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Review

The Impact of Vineyard Mechanization on Grape and Wine Phenolics, Aroma Compounds, and Sensory Properties

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Abstract: Grapes are one of the most valuable fruit crops in the United States and can be processed into a variety of products. The grape and wine industry contributes to and impacts the U.S. agricultural economy. However, rising labor costs and global competition pose challenges for the grape and wine industry. Vineyard mechanization is a promising strategy to increase efficiency and address the labor shortage and cost issues. Recent studies have focused on the impact of vineyard mechanization on general grape and wine quality. Wine phenolics, aroma compounds, and sensory characteristics are the key indicators of wine quality and consumer preference. This article aims to review the impact of vineyard mechanization, specifically mechanical harvesting, mechanical leaf removal, mechanical shoot thinning, cluster thinning, and mechanical pruning on grape and wine phenolics, and aroma compounds and sensory profile. Studies have shown that vineyard mechanization significantly affects phenolic and aroma compounds, especially grape-derived aroma compounds such as volatile thiols, terpenes, C13-norpentadiene, and methoxypyrazine. Mechanically processed grapes can produce wines of the same or better quality than wines made from hand-operated grapes. Vineyard mechanization could be a promising strategy for grape growers to reduce operating costs and maintain or improve grape and wine quality. Future research directions in the area of vineyard mechanization were discussed. It provides a comprehensive view and information on the topic to both grape growers and winemakers in the application of vineyard mechanization.

Keywords: vineyard mechanization; phenolics; aroma compounds; sensory properties

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1. Introduction

Grapes are one of the most valuable crops in the American agricultural sector. The grape and wine industry is the main economic engine of the U.S. agricultural economy. According to a market analysis report, the U.S. wine market was worth $63.69 billion in 2021 and is predicted to grow at a compounded annual growth rate (CAGR) of 6.8% through 2030 [1]. California leads the country in grape production, and 2021 grape acreage of this region totaled 881,000 acres [2]. The crop is mainly used for wine, raisins, table grapes, concentrated grape juice, and distillate. It is well known that grape production is highly labor-intensive. Labor costs account for about 60% of the annual cost of wine grape production [3]. Grape harvesting, pruning, canopy management, grapevines tying, and suckering are the most labor-intensive practices. However, over the last several years, labor-related issues are becoming increasingly challenging due to labor shortage [4,5]. Labor safety issues such as respiratory problems, high temperatures, and seasonal rainfall, and the recent effects of COVID-19 negatively affect the production cost and stable labor supply for future seasons. Short-term strategies to deal with labor shortages include raising wages, reducing workload or using immigrant labor. In the long run, adopting vineyard mechanization to manage labor demand and production costs and improving working conditions for farm workers are sustainable solutions. In addition, the increased competition from global markets with inexpensive labor is also one of the big drivers behind the faster adoption of mechanization in the vineyard to ensure competitiveness.

Vineyard mechanization has been around for about 70 years. In the early 1950s, the University of California, Davis, began to study the mechanization of vineyards [6]. In 1957, a few researchers at Cornell University's New York State Agricultural Experiment Station in Geneva, NY developed the Geneva double curtain (GDC) trellis, which facilitated the mechanical harvesting of Concord grapes [7]. Today, mechanization is used in vineyards for different purposes, from simple tillage to harvesting, pruning, defoliation, shoot positioning, and shoot and cluster thinning throughout the vine growing season. Well-trained operators can perform tasks more efficiently [8].

An increasing number of grape growers are interested in adopting mechanization in their vineyards, especially in the regions focusing on grape yield, such as the Central Valley of California. It is critical to understand better the relationship between mechanization and berry/wine quality. Vineyard mechanization is a rapidly evolving area of research and development. A number of studies have focused on the effects of vineyard mechanization of harvesting, pruning, leaf removal, and shoot thinning on berry and wine phenolics, aroma compounds, and sensory changes. Wine phenolics (polyphenols, phenols) are a diverse group of compounds that share a phenol ring in their primary chemical structure. Important groups of wine phenolics include anthocyanins, flavan-3-ols, and their derivatives, which contribute to wine color, wine texture, mouthfeel, and aging potential. The majority of phenols in wine are grape-derived, and a small proportion may be contributed by oak barrels or oak adjuncts. Aroma compounds are important secondary metabolites. Although they only accounts for a small part of grape and wine, these compounds play an essential role in shaping wine's identity. They can be grape-derived, such as terpenes, C13-norisoprene, methoxypyrazine, or microbial-derived esters. From the consumers' perspective, taste is generally considered the most important factor influencing purchase preference. This article reviews the impact of vineyard mechanization on grape and wine phenolics, aroma compounds and sensory profiles. It will help researchers, grape growers, and winemakers better understand the benefit and potential application of vineyard mechanization.

2. Mechanical Harvesting

The wine industry has been using hand-picking as a differentiator when promoting the quality and style of wine. Despite the lack of evidence to support a relationship between this practice and wine quality, it has made consumers believe that mechanically harvested grapes produce inferior wines [9].

Mechanical harvesting of wine grapes was developed in the 1950s [6,7] and widely studied in the United States in the 1970s [10]. The practice was widely adopted in Italy as early as 1980 [11]. The rudimentary technology of early mechanical harvesters led to increased mechanical stress on the fruit and could not sufficiently eliminate materials other than grapes (MOG) during the harvest. The extent of mechanical stress grapes undergo during harvesting depends on several factors, including the degree of ripeness and the overall condition and health of the berries at harvest. Technologies in mechanical harvesting have evolved over the past four decades, particularly with the addition of sorting and destemming techniques to remove MOG. Typically, the purpose of hand-sorting at the winery is to eliminate undesirable fruit picked by mechanical harvesters, but it is tedious and requires tremendous resources as inspection of individual berries is necessary to sort the already destemmed fruit. Optical sorters, however, are well-suited to sort destemmed grapes rapidly. Sorting is based on parameters, such as berry size, color, and shape, and whether there is foreign material. Nowadays, optical berry sorters have become more common in commercial wine production. There are a few studies investigating their effects on the chemical and sensory properties of wine. In a study on synergistic effects of harvest method (hand and machine) and optical sorting or none, differences in the cv. Pinot Noir grape and wine composition that were attributable to the harvest method were reduced or eliminated with the use of optical sorting. The machine-harvested grapes had higher levels of β-damascenone, linalool, β-myrcene, and -terpinene, potentially caused by glycosidic hydrolysis triggered by berry damage during harvest or from induced synthesis as a wounding response [12].

There is growing evidence that wines made from mechanically harvested grapes are of comparable quality to wines made from hand-picked grapes. One study used cv. Chardonnay wines were made with machine- and hand-harvested grapes and found that there was no significant difference between the two for both young wines and wines aged 18 months made from grapes harvested by the two methods [13]. Another study evaluated red and white grape varieties (cv. Petit Syrah, French Colombard, and Chenin Blanc) and found no difference in wines made from grapes harvested with either method [14]. In some studies, wines made from machine-picked grapes were even superior to wines made from hand-picked grapes [15]. Kaltbach et al. (2022) investigated the effects of manual and mechanical harvesting on the composition of Merlot musts and wines produced in the Campanha Gaúcha region of Brazil through comprehensive testing of physicochemical parameters. Merlot wines made from mechanically harvested grapes had slightly higher levels of pH, ethanol, and magnesium. Mechanical harvesting significantly reduced caffeic and coumaric acids in wines. All other parameters did not show significant differences. Manual and mechanical harvesting of grapes can produce identical wines [16].

The fruity aroma of Sauvignon blanc wine is dependent upon concentrations of varietal thiols, various esters, higher alcohols, methoxypyrazines, and terpenes. The intense passion fruit aroma has been associated with the varietal thiols, which includes 3-Mercaptohexanol (3MH), 3-mercaptohexyl acetate (3MHA), 4-mercapto-4-methylpentan-2-one (4MMP), 4-mercapto-4-methylpentan-2-ol (4MMPOH), 3-mercapto-3-methylbutan-1-ol (3MMB) [17]. 3MH and 3MHA are key compounds of the aroma typicity of young Sauvignon blanc wines and generated during the fermentation process by yeast from precursors initially present in the grape. Cys-3MH and glutathionyl-3MH (Glut-3MH) are two longer-lived precursors, which were the first 3MH precursors to be identified [16]. Bonnaffoux et al. (2018) identified and quantified two short-lived precursors such as 3S-cysteinylglycinylhexan-1-ol (CysGly-3SH) and 3S-glutamylcysteinylhexan-1-ol (-GluCys-3SH) in juice and wine samples [18].

Jouanneau (2011) has found that the 3-MH concentrations in commercial Marlborough cv. Sauvignon blanc made from machine-harvest grapes are 5–10 times higher than the values obtained in experimental Sauvignon blanc wines made from hand-picked fruits [19]. Allen et al. (2011) and Herbst-Johnstone et al. (2013) showed that the harvesting of cv. Sauvignon blanc by machine harvester increased certain varietal aroma compounds [20,21]. The ability to increase the aroma precursor compounds during the harvesting process provides an opportunity to alter maceration techniques to enhance the passion fruit aroma in the finished wines. Olejar et al. (2015) sourced hand and mechanically harvested grapes of cv. Sauvignon blanc from Marlborough, New Zealand [22]. There was an increase in varietal thiol content for wines made from juices that had been machine harvested compared to the hand-picked samples. Herbst-Johnstone et al. (2013) sourced cv. Sauvignon blanc grapes from five locations in Marlborough and at five stages during the harvesting process. Grapes were picked by hand and mechanical harvester. Commercial free run was pressed at one bar pressure. The study found that varietal thiols were present at relatively higher concentrations in wines made from machine-harvested fruit compared with wines made from hand-picked grapes [21]. A possible explanation is that berry damage that occurs during mechanical harvesting can release glycosidases, which may lead to higher concentrations of varietal thiols in mechanically harvested crops.

3. Mechanical Leaf Removal

Canopy management practices are carried out annually in vineyards to establish and maintain healthy canopies. Leaf removal is an integral part of canopy management practices in wine grapes (*Vitis vinifera*) to remove leaves around grape clusters, which commonly occurs in cool climate vineyards to accelerate air movement in the cluster zone, prevent disease, and promotes the biosynthesis of several important grape constituents, improve berry maturation, color and flavor [23]. Defoliation is typically performed between fruit set and veraison, but early leaf removal is a good cultural practice for yield management in grapevines and usually occurs around bloom. Due to the link between yield and the availability of carbohydrates at pre-bloom, early leaf removal suppresses yield [24], the effects of which are known to improve wine quality parameters. Leaf removal can be performed manually or mechanically. Vineyard mechanization can decrease labor costs and reduce exposure to the impact of labor shortages, but its influence on wine organoleptic properties is still not fully understood. With regard to leaf removal, research has focused on changes to red wine phenolics [25–28], white wine aroma compounds [29–31], hydroxycinnamates [32,33], and wine sensory quality [34–36], but few studies connect the effects of mechanization to wine sensory characteristics.

The timing of intervention plays a key role in the complex mechanisms involved in grape and wine aroma since it will affect the extent of berry sunlight exposure. Diago et al. (2010) investigated the effect of defoliation timing (before flowering and fruit set) on cv. Tempranillo grapes and wines. The effect of manual and mechanical defoliation on the aroma and sensory attributes of wines was compared in a vineyard in La Rioja, Spain, over two consecutive seasons, 2007 and 2008. The study confirms the effectiveness of both manual and mechanical early leaf removal. Pre-blooming leaf removal resulted in smaller berries and improved fruit health by reducing the occurrence of botrytis occurrence. Significant differences in wine aroma attributes were observed between the control and mechanical defoliation treatments [37].

Guidoni et al. (2008) studied the effects of mechanical and manual defoliation on the cv. Barbera in northwest Italy. In moderate climates, such as in northwestern Italy, leaf removal is employed to increase spray penetration and allow more light into the canopy to achieve physiological ripeness. There were significant differences in climatic conditions during the three years the experiment was conducted, which explains most of the variation in results. In terms of phenolic compounds, total phenols, proanthocyanidins, and anthocyanins were measured, but no significant differences between mechanical and hand defoliated grapes were found. Proanthocyanidins contribute to astringency in wine, a major factor for mouthfeel. From a sensory perspective, significant differences were not found between the treatment and control groups. This study suggests that the application of mechanical defoliation may vary. Climate, vineyard weather conditions, and vintage are key factors to consider when using mechanical defoliation. Under unfavorable ripening conditions, mechanical defoliation is more effective in improving grape health and quality. Excessive direct sunlight exposure needs to be prevented since it will cause berries to sunburn. This study suggests that random leaf removal by mechanical leaf removers may have greater advantages than manual leaf removal [38].

Kemp et al. (2011) in New Zealand investigated the effects of mechanical leaf removal on flavan-3-ol composition and concentration in cv. Pinot noir wine. The timing of the intervention was also explored. Flavan-3-ol is one of the phenolics that play a role in forming various tannins and influence the perception of bitterness in the wine. The study indicated that the naturally shaded fruit produced wines with lower monomer flavan-3-ol and tannin concentrations compared with the wines produced from defoliated grapevines. Leaf removal that occurred on the fruiting zone 7 days and 30 days after flowering, led to the highest tannin concentration. The second-year had higher tannin and monomer flavan-3-ols concentrations, which were attributed to either higher alcohol levels or more aggressive leaf removal in the second year or a combination of both factors [39].

Bubola et al. (2019) compared mechanical and manual defoliation with an untreated control group of Croatian cv. Istrian Malvasia grape varieties to understand their effect on wine quality. The study applied treatments at the pea-size stage of berry development. The experiment was carried out in a season characterized by abundant rainfall. Istrian Malvasia is a white *Vitis vinifera* variety that resembles cv. Sauvignon blanc. The study showed that mechanical leaf removal treatment significantly increased the concentration of some aroma compounds such as varietal thiol 3-sulfanylhexan-1-ol, monoterpenes, β-damascenone, and esters. Phenolics such as hydroxycinnamates were lower in wine made from mechanical leaf removal than wine from hand leaf removal. Sensory evaluation indicated wine made from mechanical leaf removal berries contained more enhanced floral, fruity and tropical attributes, which can be attributed to the improvement of aroma compounds [32].

4. Mechanical Shoot and Cluster Thinning

Shoot and cluster thinning are other canopy management practices that reduce crop load to the desired level for optimizing grape and wine quality [40]. Shoot thinning is a highly labor-intensive operation. Dean (2016) reports that the cost of thinning is about $650/ha. Mechanical shoot thinning is a cost-effective practice that reduces vineyard labor by 25 times compared to manual operations [41]. However, it is difficult to adjust the position and orientation of thinning end-effector to the shape of the cordons. The efficiency of mechanical thinning varies from 10% to 85%, depending on the forward speed of the tractor and the rotational speed of the thinning end effector [42]. Majeed et al. (2000) conducted research showing the performance and efficiency of mechanical shoot thinning machines can be greatly improved if the position of thinning end-effector is automatically controlled [43].

Yield management through the mechanical shoot and cluster thinning could induce berry chemical compositional changes, thus affecting wine aroma, taste, and mouthfeel. Diago et al. (2010) conducted an experiment applying mechanical cluster thinning at different intensities and different timings on cv. Grenache and cv. Tempranillo vines in Spain's Rioja region. The results indicated that mechanical cluster thinning was effective in yield reduction and resulted in more ripened fruit and wines with higher alcohol and pH values, more intense color, and increased phenolic content. The extent of the sensory implications seems dependent on several factors, such as the variety and timing of thinning applications. Regardless of the intensity of refinement, Grenache wines had less sensory impact than Tempranillo wines, which had improved aromas, acidity, and astringency from the vines subjected to mechanical cluster thinning [44].

Mechanical thinning could be combined with other vineyard management practices to improve grape and wine quality. Brillante et al. (2018) investigated the interactive effects of mechanical shoot thinning and irrigation management on the accumulation of phenolic and aroma compounds of cv. Syrah grapes and wines under the warm and semi-arid growing conditions of the San Joaquin Valley of California. The results showed that the interaction of two treatments could improve berry skin and wine phenolics and reduce herbaceous aroma, methoxypyrazines, and C_6-alcohol/aldehydes, in wine while achieving high yield if there is no precipitation from fruit set to veraison [45].

Petrie et al. (2006) studied the effects of mechanical crop removal after fruit set (when berries were pea-sized) on cv. Cabernet Sauvignon, at two vineyard sites in Australia (Riverland of South Australia and Sunraysia District of Victoria). The study indicated a significant increase in color density from the Riverland site over several vintages, while phenolic and anthocyanin concentrations in the wines showed similar trends to the grapes. Mechanical thinning successfully reduced crop level to the target yield. Mechanical thinning distorts the distribution for Brix and berry weight but can increase color and is best suited to small pruning situations. The results are consistent with other studies where either hand thinning or mechanical thinning had been used to reduce the crop level [46].

5. Mechanical Pruning

Pruning is a vineyard management practice that removes lignified growth from previous years of vines to promote new growth and fruiting while also controlling yield and growing time. Without pruning, grapevines would stimulate excessive vegetation and the proliferation of small clusters of fruit not suitable for winemaking. Leaving too many buds during pruning can lead to an imbalance in the vine's nutritional and reproductive growth, resulting in poor herbal aromas in the wine [47]. Mechanized vineyard management can reduce labor costs by 45–90%, depending on the region and trellis system [48,49]. Therefore, understanding the impact of mechanical pruning on wine phenolics, aroma, and sensory profile is essential to developing an accurate cost-benefit analysis. The effects of fully mechanized pruning systems on vine physiology, crop load, grapes, and wine quality have been studied since the early 1970s [50]. The studies showed inconsistent results about the application of mechanical pruning on grape and wine quality.

Reynolds (1988) evaluated the response of cv. Riesling vines in the Okanagan Valley, British Columbia, to different training systems and mechanical pruning. The study aimed to determine whether mechanical pruning was a viable option for maintaining profitability in an environment of increasing labor costs without negatively impacting wine quality. Vine training systems, mid-wire bilateral cordon (MBC), Hudson River Umbrella (HBU), and Lenz Moser (LM) were used for mechanical and hand pruning. The ethanol and pH levels of wines made from mechanically trimmed grapes were overall lower than those of hand-pruned wines. The sensory panelists found that mechanical pruning tended to reduce wine quality compared to manual pruning [51]. Santos et al. (2015) conducted an experiment in Brazil using cv. Cabernet Franc, IAC-Máximo, and Merlot to determine the effects of the initial adoption of mechanical pruning on the grape composition, quality, and sensory characteristics of wines. The results showed that applying mechanical pruning in traditional vineyards caused small fluctuations in grape quality [52]. Holt et al. (2008) conducted a study on the relationships between wine phenolic composition and wine sensory properties for cv. Cabernet Sauvignon between 2003–2005 at one vineyard site in the Clare Valley region of South Australia. Machine pruning was compared to hand and spur pruned vines. The results of the study showed that machine-pruned vines resulted in wines that were comparable to hand-pruned wines with respect to wine composition. Machine pruned berry and wine were significantly higher in total anthocyanins. However, color density in the finished wine was the same as in the hand-pruned treatments, suggesting that berry anthocyanins from machine-pruned vines were less extractable than their hand-harvested counterparts [53]. These results are supported by other research, which has shown no direct correlation between berry tannins and their corresponding wine tannins in various red *Vitis vinifera* L. species [54]. Higher concentrations of anthocyanins, tannins, and phenolics in berries from machine-pruned vines did not always correspond to higher concentrations in wine.

Kronfli III (2018) evaluated the sensory effects of mechanical pruning on cv. Syrah via a general descriptive analysis. The mechanically pruned Syrah wines were shown to be not significantly different from the wines made from the hand-pruned vines when harvested at equal levels of ripeness [55]. Between 2013–2015, a study was conducted in Fresno, California, to evaluate the impact of converting a non-mechanized cv. Merlot vineyard to mechanized pruning [49]. The control groups were cane pruned (CP) and bilateral cordon spur pruned (HP) vines and the treatment was a mechanically box-pruned single high-wire sprawling system (SHMP). The effects of mechanization on phenolics profile were determined by evaluating the concentration of gallic acid, total flavan-3-ol, total flavonols, total anthocyanins, and individual anthocyanins. The results of the study showed no adverse effects of mechanical pruning on berry flavonoid concentration throughout the experiment.

The interaction between mechanical pruning and plant nutrition was comprehensively investigated by Botelho et al. (2020, 2021, 2022) [56–58]. The study assessed the interaction between mechanical pruning and soil organic amendments in two trial fields in Portugal. The objective was to evaluate whether a deleterious effect on cv. Syrah berry composition could occur between mechanical pruning and organic soil amendments because their interaction has been known to negatively affect the balance between grapevine vegetative and reproductive growth and berry composition. In particular, the effects of nitrogen (N), added by sources such as organic soil amendments, have been shown to decrease polyphenol content [59]. Treatment groups included mechanical pruning and organic soil amendments of biochar, municipal solid waste compost, cattle manure, and sewage sludge.

These treatments were compared to control groups of spur pruning by hand and no organic soil amendments. The study found that the pruning method had little influence on color intensity and the color hue of wines. However, total anthocyanins were significantly lower in blocks pruned mechanically. Total phenols and tannin power showed little difference between pruning methods. The results of the sensory analysis showed that mechanical pruning reduced aroma balance, body, and astringency. Based on this study, mechanical pruning had significant effects on wine quality when the yield was above a certain level (6 kg/vine in the cooler climate and 8 kg/vine in the warmer climate. Thus, with this pruning system, the choice of the organic amendment and its amount may be critical. The combination of these two treatments is more suitable for the warm-climate region. In warm regions, harvest can be delayed with no threat of *B. cinerea* infections.

6. Conclusions and Future Directions

Wine-grape producers in many viticultural regions face many challenges. The major challenges are the increasing shortage and cost of skilled manual labor for vineyard management tasks that could suppress economic margins. This has driven more research investigating the potential of vineyard mechanization to manage vineyards cost-effectively.

Viticultural practices are known to influence secondary metabolites, phenolics, and aroma compounds. The berries' chemical composition is very sensitive to the microclimate. Vineyards are subjected to a large number of management practices, including row orientation and spacing, density, pruning, clipping, tilling, soil surface management, or manipulation of the canopy structure, among others, which leads to changes in the microclimate of the cluster. Most of them can be converted to mechanization. Some studies have demonstrated that phenolics and aroma compounds are affected by different types of vineyard mechanization (Tables 1 and 2). Some other studies have shown that mechanically treated grapes could produce wine of equal or better quality than wine made from grapes that had been operated manually. Vineyard mechanization could be a promising strategy for grape growers, especially in the regions focusing on yield. However, more research needs to be conducted to understand additional cultivars in different wine regions since this factor could be a variable.

Table 1. The impact of vineyard mechanization on grape and wine phenolics.

Phenolics	Functions	Vineyard Mechanization	Varieties	References	Impact
Hydroxycinnamate	Major phenolic compounds in white wine and are important in white wine color [60]	Mechanical harvesting	Merlot	Kaltbach et al. (2022) [16]	Reduced caffeic and coumaric acids in wines
		Mechanical leaf removal	Istrian Malvasia	Bubola et al. (2019) [32]	Reduced hydroxycinnamatein wines
Anthocyanin	Responsible for red wine color [60]	Mechanical harvesting with optical sorting	Pinot noir	Hendrickson et al. (2016) [12]	Increased total anthocyanins in berries
		Mechanical leaf removal	Barbera	Guidoni et al. (2008) [38]	Comparable to hand leaf removal
		Mechanical crop thinning	Cabernet Sauvignon	Petrie et al. (2006) [46]	Increased total anthocyanins in berries
		Mechanical pruning	Merlot	Kurtural et al. (2019) [49]	Comparable to hand pruning
			Cabernet Sauvignon	Holt et al. (2008) [53]	Increased anthocyanins in both berries and wines

Table 1. *Cont.*

Phenolics	Functions	Vineyard Mechanization	Varieties	References	Impact
		Mechanical pruning and soil amendment	Syrah	Botelho et al. (2020) [58]	Combination of two practices reduced anthocyanins
Flavan-3-ol monomers	Responsible for bitterness in wine and may also have some associated astringency [60]	Mechanical leaf removal	Pinot noir	Kemp et al. (2011) [39]	Increased flavan-3-ols in wines
		Mechanical pruning	Merlot	Kurtural et al. (2019) [49]	Comparable to hand pruning
Proanthocyanidins (condensed tannin)	Impart astringency to red wines [60]	Mechanical leaf removal	Barbera	Guidoni et al. (2008) [38]	Comparable to hand leaf removal
			Pinot noir	Kemp et al. (2011) [39]	Increased tannin in wines
		Mechanical pruning and soil amendment	Syrah	Botelho et al. (2020) [58]	Combination of two practices reduced tannin in wines

Table 2. The impact of vineyard mechanization on grape and wine aroma compounds.

Aroma Compounds		Odor Descriptor	Precursors	Vineyard Mechanization	Varieties	References	Impact
Varietal thiols	3-Mercaptohexanol (3MH or 3SH); 3-mercaptohexyl acetate (3MHA or 3SHA)	Passion fruit, Grapefruit	S-3-(hexan-1-ol)-L-cysteine (Cys-3MH); S-3-(hexan-1-ol)-glutathione (Glut-3MH)	Mechanical harvesting	Sauvignon blanc	Jouanneau (2011) [19] Allen et al. (2011) [20] Herbst-Johnstone et al. (2013) [21] Olejar et al. (2015) [22]	Increased 3MH and 3MHA in both berries and wines
				Mechanical leaf removal	Sauvignon blanc	Bubola et al. (2019) [32]	Increased 3MH in wines
Methoxypyrazine	IBMP	Bell pepper	Leucine	Mechanical shoot thinning and deficit irrigation	Syrah	Brillante et al. (2018) [45]	Reduced IBMP in wines
C13-norisoprenoid	β-Damascenone	Cooked apple, quince, floral	Glycosylated aroma compound	Mechanical leaf removal	Sauvignon blanc	Bubola et al. (2019) [32]	Increased β-Damascenone in wines
				Mechanical harvesting with optical sorting	Pinot noir	Hendrickson et al. (2016) [12]	Increased β-Damascenone in wines
Alcohols	C_6 Alcohol	Grass, green	Linoleic acid and linolenic acid	Mechanical shoot thinning and deficit irrigation	Syrah	Brillante et al. (2018) [45]	Reduced C_6 alcohol in wines
Monoterpenes	Citronellol Nerol Geraniol α-terpinene	Rose, citrus Floral	Glycosylated aroma compound	Mechanical leaf removal	Sauvignon blanc	Bubola et al. (2019) [32]	Increased monoterpenes in wines
				Mechanical harvesting with optical sorting	Pinot noir	Hendrickson et al. (2016) [12]	Increased α-terpinene in berries

Based on the previous studies, vineyard mechanization has a significant impact on aroma compounds, especially grape-derived aroma compounds such as volatile thiols, terpene, C13-norisoprenoid, and methoxypyrazine (Table 2). Grape-derived aroma compounds are one area of particular importance for wine quality due to their distinctiveness and ability to impart 'varietal aromas' to wines. Despite the noticeability of these odorants in the finished wines, these compounds are exclusively produced during fermentation and are not found in distinctive levels in the grape berry or pressed juice. It is the amounts of precursors (glycosides) that provide these aroma potentials. Although their proportion is not directly related to the organoleptic properties of the grapes, the concentration of precursor compounds in grapes could be an indicator of their aromatic potential. Moreover, these aroma precursors change throughout berry development, which is highly dependent on enzyme activity. To date, there are many studies on the impact of manual vineyard operation on grape and wine quality, but few have focused on the effect of vineyard mechanization on aroma precursors. Only Sauvignon blanc wine has been studied. Several volatile thiol precursors have been identified (3S-glutathionylhexan-1-ol (glut-3MH) and 3S-cysteinylhexan-1-ol (cys-3MH). Some studies showed enhanced enzymatic activity that follows mechanical harvesting might be very important in the formation of 3MH precursors in many grape lots and the subsequent release of the free thiols during fermentation. Additional research is needed to identify new aroma precursors, the effects of mechanical practice on enzymatic activity and aroma precursors' synthesis. A scientific understanding of precursors' change during berry development from fruit set to harvest is also critical.

The key to vineyard mechanization is to optimize aroma precursors and phenolics (hydroxycinnamate, anthocyanin, flavan-3-ol, condensed tannin, etc.) using different mechanical treatments during the vine growing and berry development period, which will give growers good guidance on the timing of operation application. More integrated work needs to be explored, such as mechanical harvesting with advanced sorting techniques, mechanical defoliation, mechanical crop thinning, mechanical pruning with vineyard irrigation, soil, or cover crop management.

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References

1. California Grape Acreage Report, 2021 Summary. Available online: https://www.nass.usda.gov/Statistics_by_State/California/Publications/Specialty_and_Other_Releases/Grapes/Acreage/2022/grpacSUMMARY2021Crop.pdf (accessed on 15 May 2022).
2. U.S. Wine Market Size, Share & Trends Analysis Report By Product (Table Wine, Dessert Wine, Sparkling Wine), By Distribution Channel (On-trade, Off-trade), And Segment Forecasts, 2022–2030. Available online: https://www.grandviewresearch.com/industry-analysis/us-wine-market/request/rs1 (accessed on 30 June 2022).
3. Developing a Viable Vineyard Workforce for the Future. Available online: https://grapesandwine.cals.cornell.edu/newsletters/appellation-cornell/2019-newsletters/issue-36-february-2019/viewpoints/ (accessed on 15 May 2022).
4. Brady, M.P.; Gallardo, R.K.; Badruddozza, S.; Jiang, X. Regional equilibrium wage rate for hired farm workers in the tree fruit industry. *Western Econ. Forum* **2016**, *15*, 20–31.
5. Brat, I. On U.S. Farms, Fewer Hands for the Harvest. Available online: https://www.newamericaneconomy.org/news/u-s-farms-fewer-hands-harvest/ (accessed on 12 May 2022).
6. Winkler, A.J.; Lamouria, L.H.; Abernathy, G.H. Mechanical grape harvest problems and progress. *Am. J. Enol. Vitic.* **1957**, *8*, 182–187.
7. Shaulis, N.J.; Shepardson, E.S.; Moyer, J.C. Grape harvesting research at Cornell NY State. *Hort. Soc.* **1960**, *105*, 250–254.
8. Kurtural, S.K.; Fidelibus, M.W. Mechanization of Pruning, Canopy Management, and Harvest in Winegrape Vineyards. *Catal. Discov. Pract.* **2021**, *5*, 29–44. [CrossRef]
9. Dominici, A.; Boncinelli, F.; Gerini, F.; Marone, E. Consumer Preference for Wine from Hand-Harvested Grapes. *Br. Food J.* **2019**, *122*, 2551–2567. [CrossRef]
10. Johnson, S.S. Mechanical harvesting of wine grapes. USDA, Economic Research Service. *Agric. Econ. Rep.* **1977**, *385*, 1–22.
11. Intrieri, C.; Filippetti, I. Innovations and outlook in grapevine training systems and mechanization in north-Central Italy. In Proceedings of the ASEV 50th Anniversary Annual Meeting, Seattle, WA, USA, 19–23 June 2000.

12. Hendrickson, D.A.; Lerno, L.A.; Hjelmeland, A.K.; Ebeler, S.E.; HHeymann, H.; Hopfer, H.; Block, K.L.; Brenneman, C.A.; Oberholster, A. Impact of Mechanical Harvesting and Optical Berry Sorting on Grape and Wine Composition. *Am. J. Enol. Vitic.* **2016**, *67*, 385–397. [CrossRef]
13. Clary, C.D.; Steinhauer, R.E.; Frisinger, J.E.; Peffer, T.E. Evaluation of machine- vs. hand-harvested Chardonnay. *Am. J. Enol. Vitic.* **1990**, *41*, 176–181.
14. Noble, A.C.; Ough, C.S.; Kasimatis, A.N. Effect of leaf content and mechanical harvest on wine "quality". *Am. J. Enol. Vitic.* **1975**, *26*, 158–163.
15. Kilmartin, P.A.; Oberholster, A. Grape Harvesting and Effects on Wine Composition. In *Managing Wine Quality*, 2nd ed.; Reynold, A., Ed.; Woodhead Publishing: Sawston, UK, 2022; Volume 1, pp. 705–726.
16. Kaltbach, S.B.A.; Kaltbach, P.; Santos, C.G.; Cunha, W.; Giacomini, M.; Domingues, F.; Malgarim, M.; Herter, F.G.; Costa, V.B.; Couto, J.A. Influence of manual and mechanical grape harvest on Merlot wine composition. *J. Food Compos. Anal.* **2022**, *110*, 1045–1048. [CrossRef]
17. Jeffery, D.W. Spotlight on Varietal Thiols and Precursors in Grapes and Wines. *Aust. J. Chem.* **2017**, *69*, 1323–1330. [CrossRef]
18. Bonnaffoux, H.; Delpech, S.; Rémond, E.; Schneider, R.; Roland, A.; Cavelier, F. Revisiting the evaluation strategy of varietal thiol biogenesis. *Food Chem.* **2018**, *268*, 126–133. [CrossRef]
19. Jouanneau, S. Survey of Aroma Compounds in Marlborough Sauvignon Blanc Wines—Regionality and Small Scale Winemaking. Ph.D. Thesis, The University of Auckland, Auckland, New Zealand, 2011.
20. Allen, T.; Herbst-Johnstone, M.; Girault, M.; Butler, P.; Logan, G.; Jouanneau, S. Influence of grape-harvesting steps on varietal thiol aromas in Sauvignon blanc wines. *J. Agric. Food Chem.* **2011**, *59*, 10641–10650. [CrossRef]
21. Herbst-Johnstone, M.; Araujo, L.D.; Allen, T.A.; Logan, G.; Nicolau, L.; Kilmartin, P.A. Effects of Mechanical Harvesting on 'Sauvignon Blanc' Aroma. *Acta Hortic.* **2013**, *978*, 179–186. [CrossRef]
22. Olejar, K.J.; Fedrizzi, B.; Kilmartin, P.A. Influence of Harvesting Technique and Maceration Process on Aroma and Phenolic Attributes of Sauvignon Blanc Wine. *Food Chem.* **2015**, *183*, 181–189. [CrossRef]
23. Downey, M.O.; Dokoozlian, N.K.; Krstic, M.P. Cultural Practice and Environmental Impacts on the Flavonoid Composition of Grapes and Wine: A Review of Recent Research. *Am. J. Enol. Vitic.* **2006**, *57*, 257–268.
24. Caspari, H.V.; Lang, A. Carbohydrate supply limits fruit-set in commercial Sauvignon blanc grapevines. In Proceedings of the 4th International Symposium on Cool Climate Enology and Viticulture, Rochester, NY, USA, 16–20 July 1996.
25. Feng, H.; Qian, M.C.; Skinkis, P.A. Pinot Noir Wine Volatile and Anthocyanin Composition under Different Levels of Vine Fruit Zone Leaf Removal. *Food Chem.* **2017**, *214*, 736–744. [CrossRef]
26. Bubola, M.; Sivilotti, P.; Janjanin, D.; Poni, S. Early Leaf Removal Has a Larger Effect than Cluster Thinning on Grape Phenolic Composition in Cv. Teran. *Am. J. Enol. Vitic.* **2017**, *68*, 234–242. [CrossRef]
27. Osrečak, M.; Karoglan, M.; Kozina, B. Influence of Leaf Removal and Reflective Mulch on Phenolic Composition and Antioxidant Activity of Merlot, Teran and Plavac Mali Wines (*Vitis Vinifera* L.). *Sci. Hortic.* **2016**, *209*, 261–269. [CrossRef]
28. Palliotti, A.; Gardi, T.; Berrios, J.G.; Civardi, S.; Poni, S. Early Source Limitation as a Tool for Yield Control and Wine Quality Improvement in a High-Yielding Red *Vitis Vinifera* L. Cultivar. *Sci. Hortic.* **2012**, *145*, 10–16. [CrossRef]
29. Friedel, M.; Frotscher, J.; Nitsch, M.; Hofmann, M.; Bogs, J.; Stoll, M.; Dietrich, H. Light Promotes Expression of Monoterpene and Flavonol Metabolic Genes and Enhances Flavour of Winegrape Berries (*Vitis Vinifera* L. Cv. Riesling). *Aust. J. Grape Wine Res.* **2016**, *22*, 409–421. [CrossRef]
30. Gregan, S.M.; Wargent, J.J.; Liu, L.; Shinkle, J.; Hofmann, R.; Winefield, C.; Trought, M.; Jordan, B. Effects of Solar Ultraviolet Radiation and Canopy Manipulation on the Biochemical Composition of Sauvignon Blanc Grapes. *Aust. J. Grape Wine Res.* **2012**, *18*, 227–238. [CrossRef]
31. Martin, D.; Albright, A.; McLachlan, A.; Fedrizzi, B.; Grose, C.; Stuart, L. Grape Cluster Microclimate Influences the Aroma Composition of Sauvignon Blanc Wine. *Food Chem.* **2016**, *210*, 640–647. [CrossRef] [PubMed]
32. Bubola, M.; Vanzo, A.; Bavčar, D.; Lukić, I.; Lisjak, K.; Grozić, K.; Sivilotti, P.; Radeka, S. Enhancement of Istrian Malvasia Wine Aroma and Hydroxycinnamate Composition by Hand and Mechanical Leaf Removal. *J. Sci. Food Agric.* **2019**, *99*, 904–914. [CrossRef]
33. Lemut, M.S.; Sivilotti, P.; Franceschi, P.; Wehrens, R.; Vrhovsek, U. Use of Metabolic Profiling to Study Grape Skin Polyphenol Behavior as a Result of Canopy Microclimate Manipulation in a 'Pinot Noir' Vineyard. *J. Agric. Food Chem.* **2013**, *61*, 8976–8986. [CrossRef]
34. Coniberti, A.; Ferrari, V.; Dellacassa, E.; Boido, E.; Carrau, F.; Gepp, V.; Disegna, E. Kaolin over Sun-Exposed Fruit Affects Berry Temperature, Must Composition and Wine Sensory Attributes of Sauvignon Blanc. *Eur. J. Agron.* **2013**, *50*, 75–81. [CrossRef]
35. Šuklje, K.; Antalick, G.; Coetzee, Z.; Schmidtke, L.M.; Baša Česnik, H.; Brandt, J.; Toit, W.J.; Lisjak, K.; Deloire, A. Effect of Leaf Removal and Ultraviolet Radiation on the Composition and Sensory Perception of *Vitis Vinifera* L. Cv. Sauvignon Blanc Wine. *Aust. J. Grape Wine Res.* **2014**, *20*, 223–233. [CrossRef]
36. Šuklje, K.; Antalick, G.; Buica, A.; Langlois, J.; Coetzee, Z.A.; Gouot, J.; Schmidtke, L.M.; Deloire, A. Clonal Differences and Impact of Defoliation on Sauvignon Blanc (*Vitis Vinifera* L.) Wines: A Chemical and Sensory Investigation. *J. Sci. Food Agric.* **2016**, *96*, 915–926. [CrossRef]
37. Diago, M.P.; Vilanova, M.; Blanco, J.A.; Tardaguila, J. Effects of Timing of Manual and Mechanical Early Defoliation on the Aroma of *Vitis vinifera* L. Tempranillo Wine. *Am. J. Enol. Vitic.* **2010**, *61*, 382–391.

38. Guidoni, S.; Oggero, G.; Cravero, S.; Rabino, M.; Cravero, M.C.; Balsari, P. Manual and Mechanical Leaf Removal in the Bunch Zone (*Vitis Vinifera* L., Cv Barbera): Effects on Berry Composition, Health, Yield and Wine Quality, in a Warm Temperate Area. *OENO One* **2008**, *42*, 49–58. [CrossRef]
39. Kemp, B.S.; Harrison, R.; Creasy, G.L. Effect of Mechanical Leaf Removal and Its Timing on Flavan-3-ol Composition and Concentrations in *Vitis Vinifera* L. Cv. Pinot Noir Wine. *Aust. J. Grape Wine Res.* **2011**, *17*, 270–279. [CrossRef]
40. Smart, R.E. Shoot spacing and canopy light microclimate. *Am. J. Enol. Vitic.* **1988**, *39*, 325–333.
41. Dean, S. Mechanical Shoot & Leaf Removal Practices. 2016. Available online: https://www.awri.com.au/wp-content/uploads/2016/06/4-Mechanical-Shoot-Leaf-Removal_Sean_Dean.pdf (accessed on 15 May 2022).
42. Dokoozlian, N. The evolution of mechanized vineyard production systems in California. *Acta Hortic.* **2013**, *978*, 265–278. [CrossRef]
43. Majeed, Y.; Karkee, M.; Zhang, Q.; Fu, L.; Whiting, M.D. Determining grapevine cordon shape for automated green shoot thinning using semantic segmentation-based deep learning networks. *Comput. Electron. Agric.* **2000**, *171*, 105308. [CrossRef]
44. Diago, M.P.; Vilanova, M.; Blanco, J.A.; Tardaguila, J. Effects of Mechanical Thinning on Fruit and Wine Composition and Sensory Attributes of Grenache and Tempranillo Varieties (*Vitis Vinifera* L.): Mechanical Thinning on Fruit and Wine Composition. *Aust. J. Grape Wine Res.* **2010**, *16*, 314–326. [CrossRef]
45. Brillante, L.; Martínez-Lüscher, J.; Kurtural, S.K. Applied Water and Mechanical Canopy Management Affect Berry and Wine Phenolic and Aroma Composition of Grapevine (*Vitis Vinifera* L., Cv. Syrah) in Central California. *Sci. Hortic.* **2018**, *227*, 261–271. [CrossRef]
46. Petrie, P.R.; Clingeleffer, P.R. Crop Thinning (Hand versus Mechanical), Grape Maturity and Anthocyanin Concentration: Outcomes from Irrigated Cabernet Sauvignon (*Vitis Vinifera* L.) in a Warm Climate. *Aust. J. Grape Wine Res.* **2006**, *12*, 21–29. [CrossRef]
47. Terry, D.B.; Kurtural, S.K. Achieving Vine Balance of Syrah with Mechanical Canopy Management and Regulated Deficit Irrigation. *Am. J. Enol. Vitic.* **2011**, *62*, 426–437. [CrossRef]
48. Morris, J.R. Development and Commercialization of a Complete Vineyard Mechanization System. *Horttechnology* **2007**, *17*, 411–420. [CrossRef]
49. Kurtural, S.K.; Beebe, A.E.; Martínez-Lüscher, J.; Zhuang, S.J.; Lund, K.T.; McGourty, G.; Bettiga, L.J. Conversion to Mechanical Pruning in Vineyards Maintains Fruit Composition While Reducing Labor Costs in "Merlot" Grape Production. *Horttechnology* **2019**, *29*, 128–139. [CrossRef]
50. Poni, S.; Tombesi, S.; Palliotti, A.; Ughinia, V.; Gatti, M. Mechanical winter pruning of grapevine: Physiological bases and applications. *Sci. Hortic.* **2016**, *204*, 88–98. [CrossRef]
51. Reynolds, A.G. Response of Okanagan Riesling Vines to Training System and Simulated Mechanical Pruning. *Am. J. Enol. Vitic.* **1988**, *39*, 205–212.
52. Santos, A.O.; Pereira, S.E.; Moreira, C.A. Physical-Chemical Quality of Grapes and wine sensory profile for different varieties of vine subjected to mechanical pruning. *Rev. Bras. Frutic.* **2015**, *37*, 432–441. [CrossRef]
53. Holt, H.E.; Francis, I.L.; Field, J.; Herderich, M.J.; Iland, P.G. Relationships between Wine Phenolic Composition and Wine Sensory Properties for Cabernet Sauvignon (*Vitis Vinifera* L.). *Aust. J. Grape Wine Res.* **2008**, *14*, 162–176.
54. Harbertson, J.F.; Kennedy, J.A.; Adams, D.O. Tannin in Skins and Seeds of Cabernet Sauvignon, Syrah, and Pinot Noir Berries during Ripening. *Am. J. Enol. Vitic.* **2002**, *53*, 54–59.
55. Kronfli, E.J., III. Sensory Effect of Regulated Deficit Irrigation and Mechanical Pruning on Washington State Wines. Master's Thesis, University of California, Davis, CA, USA, 2018.
56. Botelho, M.; Cruz, A.; Ricardo-da-Silva, J.; de Castro, R.; Ribeiro, H. Mechanical Pruning and Soil Fertilization with Distinct Organic Amendments in Vineyards of Syrah: Effects on Vegetative and Reproductive Growth. *Agronomy* **2020**, *10*, 1090. [CrossRef]
57. Botelho, M.; Ribeiro, H.; Cruz, A.; Duarte, D.F.; Faria, D.L.; de Castro, R.; Ricardo-Da-Silva, J. Mechanical Pruning and Soil Organic Amendments in Vineyards of Syrah: Effects on Grape Composition. *OENO One* **2021**, *55*, 267–277. [CrossRef]
58. Botelho, M.; Ribeiro, H.; Cruz, A.; Duarte, D.F.; Faria, D.L.; Khairnar, K.S.; Pardal, R.; Susini, M.; Correia, C.; Catarino, S.; et al. Mechanical Pruning and Soil Organic Amending in Two Terroirs. Effects on Wine Chemical Composition and Sensory Profile. *Am. J. Enol. Vitic.* **2022**, *73*, 26–38. [CrossRef]
59. Delgado, R.; Martin, P.; del Alamo, M.; Gonzalez, M.R. Changes in the Phenolic Composition of Grape Berries during Ripening in Relation to Vineyard Nitrogen and Potassium Fertilisation Rates. *J. Sci. Food Agric.* **2004**, *84*, 623–630. [CrossRef]
60. Kennedy, J.A.; Saucier, C.; Glories, Y. Grape and Wine Phenolics: History and Perspective. *Am. J. Enol. Vitic.* **2006**, *57*, 239–248.