may be influencing the precipitation of acid during fermentation, and this highlights the need for further investigation, with implications for the reduction of inputs for the cold stabilisation of the wine.

TABLE 3. The effect of biodynamic silica and potassium silicate on reproductive variables of Semillon in the 2011/2012 and 2014/2015 growing seasons, Coombe vineyard, Adelaide, Australia.

Variable	Season	Treatments			P-value
		Control	Potassium Silicate	Biodynamic Silica	
Yield (kg) per m cordon	2011/2012	5.25 a	4.94 a	5.29 a	0.640
	2014/2015	4.42 b	7.88 a	5.20 b	0.005
Bunch number per vine	2011/2012	87.2 a	93.7 a	99.0 a	0.568
	2014/2015	54.8 b	68.5 a	60.7 ab	0.031
Bunch weight (g)	2011/2012	160 a	172 a	154 a	0.512
	2014/2015	147 b	193 a	149 b	0.048
Berry weight (g)	2011/2012	1.251 a	1.375 a	1.295 a	0.211
	2014/2015	1.412 a	1.892 b	1.348 a	0.043
Berries per bunch	2011/2012	127.3 a	125.7 a	119.4 a	0.767
	2014/2015	86.6 a	83.3 a	95.3 a	0.655
Seeded berries per bunch	2011/2012	124.2 a	122.0 a	115.6 a	0.720
	2014/2015	84.2 a	81.7 a	92.6 a	0.677
Seedless berries per bunch	2011/2012	3.1 a	3.7 a	3.7 a	0.835
	2014/2015	2.4 a	1.6 a	2.7 a	0.601
Live green ovaries per bunch	2011/2012	10.6 a	10.0 a	7.8 a	0.531
	2014/2015	5.1 a	5.1 a	5.1 a	0.999
Seed number per berry	2011/2012	1.8 a	1.9 a	1.8 a	0.223
	2014/2015	1.7 a	1.9 a	1.9 a	0.683
Rachis weight (g)	2011/2012	5.6 a	6.4 a	4.9 a	0.113
	2014/2015	5.9 a	6.3 a	7.0 a	0.159

Different superscript letters within rows indicate statistical differences using LSD at a 5 % level and within one growing season.

3. Berry and wine sensory assessments

Numerous significant differences in berry sensory assessment (BSA) were observed for both Semillon and Cabernet-Sauvignon grapes across different treatments (Figures 2 and 3, Tables S12-S15). For Semillon, attributes such as pulp detachability, pulp sweetness, skin disintegration, skin acidity, skin tropical flavour, skin flavour intensity, and seed tannin size varied significantly. In Cabernet-Sauvignon, significant differences included pulp detachability, pulp juiciness, pulp ripe dark fruit flavour, skin ripe dark fruit flavour, skin re-salivation, seed astringency, the grain size of tannin, and seed flavour.

Pulp detachability, which positively correlates with wine quality (Olarte Mantilla *et al.,* 2015), was lower for potassium silicate, indicating firmer attachment and potentially higher quality. This may be linked to silicon's role in strengthening cell walls. Pulp sweetness was higher for biodynamic silica in Semillon in the second season, mirroring compositional analysis results. Interestingly, while no significant difference in °Brix was observed between the biodynamic silica application and the control for Cabernet-Sauvignon, the sensory panel detected differences in the first season, suggesting that sensory assessments can perceive subtler changes than compositional analysis. Potassium silicate resulted in lower pulp juiciness in Cabernet-Sauvignon, possibly due to enhanced cell wall strength from silica (Epstein, 1999) making juice release more difficult. Skin acidity was higher for potassium silicate in Semillon, indicating a potential area for future research on silica and acid metabolism in grapevines. Flavour modifications were noted with silica applications: potassium silicate increased skin citrus flavour in Semillon, while potassium silicate and biodynamic silica enhanced skin flavour intensity. In Cabernet-Sauvignon, potassium silicate increased pulp and skin ripe dark fruit flavour. Seed flavour was also altered with silica application. These findings align with other research showing silicon improves the taste of various crops (Wang *et al.,* 2001; Wang *et al.,* 2024; Yang *et al.,* 2024) and highlight the need for further study on silica and flavour molecule synthesis in grapevines.

TABLE 4. The effect of biodynamic silica and potassium silicate on reproductive variables of Cabernet-Sauvignon in the 2011/2012 and 2014/2015 growing seasons, Coombe vineyard, Adelaide, Australia.

Variable	Season	Treatments			P-value
		Control	Potassium Silicate	Biodynamic Silica	
Yield (kg) per m cordon	2011/2012	1.62 b	2.92 a	2.11 ab	0.049
	2014/2015	0.75 b	1.49 a	1.04 ab	0.045
Bunch number per vine	2011/2012	76 a	71.5 a	75.5 a	0.644
	2014/2015	45 a	35.7 a	37.2 a	0.347
Bunch weight (g)	2011/2012	65.7 b	89.2 a	77.1 ab	0.034
	2014/2015	51.3 a	34.2 a	45.0 a	0.238
Berry weight (g)	2011/2012	0.629 b	0.799 a	0.758 a	0.010
	2014/2015	0.562 b	0.656 a	0.638 a	0.046
Berries per bunch	2011/2012	94.4 a	111.4 a	100.8 a	0.577
	2014/2015	74.3 a	82.9 a	109.9 a	0.067
Seeded berries per bunch	2011/2012	91.8 a	110.0 a	99.4 a	0.555
	2014/2015	109.3 a	82.3 a	74.5 a	0.216
Seedless berries per bunch	2011/2012	2.63 a	1.33 a	1.47 a	0.477
	2014/2015	0.53 a	0.53 a	0.47 a	0.982
Live green ovaries per bunch	2011/2012	23.4 b	37.2 a	27.7 ab	0.042
	2014/2015	8.5 a	6.8 a	5.7 a	0.448
Seed number per berry	2011/2012	1.2 a	1.2 a	1.3 a	0.259
	2014/2015	1.2 a	1.2 a	1.2 a	0.333
Rachis weight (g)	2011/2012	4.2 a	4.9 a	4.5 a	0.630
	2014/2015	5.7 a	4.8 a	4.2 a	0.390

Different superscript letters within rows indicate statistical differences using LSD at a 5 % level and within one growing season.

Berry sensory evaluation revealed numerous differences in mouthfeel characteristics, with finer seed tannin size for biodynamic silica compared to potassium silicate and the control. Potassium silicate and biodynamic silica treatments resulted in longer re-salivation times, indicating higher astringency. Skin disintegration was also harder with potassium silicate, possibly due to increased skin thickness and the enhanced mechanical strength provided by silica (Epstein, 1994). Silica is believed to crosslink pectic polysaccharide rhamnogalacturonan II (RG II) residues within the primary cell wall providing greater mechanical strength to cell walls in many plants (Epstein, 1999; Broadley *et al.,* 2012). In Cabernet-Sauvignon, biodynamic silica increased seed astringency, while potassium silicate reduced tannin grain size. Despite no significant differences in total phenolics or epicatechin concentration, the sensory panel detected differences, suggesting silica may influence tannin type or structure. To better understand these sensory differences, further research should focus on the phenolic composition of berries, as differences in tannin type or structure can alter sensory perception. Silica has been linked to the development of peristomatal protuberances, and its foliar application may affect phenolic compound accumulation during berry maturation (Blanke *et al.,* 1999).

Descriptive analysis for Semillon wine showed few differences, only a reduction in phenolic length when potassium silicate was applied (Table S16). Cabernet-Sauvignon showed differences in wine colour, transparency, dark fruit aroma, flavour intensity, and tannin size (Figure 4 and Table S17). The colour of the wine is an important indicator of the quality of the wine. Both potassium silicate and biodynamic silica showed a darker red and more opaque colour than the control, suggesting a quality improvement (Jackson, 2002). Dark fruit aroma was higher for both silica treatments than the control and flavour intensity was higher for potassium silicate compared to biodynamic silica and the control. Aroma and flavour intensity positively correlate to wine quality and highlight improved quality with silica application (Jackson, 2002). Tannin size was finer for biodynamic silica in Cabernet-Sauvignon, which correlated to seed astringency, further highlighting a possible link between silica and phenolic compounds in grapes.

TABLE 5. The effect of biodynamic silica and potassium silicate on berry juice compositional measures of Semillon in the 2011/12 and 2014/15 growing seasons, Coombe vineyard, Adelaide, Australia.

Variable	Season	Treatments			P-value
		Control	Potassium Silicate	Biodynamic Silica	
TSS (°Brix)	2011/2012	22.3 a	20.3 a	20.3 a	0.464
	2014/2015	23.6 a	21.7 b	24.0 a	< 0.00001
pH	2011/2012	3.32 a	3.29 a	3.21 a	0.086
	2014/2015	3.44 a	3.44 a	3.47	0.880
Titratable acidity (g/L)	2011/2012	6.1 a	5.9 a	6.2 a	0.396
	2014/2015	5.3 a	6.1 a	6.1 a	0.082
Epicatechin concentration (g/L)	2011/2012	0.27 a	0.41 a	0.3 a	0.642
	2014/2015	0.72 a	0.64 a	0.70 a	0.288
Total phenolics/g berry weight	2011/2012	348 a	379 a	334 a	0.337
	2014/2015	< 300	< 300	< 300	na
Anthocyanin/g berry weight	2011/2012	0.18 a	0.16 a	0.17 a	0.875
	2014/2015	0.18 a	0.24 a	0.13 a	0.661
N (mg/L)	2011/2012	0.84 a	0.93 a	0.83 a	0.208
	2014/2015	0.55 a	0.41 a	0.50 a	0.404
Fe (mg/L)	2011/2012	7.2 a	7.7 a	7.0 a	0.100
	2014/2015	7.5 a	5.0 b	8.0 a	0.010
Mn (mg/L)	2011/2012	0.61 a	0.64 a	0.69 a	0.277
	2014/2015	0.36 a	0.31 a	0.34 a	0.453
B (mg/L)	2011/2012	0.74 a	0.80 a	0.75 a	0.58
	2014/2015	0.24 a	0.22 a	0.27 a	0.258
Cu (mg/L)	2011/2012	85 a	82 a	83 a	0.884
	2014/2015	54 a	41 a	67 a	0.052
Zn (mg/L)	2011/2012	70 a	69 a	70 a	0.963
	2014/2015	57 ab	48 b	61 a	0.032
Ca (mg/L)	2011/2012	13 a	11 a	12 a	0.442
	2014/2015	16 a	10 a	14 a	0.331
Mg (mg/L)	2011/2012	1120 b	1222 a	1080 b	0.007
	2014/2015	933 a	950 a	753 a	0.201
Na (mg/L)	2011/2012	162 b	183 a	167 b	0.004
	2014/2015	123 ab	102 b	129 a	0.036
K (mg/L)	2011/2012	53 a	55 a	54 a	0.871
	2014/2015	45 a	41 a	50 a	0.297
P (mg/L)	2011/2012	185 a	144 a	160 a	0.189
	2014/2015	119 a	177 a	128 a	0.343
S (mg/L)	2011/2012	103 a	80 a	79 a	0.065
	2014/2015	64 a	93 a	64 a	0.394

Different superscript letters within rows indicate statistical differences using LSD at a 5 % level and within one growing season.

CONCLUSION

The results of this paper highlight numerous benefits of silica application, including increases in yield and overall vine growth, reduced boron accumulation, increased flavour intensity in grapes, enhanced aroma and flavour in Cabernet-Sauvignon wines, increased colour intensity, altered sensory perception of phenolics in both grapes and wine. Noteworthy changes in berry skin and seed attributes were observed, particularly increases in mouthfeel attributes in both silica

TABLE 6. The effect of biodynamic silica and potassium silicate on berry juice compositional measures of Cabernet-Sauvignon in the 2011/12 and 2014/15 growing seasons, Coombe vineyard, Adelaide, Australia.

Variable	Season	Treatments			P-value
		Control	Potassium Silicate	Biodynamic Silica	
TSS (°Brix)	2011/2012	24.1 a	24.6 a	24.4 a	0.728
	2014/2015	24.5 a	23.0 a	24.1 a	0.375
pH	2011/2012	3.69 a	3.47 a	3.68 a	0.322
	2014/2015	3.96 a	4.06 a	3.96 a	0.381
Titratable acidity (g/L)	2011/2012	2.5 a	3.6 a	3.4 a	0.075
	2014/2015	4.6 a	4.7 a	4.4 a	0.231
Epicatechin concentration (g/L)	2011/2012	na	na	na	na
	2014/2015	2.71 a	3.51 a	2.95 a	0.318
Total phenolics/g berry weight	2011/2012	1.52 a	1.20 a	1.34 a	0.649
	2014/2015	1.79 a	2.38 a	2.02 a	0.303
Anthocyanin/g berry weight	2011/2012	3.02 a	2.40 a	2.81 a	0.829
	2014/2015	1.61 a	1.92 a	1.90 a	0.067
N (mg/L)	2011/2012	610 a	550 ab	500 b	0.037
	2014/2015	453 a	567 a	453 a	0.675
Fe (mg/L)	2011/2012	0.35 a	0.28 a	0.37 a	0.544
	2014/2015	0.54 a	0.90 a	0.65 a	0.524
Mn (mg/L)	2011/2012	1.53 a	0.62 b	0.86 b	0.010
	2014/2015	0.4 a	1.03 a	0.63 a	0.475
B (mg/L)	2011/2012	17 a	14 a	14 a	0.509
	2014/2015	12 a	18 a	14 a	0.485
Cu (mg/L)	2011/2012	1.1 a	1.2 a	1.1 a	0.722
	2014/2015	0.5 a	0.7 a	0.6 a	0.240
Zn (mg/L)	2011/2012	0.59 a	0.55 a	0.48 a	0.376
	2014/2015	0.45 ab	0.85 a	0.39 b	0.029
Ca (mg/L)	2011/2012	126 a	91 a	91 a	0.052
	2014/2015	73 a	110 a	80 a	0.309
Mg (mg/L)	2011/2012	120 a	88 a	90 a	0.125
	2014/2015	90 a	123 a	95 a	0.371
Na (mg/L)	2011/2012	16 a	13 b	12 b	0.019
	2014/2015	13 a	15 a	12 a	0.510
K (mg/L)	2011/2012	2263 a	2037 a	2213 a	0.566
	2014/2015	1190 a	1843 a	1190 a	0.136
P (mg/L)	2011/2012	185 a	144 a	160 a	0.189
	2014/2015	119 a	177 a	128 a	0.343
S (mg/L)	2011/2012	103 a	80 a	79 a	0.065
	2014/2015	64 a	93 a	64 a	0.394

Different superscript letters within rows indicate statistical differences using LSD at a 5 % level and within one growing season.

treatments. The experiment indicated that potassium silicate yielded more significant benefits, possibly due to the lower silica concentration in the biodynamic application.

Although more significant variation was seen between treatments in berry sensory attributes than in compositional or vine attributes, it remains to be seen if these treatments will differ significantly over the long term. Silicon has been shown to influence phenolic concentration in the cell walls of grasses and cereal crops but has not been observed in fruit previously (Ma and Takahashi, 2002). Increases in perceived

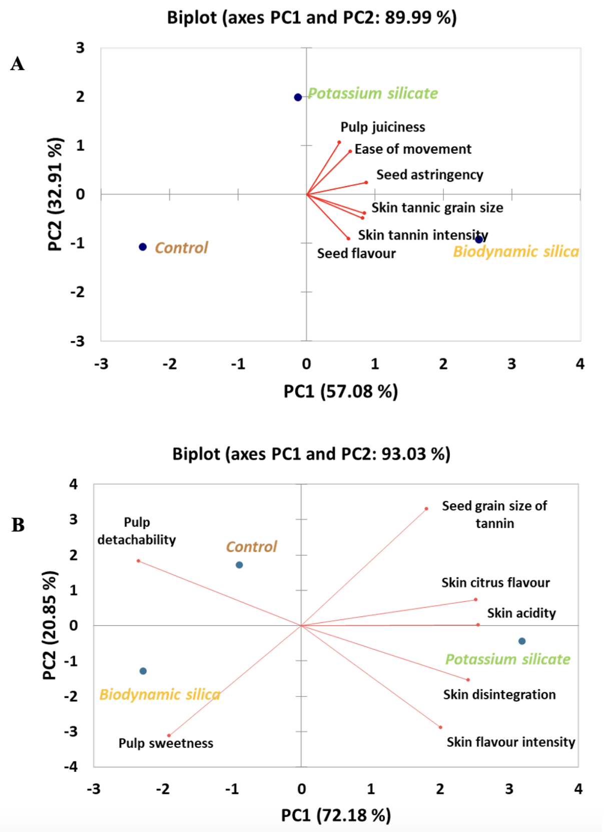

FIGURE 2. Principal component analysis of significantly different berry sensory attributes for Semillon from Control, Commercial potassium silicate, and Biodynamic silica treatments. A = Semillon 2011/12 season, B = Semillon 2014/2015 season, Coombe vineyard, Adelaide, Australia.

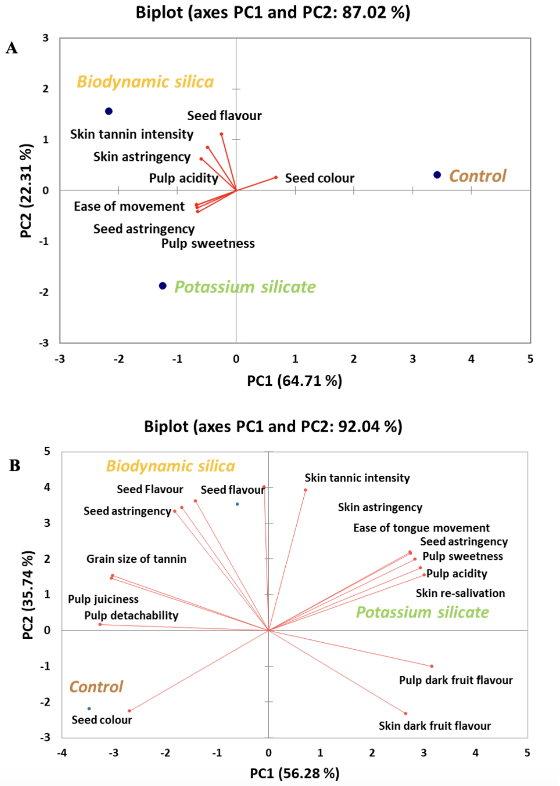

FIGURE 3. Principal component analysis of significantly different berry sensory attributes for Cabernet-Sauvignon from Control, Commercial potassium silicate, and Biodynamic silica treatments. A = Cabernet-Sauvignon 2011/12 season, B = Cabernet-Sauvignon 2014/15 season, Coombe vineyard, Adelaide, Australia.

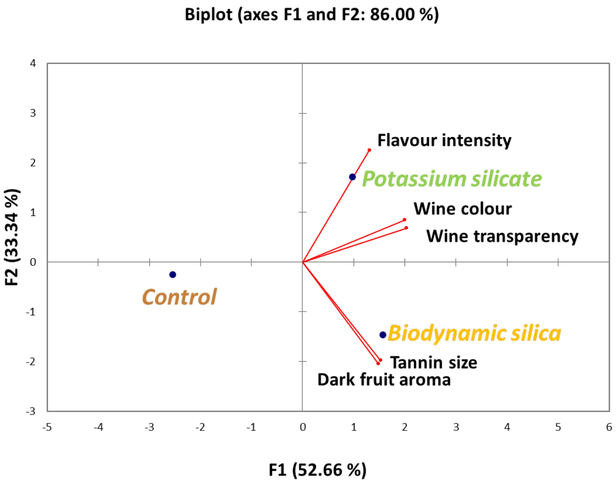

FIGURE 4. Principal component analysis of significantly different wine sensory attributes for Cabernet-Sauvignon from Control, Commercial potassium silicate, and Biodynamic silica treatments in the 2014/15 season, Coombe vineyard, Adelaide, Australia.

astringency may be attributable to changes in tannin type and structure; further research will help elucidate this effect and substantiate biodynamic producer claims of increased light interception or a direct binding of silicon with polyphenols. Quantifying the links between grape composition and wine sensory attributes will aid in determining whether these skin and seed attributes are positive, thereby confirming anecdotal evidence of improved fruit quality through silica application in vineyards.

The study suggests that applying silica could help to improve vine growth and fruit quality. Further research should explore the specific mechanisms by which silica interacts with phenolics, the optimal concentrations for different grape varieties, and the long-term impacts on vineyard health and productivity. Understanding these factors will help optimise silica applications for maximum benefit, supporting sustainable viticulture practices.

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