iVES OENO One vine & wine

DOI: https://doi.org/10.20870/oeno-one.2025.59.1.8238

OPEN ACCESS

REVIEW ARTICLES

Unravelling the influence of cluster thinning on wine quality: A narrative systematic review

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Article number: 8238

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Associate editor:
Matteo Marangon

Received:
24 July 2024

Accepted:
30 September 2024

Published:
9 January 2025

ABSTRACT

This review examines the impact of cluster thinning (CT) on wine quality. CT is a vineyard management technique intended to enhance the sensory attributes of wine, such as aroma and flavour. We employed a narrative approach, synthesising findings from various studies without the use of statistical meta-analysis. This method allowed us to capture a broad spectrum of insights and draw practical conclusions for winemakers. Our review spans different grape varieties and climates. The studies reviewed include CT interventions at various growth stages—flowering, fruit set, veraison, and post-veraison—with varying levels of thinning severity. Methods range from manual thinning to mechanical approaches, with comparisons made to control groups that did not undergo CT. Our primary focus was on sensory analysis, wine phenolic composition volatile compound composition, and overall quality assessments. We paid particular attention to sensory descriptors related to aroma and flavour profiles, evaluating quality and preference scores. This review consolidates existing research to provide a comprehensive understanding of CT's role in viticulture. It offers practical guidance for optimising CT practices to improve wine quality and identifies areas where further research is needed. By integrating diverse findings, this review contributes valuable insights for winemakers aiming to enhance their vineyard management techniques.

KEYWORDS: narrative analysis, systematic review, cluster thinning, quality, sensory analysis

INTRODUCTION

For centuries, the pursuit of exceptional wine has revolved around attention to detail, from choosing particular grape varieties to the interplay of sun exposure, soil composition, and vine balance. Among these practices, cluster thinning (CT) remains a popular practice, its history stretching back to the beginnings of viticulture. From Roman texts praising its impact on grape quality to its enduring presence in renowned wine regions worldwide, cluster thinning has held a consistent place in grapevine management (Keller *et al.*, 2005; Matthews, 2015). However, despite its historical significance and continued practice, its precise influence on wine quality remains difficult to interpret due to the vast amount of research and sometimes conflicting anecdotal evidence.

1. Understanding cluster thinning

Cluster thinning, the purposeful removal of grape clusters partway through the season, aims to achieve optimal vine balance to influence key berry quality attributes like sugar content (Brix), titratable acidity (TA), total phenolics, total anthocyanin content, and aromatic compounds (Ough & Nagaoka, 1984; Rutan *et al.*, 2018). Driven by this established notion that smaller yields lead to less dilution and potentially richer flavour and aroma profiles, many viticulturists implement practices that encourage smaller berries or lower yields. However, translating this adage into practice has proven more difficult, with various studies reporting conflicting results on cluster thinning's effectiveness in improving specific quality parameters (Chapman *et al.*, 2004; Vanderweide *et al.*, 2024). This underscores the need for a comprehensive analysis examining the impact of cluster thinning specifically on wine quality parameters and sensory implications.

Cluster thinning serves multiple purposes in vineyard management. Its implementation is often driven by the need to optimise grape ripening and enhance fruit quality under varying climatic conditions while maintaining vine balance (Howell, 2001). Vine balance was initially conceptualised through the Ravaz index, which divides a vine's yield at harvest by its dormant pruning weight, yielding a ratio used to assess cropping levels (Mawdsley *et al.*, 2018). While widely adopted for its simplicity, the Ravaz index lacks a direct correlation with grape quality and overlooks crucial factors such as grape variety, climate, and vineyard management practices. Subsequently, Kliewer and Dokoozlian (2005) introduced an alternative metric based on the ratio of leaf area to unit weight of fruit, offering increased sensitivity to variations in vine balance dynamics. However, like the Ravaz index, this metric faces challenges in achieving universal applicability across diverse viticultural contexts.

In cool climates, where growing degree days may be limited, cluster thinning aims to modify the vine balance by increasing the leaf area to fruit ratio (Frioni *et al.*, 2017; Zhuang *et al.*, 2014). This adjustment optimises the vine's ability to fully ripen grapes by redirecting assimilates towards fruit development. The idea behind reducing the number of grape clusters is that resources are allocated more efficiently, fostering improved sugar accumulation, phenolic ripeness, and flavour complexity (Frioni *et al.*, 2017).

In contrast, warm climate viticulture presents unique challenges characterised by vine vigour and excessive vegetative growth. In such environments, cluster thinning provides an option to mitigate intense vine vigour and enhance fruit maturation (Rescic *et al.*, 2015; Suklje *et al.*, 2022). An overabundance of vine growth can lead to a range of difficulties including the formation of dense groups of leaves, reduced access of grape clusters to sunlight, and postponed ripening, all of which may negatively affect the overall quality of wine. (Suklje *et al.*, 2022). The presence of dense foliage can lead to grapes being shielded from direct sunlight, which can affect both the characteristics and ripening process of the wine (Kok & Bal, 2019; Roberts *et al.*, 2007). The quality of grapes, encompassing their chemical makeup and crucial features such as sugar content, acidity, pH levels, and phenolic components, is greatly shaped by the techniques employed in vine cultivation and external environmental factors (McDonnell, 2011).

Strategies associated with canopy management, such as cluster thinning, lower leaf removal, and excess growth trimming, are employed to address issues of excessive vine growth and shading. These strategies aim to improve light absorption, photosynthesis, and the microclimate surrounding grape clusters (Bubola *et al*., 2017a; Feng, 2014). Shading effects can vary based on the grape variety, with some showing reduced anthocyanin proportions under shading conditions (Kok *et al.*, 2013). Overall, addressing canopy management concerns is crucial for maintaining optimal grape quality and vine health with cluster thinning providing one possible solution to these mentioned issues.

2. Understanding wine quality

Understanding wine quality involves a variety of components. The quality of wine can be determined by a combination of factors such as the sensory aspects, volatile aromas, and the absence of faults with various definitions trying to encompass this multifaceted concept. One of the most cited definitions is from Charters & Pettigrew, (2007) who determined wine quality encompasses both intrinsic properties of the wine itself and extrinsic factors. Intrinsic dimensions included the raw materials, such as the quality of grapes and winemaking methods, while extrinsic dimensions incorporated marketing-related cues. Hopfer & Heymann (2014) concluded that wine quality is perceived differently by experts, trained panellists, and consumers, with experts combining descriptive and hedonic terms and consumers showing varied preferences. They also found quality perception is not always aligned with technical quality scores, and hedonic liking is highly correlated with perceived quality across different consumer segments. Different consumer segments show preferences for specific wine attributes, highlighting the complexity of wine quality perception among diverse groups. One study indicates that individuals who heavily engage in drinking tend to place importance on uniqueness and intricacy, whereas individuals who consume alcohol less frequently may pay more attention to immediate sensory experiences such as taste and visual appeal. (Charters & Pettigrew, 2007).

Sensory analysis plays a crucial role in determining wine quality by evaluating various aspects such as aroma, flavour, and balance (Sharma *et al.*, 2018; Sinton *et al.*, 1978; Villamor, 2012). Trained tasters assess these sensory attributes using standardised methods, and researchers can then correlate them with factors like crop levels, pruning timing, and the grape's chemical composition (Bubola *et al.*, 2023; Preszler, 2012). By using sensory evaluation, it is possible to statistically evaluate the influence of environmental factors, grape ripeness, and vineyard techniques on the quality of wine (Sun *et al.*, 2012). This can provide valuable insights into vineyard operations and winemaking processes. Sensory evaluation is a valuable resource within the wine sector, enabling producers to make well-informed choices regarding their products which will assist them in producing premium quality wines.

Volatile organic compounds (VOCs) include acids, alcohols, and esters which partially make up the chemical composition of the wine but significantly influence the aroma and flavour profile of the wine (Alba *et al.*, 2022). These compounds play a critical role, with their complex interactions contributing to a wine's sensory attributes where some can be highly impactful, while others may enhance or depress the aroma (Reynolds, 2010). VOCs can be measured using Gas Chromatography-Mass Spectrometry (GC-MS) which allows researchers to identify and quantify different VOCs in a wine sample (Bowen *et al.*, 2016). The different Odour Activity Values (OAV) of the VOCs are what help researchers determine the impact each individual compound might have on the sensory experience (Feng, 2014; Roberts *et al.*, 2007). However, this paper will dive deeper into the differences researchers are seeing between the composition of volatile organic compounds (VOCs) in wine and the sensory experience it delivers.

3. How cluster thinning affects wine quality

The hypothesis behind cluster thinning suggests that the practice can have a positive effect on wine quality. The idea stems from thinning grapes to obtain a better vine balance, and that by reducing the number of grape clusters/berries on the vine, the remaining grapes receive more nutrients and energy from the vine, leading to a higher concentration of sugars, aromas, and phenolic compounds in the grapes (Bubola *et al*., 2017a; Condurso *et al.*, 2016; Gil-Munoz *et al.*, 2009; Martinez-Luscher & Kurtural, 2023; Naor *et al.*, 2002; Ough & Nagaoka, 1984; Sivilotti *et al.*, 2020; Suklje *et al.*, 2022; Wang *et al.*, 2019a). This can result in wines with greater complexity and depth (Mucalo *et al.*, 2022; Rescic *et al.*, 2015). However, some studies have found that cluster thinning may not always have a significant impact on wine quality (Alba *et al.*, 2022; Bubola *et al*., 2017b; Condurso *et al.*, 2016; Gil-Munoz *et al.*, 2009; Rescic *et al.*, 2015; Sivilotti *et al.*, 2020). Factors such as vineyard location, grape variety, and environmental conditions can influence the effectiveness of cluster thinning (Ough & Nagaoka, 1984; Preszler, 2012; Suklje *et al.*, 2022; Wang *et al.*, 2019a). Therefore, while cluster thinning can often lead to improved wine quality, its effects may vary depending on a variety of factors.

The abundance of research findings regarding the impact of cluster thinning on wine quality, coupled with conflicting conclusions, can present a challenge for researchers. This paper seeks to address this issue by offering a clearer understanding of the effects of cluster thinning and the potential factors contributing to contradictory results. Specifically, this review will concentrate on the sensory aspects of wine, focusing on aroma, volatile compounds, and sensory analysis. Our goal is to perform a comprehensive analysis of primary research articles and academic publications to clarify the impacts of cluster thinning on sensory attributes. By integrating this broad range of data, the purpose of this evaluation is to offer the wine-making industry practical guidance on cluster thinning for wine quality.

METHODOLOGY

This narrative systematic review will use a specific set of criteria to ensure the inclusion of relevant and high-quality research on the impact of cluster thinning on wine quality. The focus here is to synthesise findings with a narrative approach and explore the trends within the research, rather than conducting a meta-analysis due to potential heterogeneity in outcome measures.

A narrative review is usually used to synthesise a body of evidence on a topic and to provide robust and broad conclusions by integrating findings from various studies (Stott *et al.*, 2024). This type of review is particularly good at handling conflicting results by integrating studies with various methodologies and results for reinterpretation or interconnection, which will help contribute to a better understanding of theories (Siddaway *et al.*, 2019). It allows for the description and interpretation of results without solely focusing on statistical significance (Siddaway *et al.*, 2019; Sperkowska *et al.*, 2021). Narrative reviews have traditionally been useful for linking studies on different topics to develop or evaluate new theories sometimes offering historical accounts of the theory's development and providing insights into emerging hypotheses (Lovell *et al.*, 2014). By bringing together and integrating a body of research, narrative reviews can draw conclusions about a topic and can help in better understanding the literature and pointing out future research needs (Li *et al.*, 2023).

1. PICO framework

This will also be a systematic review that will encompass viticulture and oenology studies investigating the effects of cluster thinning on wine quality parameters. Systematic reviews are a more replicable, formal, and traceable approach to searching and reviewing the literature (Gregory & Denniss, 2018). To conduct this study within a systematic review methodology, a PICO framework for eligibility will be used (Figure 1). PICO simply stands for the Participants, Intervention, Comparators,

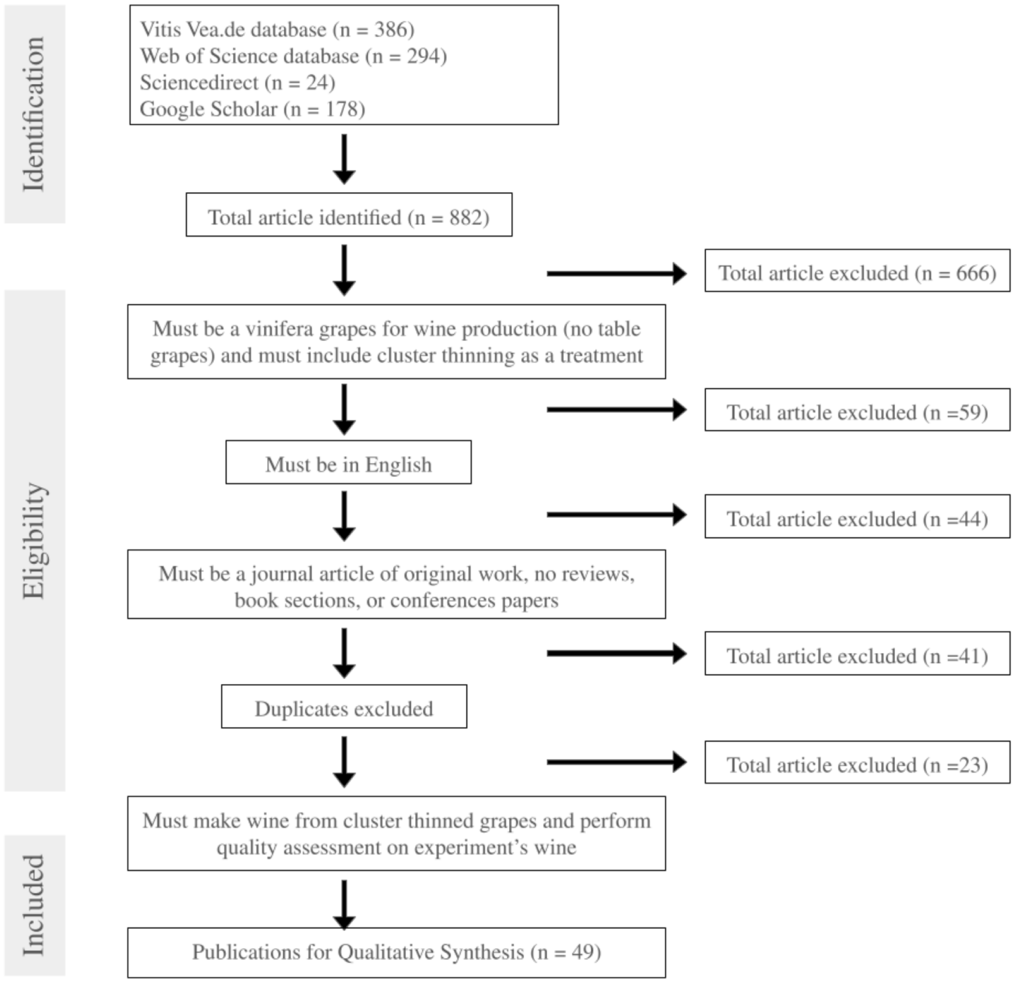

FIGURE 1. PICO flow chart for cluster thinning systematic review.

and Outcomes involved in a study (Tawfik *et al.*, 2019). The studies must involve grapevines (*Vitis vinifera*) cultivated in various wine-producing regions. To account for potential vine maturity effects, studies encompassing both young and mature vineyards will be included. The review will incorporate research on a wide range of grapevine cultivars.

When looking at interventions this review will focus on studies that employ cluster thinning practices at distinct growth stages of the grapevines. These stages may include flowering, fruit set, veraison (ripening onset), and post-veraison. Furthermore, the severity of cluster thinning will be considered, with studies implementing light, moderate, and heavy thinning techniques being evaluated. Finally, the review will encompass studies that use various cluster thinning methods, including selective hand pruning, mechanical thinning, or a combination of both approaches.

The comparators included in this review will include studies that employ a control group of grapevines that have not undergone any cluster thinning intervention. Additionally, studies that compare the effects of different cluster thinning techniques on wine quality parameters will be considered. Finally, the review will incorporate research that evaluates the impact of cluster thinning at various growth stages compared to control groups.

The outcomes that will be analysed in this review will focus on three areas related to wine quality with the first being sensory analysis. The review will prioritise studies that employ sensory evaluation to assess the impact of cluster thinning on wine quality. This will encompass analysis of sensory descriptors used to describe the aroma and flavour profile of the wine, with some emphasis on quality assessments and preference scores. The second area is volatile composition. The review will incorporate studies that utilise Gas Chromatography-Mass Spectrometry (GC-MS) analysis to investigate the impact of cluster thinning on the volatile organic compound profile of the wine. This will involve examining the makeup and composition of these compounds, which significantly influence the aroma characteristics of the wine. The final smaller focus is polyphenol content. Studies that employ High-Performance Liquid Chromatography (HPLC) to quantify the content of various polyphenols in the wine will be included. Polyphenols are a diverse group of compounds that contribute to the colour, astringency, and potentially, health benefits of wine. Analysing their content through HPLC will provide valuable insight into how cluster thinning practices may influence these aspects of wine quality. Lastly, there will be a brief overview of the consensus regarding the economic impact of cluster thinning on vineyard management.

2. Systematic review

The literature review aimed to identify research articles investigating the impact of cluster thinning on wine quality parameters. Searches were conducted on the *Vitis Vea*, Web of Science, and Science Direct databases using keywords such as "cluster thinning grapes," "bunch removal grapes," "crop load adjustment grapes," and "bunch thinning grapes." Additionally, a Boolean search was performed on Google Scholar using the query "Cluster thinning" ("Wine quality" OR "Wine attributes" OR "Oenological parameters") Aroma* OR Flavour? OR Acidity OR Tannin* OR Phenolic* OR "Sensory analysis" to further refine the search. Initially, 178 articles were identified through Google Scholar pertaining to cluster thinning and its impact on various wine quality parameters.

It is noteworthy that the articles included in the narrative analysis were required to evaluate wine quality using specific methods, namely High-Performance Liquid Chromatography (HPLC) or Gas Chromatography-Mass Spectrometry (GCMS) conducted on wine samples, or through sensory analysis.

The objective of this narrative review aims to synthesise findings from various studies to identify conclusive patterns and draw overarching conclusions about the effects of cluster thinning on wine quality, providing insights into the conditions where cluster thinning can be most beneficial for wine producers.

EVIDENCE FOR CLUSTER THINNING'S EFFECT ON WINE COMPOSITION QUALITY

In this narrative systematic review, a total of 49 papers were evaluated, focusing on the impact of cluster thinning on specific wine quality parameters, particularly related to volatile compounds and polyphenolics. Among these papers, 33 investigated the effects of cluster thinning on these parameters (Table 1). The studies were conducted in diverse locations, encompassing both new and old-world wine-growing regions. Notably, only 5 out of the 33 studies specifically examined white wine varieties.

1. Cluster thinning effects on Cabernet-Sauvignon (GC-MS and HPLC Results)

The majority of the studies included in the chemical analysis for wine quality centred on Cabernet-Sauvignon and were primarily cultivated in warm continental regions. Interestingly, most of the findings from the studies on Cabernet-Sauvignon indicated varied or minimal effects of cluster thinning on the phenolic and volatile composition of the wine (Artem & Antoce, 2018; Black *et al.*, 2016; Bravdo *et al.*, 1985; Cojocaru & Antoce, 2018; King *et al.*, 2012, King *et al.*, 2015; Wang *et al.*, 2019b). In Artem and Antoce (2018), they found the main separation of wine samples was determined by the cultivation system, while grape thinning accounted for a smaller portion of the variability. Black *et al.* (2016) suggested that the variability in their findings may have been influenced by the vines already being in a balanced state before crop reduction. However, they noted a slight increase in secondary metabolites, which is consistent with findings from Pérez-Magariño and González-San José (2004), and Pérez-Magariño and González-San José (2006). These earlier studies associated a later harvest date with higher levels of secondary metabolites. This indicates that the timing of harvest might be a more probable factor contributing to variability in phenolic development compared to crop reduction alone.

Bravdo *et al.* (1985) is a highly cited study (cited 281 times according to Google Scholar), known for its controversial findings suggesting that un-thinned (UT) vines produce higher quality wines than CT vines. However, the study's definition of "wine quality" is vague and not easily applicable to other studies focusing on wine quality assessment. The ranking system used to determine wine quality is mentioned but not explained. In Figure 2 of the study, which displays different wine quality "levels" for various treatments, no statistically significant differences are observed in these quality scores. Therefore, the claim that UT vines yield superior wines in this study seems unsupported and lacks sufficient evidence to justify such a bold conclusion.

Cojocaru and Antoce (2018) employed a novel approach by using a Gas Chromatography electronic nose (GC e-nose) to analyse the aromatic characteristics of wines produced using cluster thinning (CT) as a viticultural practice. This study stands out for its robust methodology. The research yielded intriguing results that align with the previous findings of King *et al.* (2012), and King *et al.* (2015), which found that CT does not significantly impact the sensory attributes or anthocyanin profile of Cabernet-Sauvignon wine in warmer climates. Lastly, in a notable study investigating Cabernet-Sauvignon grapes cultivated in a cool climate, researchers observed no significant differences in wine quality related to terpene concentrations (Wang *et al.*, 2018). As a result, they determined that adopting this practice was not economically feasible in that specific climate.

The studies conducted by Artem *et al.* (2015), and Martinez-Luscher and Kurtural (2023), focusing on Cabernet-Sauvignon, have all reported a notable increase in the volatile profile and polyphenolic potential from cluster thinning for this grape variety. Artem *et al.* (2015) also supported the findings of Gil-Muñoz (2009) and Kok and Bal (2019), indicating that cluster thinning can enhance the levels of anthocyanins and potential volatile terpenes in grapes and potentially in wine. It is important to highlight that Artem *et al.* (2015) used a less familiar methodology known as the Glories method. Notably, their study did not involve wine production but is recognised for its distinctive approach and divergent outcomes.

1.1. Other red wine varieties (GC-MS Results)

The other red grape varieties that were studied for their volatile or polyphenolic makeup were Sangiovese, Tempranillo, Cabernet franc, Grenache, Merlot, Teran [Terrano], Syrah, Pinot noir, Kalecik Karasi, Marastina [Malvasia bianca lunga], and Refosco dal peduncolo rosso. Of these studies,

TABLE 1. Summary of findings on wine composition.

Study	Climate type	Cultivars studied	Quality assessment method	Findings
Alba *et al.* (2022)	Warm-Mediterranean	Sangiovese	GC-MS	CT had no impact on the volatile organic compounds (VOCs) of wines, except for diethyl succinate.
Artem *et al.* (2015)	Warm-continental	Cabernet-Sauvignon	Glories' method	Extractable anthocyanins increased significantly with CT.
Artem and Antoce (2018)	Warm-continental	Cabernet-Sauvignon	GC-MS	The majority of variability in volatile aroma compounds was due to the cultivation system, not CT.
Avizcuri-Inac *et al* (2013)	Warm-continental	Tempranillo & Grenache	HPLC	Higher phenolics for CT vines.
Black *et al.* (2016)	Warm-continental	Cabernet-Sauvignon	HPLC	Inconsistent results for CT's effect on phenolics.
Bravdo *et al* (1985)	Hot-Mediterranean	Cabernet-Sauvignon	wine colour	CT produced variable to negative results on improving wine composition.
Bubola *et al.* (2011)	Warm-Mediterranean	Merlot	HPLC	Increased polyphenolics and lower acidity in CT wines.
Cojocaru *et al* (2018)	Warm-continental	Cabernet-Sauvignon & Fetească neagră	GC-enose	No significant differentiation between CT wines and control.
Condurso *et al* (2016)	Hot-Mediterranean	Syrah	GC-MS	CT increased colour stability, ester quantities, and overall wine quality.
Devarajan (2009)	Warm-subtropical	Cabernet franc & Merlot	GC-MS	Volatile aroma concentrations were higher in unthinned wines.
Feng (2014)	Warm-continental	Pinot noir	GC-MS	CT had variable effects on volatile composition over three seasons.
Gatti *et al.* (2011)	Warm-Mediterranean	Barbera	HPLC	CT vines showed higher anthocyanin and polyphenol concentrations
Gil-Munoz *et al.* (2009)	Warm-continental	Syrah	HPLC	No difference in methoxypyrazine and resveratrol concentrations due to cluster thinning.
Gonzalez-Neves (2002)	Cool maritime	Tannat	Glories' method	Variable results from CT on total phenolic and anthocyanin content in wine.
Karoglan *et al.* (2014)	Warm-continental	Cabernet-Sauvignon & Merlot	HPLC	CT alone showed variable effects on wine quality.
King *et al.* (2012)	Warm-maritime	Cabernet-Sauvignon & Nebbiolo	HPLC	CT had no effect on wine anthocyanin levels.
King *et al.* (2015)	Warm-maritime	Cabernet-Sauvignon & Nebbiolo	HPLC	Found season variation to influence wine composition more than CT.
Martínez-Lüscher *et al.* (2023)	Warm-Mediterranean	Cabernet-Sauvignon	HS-SPME-GC–MS	CT significantly altered the aroma profile of the wine.
Mucalo *et al.* (2022)	Warm-Mediterranean	Marastina [Malvasia bianca lunga]	GC-MS	CT did not negatively impact yield and increased desirable volatile compounds.
Prajitna *et al* (2007)	Cool-continental	Chambourcin	HPLC	Found an increase in total antioxidant capacity in CT wines.
Rescic *et al.* (2015)	Warm-continental	Blauer Portugieser	HPLC	Increased phenolics in CT wine.
Rutan *et al.* (2018)	Warm-continental	Pinot noir	GC-MS	CT lead to more sweet and spicy volatile compounds.
Škrab *et al.* (2021)	Warm-maritime	Ribolla Gialla	GC-MS	CT lead to more acetaldehyde.
Somkuwar *et al.* (2018)	Humid-subtropical	Chenin blanc & Syrah	HPLC	CT elevated phenolic content.
Suklje *et al.* (2022)	Cool-continental	Welschriesling	GC-MS	Varietal thiols trended higher in CT-treated wines.
Tahmaz (2023)	Hot-Mediterranean	Syrah	HPLC	Only CT combined with leaf removal leads to increased polyphenols.
Talaverano *et al.* (2017)	Warm-Mediterranean	Tempranillo	GC-MS	CT lead to an increase in volatile aromas.
Vilanova *et al.* (2020)	Warm-continental	Verdejo	GC-MS	Varying effects of CT on volatile compounds.

7 of them used GC-MS to determine wine quality with 3 of them showing variable to negative effects from CT and 4 showing positive effects. The 4 studies that found there to be positive effects of cluster thinning were on Sangiovese, Syrah, Pinot noir, and Tempranillo all in warm climates (Alba *et al.*, 2022; Condurso *et al.*, 2016; Feng, 2014; Rutan *et al.*, 2018; Talaverano *et al.*, 2017). Their findings are summarised in Table 1. Alba *et al*. (2022) and Condurso *et al*. (2016) have similar results, both finding that cluster thinning approximately 40–50 % of the vine's clusters resulted in increased pH, total polyphenols, proanthocyanins, and total free and bound aroma compounds. Aroma compounds, particularly esters, were found in higher quantities in thinned samples, contributing to the sensory quality.

Two GC-MS studies investigating the impact of cluster thinning on Pinot noir grapes yielded contrasting outcomes. Feng (2014) reported that cluster thinning had limited and variable effects on grape and wine volatile compositions, exhibiting substantial variation over three seasons. Nevertheless, Feng observed a significant increase in certain higher alcohols in wine following severe thinning, coupled with a decrease in others. In contrast, Rutan *et al.* (2018) found that moderate thinning sufficiently enhanced specific wine attributes, implying that intensive thinning might be unnecessary.

Several factors could explain the disparities between these studies. Firstly, the climatic conditions differed markedly: Rutan *et al.* (2018) conducted their study in a warm continental climate, whereas Feng *et al.* (2014) operated in a hot Mediterranean climate. Climate variations can profoundly influence grapevine physiology, affecting aspects such as berry development, ripening, and secondary metabolite accumulation. Warmer climates generally accelerate ripening and alter chemical profiles compared to cooler regions, which could explain why the effects of thinning differed between the two studies. It's important to note the severity of cluster thinning potentially varied significantly between the studies. Feng *et al.* (2014) implemented a 50 % cluster removal rate, whereas Rutan *et al.* (2018) did not specify the degree of thinning applied in their experiment. This discrepancy in thinning severity could have led to different physiological responses in the grapevines.

When considering grapevine physiology, it is possible that the extent of cluster thinning interacts intricately with grapevine stress responses and subsequent metabolic pathways. Moderate thinning may trigger specific physiological mechanisms that enhance desirable wine attributes without causing excessive stress, as observed by Rutan *et al.* (2018). Conversely, severe thinning, as applied by Feng *et al.* (2014), might cause more pronounced stress responses leading to different volatile compositions in the grapes and resulting wines.

1.2. Other red wine varieties (HPLC Results)

In the literature exploring the effects of cluster thinning (CT) on wine quality through changes in phenolic concentrations, a total of eight studies were reviewed. While most of these studies focused on red wine grapes, a few also included investigations on white grape varieties. It is important to highlight that phenolic concentrations in wine contribute significantly to its overall quality by affecting attributes such as mouthfeel, flavour, and colour (Avizcuri-Inac *et al.*, 2013). HPLC has been used as one of the main methods for quantifying these phenolic compounds in wines and grapes and will be the focus of this section of the narrative analysis. Studies on red wine phenolics revealed mixed outcomes.

Avizcuri-Inac *et al.* (2013) observed higher phenolic levels in Tempranillo and Grenache wines subjected to cluster thinning. However, the consistency of these results varied in the second year of their study. Furthermore, subsequent studies continued to demonstrate the positive impacts of cluster thinning on wine phenolics, showing increases in total anthocyanins, total phenolics, and antioxidants (Bubola *et al.*, 2011; Prajitna *et al.*, 2007; Rescic *et al.*, 2015; Somkuwar *et al.*, 2018).

Both Bubola *et al.* (2017a) and Tahmaz (2023) reported that cluster thinning, especially when combined with leaf removal, significantly improved the chemical composition of the wines studied. Nevertheless, both studies concluded that cluster thinning alone had minimal impact on improving these phenolic profiles in the wines examined. Some other studies that looked at the impact of cluster thinning (CT) on phenolic profiles, albeit without analysing wine, consistently reported positive effects from CT (Kok *et al.*, 2013; Salazar *et al.*, 2021). Only one study among these included in the review reported variable effects. Notably, this particular study (Gonzalez-Neves *et al.*, 2002) was conducted in a cool climate, distinguishing it from the others in this subset.

2. White grape varieties (GC-MS Results)

There were three notable studies exclusively examining white wine varieties, each yielding varied outcomes. Škrab *et al.* (2021) conducted a unique investigation centred on sparkling wine production with cluster thinning (CT) applied to vines. Typically, white wines may be less inclined to undergo cluster thinning due to the lesser need for acidity reduction through full grape ripening, given that acidic, crisp white wines are often desired. Škrab *et al.* (2021) revealed that wines produced from CT vines, even after normalising the data for location and seasonal variation, exhibited variable effects, with the study suggesting that only extreme cases of overproduction benefited from CT.

In another study by Suklje *et al*. (2022), focused on Welschriesling in a cool climate region, cluster thinning (CT) showed a significant impact on wine quality during cooler vintages with over 40 % yield reduction, leading to increased concentrations of 3-mercaptohexyl acetate, associated with tropical fruit aromas, in wines. Conversely, in a warmer vintage with only a 30 % yield reduction, CT did not affect fundamental wine parameters such as alcohol content, titratable acidity (TA), and pH. However, varietal thiols tended to be higher in CT wines.

The third study by Vilanova *et al.* (2020) examined Verdejo with an estimated 27 % cluster removal. Notably, this study observed that the vine seemed to recover the lost weight from the minimal cluster thinning during the third year of the experiment. However,

TABLE 2. Summary of findings for sensory analysis.

Study	Climate type	Cultivars studied	Quality assessment method	Findings
Avizcuri-Inac *et al.* (2013)	Warm-continental	Tempranillo & Grenache	duo-trio & descriptive analysis	CT had lower herbaceous attributes but higher astringency, bitterness, fruit, and flower aromas
Bowen *et al.* 2016	Cool-continental	Riesling	descriptive analysis	Wines made from grapes with CT at the fruit set showed higher positive intensity ratings
Bravdo *et al.* (1984)	Hot-Mediterranean	Carignane	0–20 points tasting score	A certain level of CT had increased wine quality scored
Bubola *et al.* (2023)	Warm-Mediterranean	Merlot	quantitative descriptive	CT enhanced wine quality overall including body and aromas.
Chapman *et al.* (2004)	Did not mention	Cabernet-Sauvignon	descriptive analysis	Did not see significant effects on wine from CT
De Bei (2022)	Warm-Mediterranean	Semillon & Shiraz	descriptive analysis	CT had no effect on wine sensory characteristics
Diago *et al.* (2010)	Warm-continental	Grenache & Tempranillo	descriptive analysis	CT increased astringency and phenolic content but decreased aroma intensity
Essary (2021)	Hot-continental	Tempranillo	consumer preference	CT wines were preferred for appearance and colour but not for aroma
Fertel (2011)	Hot-Mediterranean	Cabernet-Sauvignon	triangle test	No difference in wine preferences between CT and no CT
Gil *et al.* (2013)	Warm-continental	Syrah	triangle test	Tasters found a significant difference between CT wines and control
Lohitnavy *et al* (2010)	Warm-Mediterranean	Semillon	berry sensory	Berries pulp increased in grassiness with CT
Macfarlane (2017)	Cool-maritime	Pinot gris	Rate-all-that-apply	No significant sensory difference between CT wines and control
Mawdsley (2019)	Cool-maritime	Pinot noir	duo-trio	Increased berry anthocyanin and phenolics in berries from CT but not in wine
McDonnell (2011)	Warm-Mediterranean	Cabernet-Sauvignon	expert descriptive & consumer preference	Decrease crop load led to improved quality scores but not significant enough to warrant the practice
Naor *et al.* (2002)	Hot-Mediterranean	Sauvignon blanc	0–20 points tasting score	Quality increased with decreasing crop load
Ough and Nagaoka. (1984)	Warm-Mediterranean	Cabernet-Sauvignon	Expert tasting scale	Cluster-thinned wines were slightly higher quality in some years
Prezler (2012)	Cool-continental	Riesling	expert preference	Preferences were for non-CT wines and CT did not make economic sense
Reeve *et al.* (2018)	Warm-maritime	Pinot noir	consumer and expert preference test	CT did not ensure higher wine quality rankings. Non-CT wines were ranked higher sometimes
Reynolds and Wardle (1989)	Cool-continental	Gewurztraminer	descriptive analysis	CT lowered astringency perception and fruity aromas and increased grassy aromas
Reynolds *et al.* (2007)	Cool-continental	Chardonnay Musqué	quantitative descriptive analysis	Oenological treatments had more effect on sensory characteristics than CT
Roberts *et al.* (2007)	Cool-continental	Chardonnay Musqué	descriptive analysis	Higher volatile terpenes for muscat flavours were in CT wines
Rutan *et al.* (2018)	Warm-continental	Pinot noir	triangular & paired-comparison	Moderate thinning enhanced positive wine descriptors
Škrab *et al.* (2021)	Warm-maritime	Ribolla Gialla	0–10 point tasting scale	Conflicting results where non-CT wines were preferred
Sun *et al.* (2012)	Cool-continental	Corot noir	2-alternative-forced choice	CT combined with shoot thinning was perceived as fruitier than control
Tahmaz (2023)	Hot-Mediterranean	Syrah	expert 0–10 point tasting scale	CT lead to improved sensory profile
Van Schalkwyk (1995)	Hot-Mediterranean	Chardonnay	expert 0–9 point tasting scale	Tasters did not rate CT wines as higher quality

throughout the study years, variable results were observed with no conclusive difference attributed to cluster thinning.

IMPACT OF CLUSTER THINNING ON SENSORY ANALYSIS

In examining the existing literature concerning sensory evaluations of wines derived from cluster-thinned vines, a discernible pattern emerges which will be discussed further. The selected studies for this review used a range of techniques such as due-trio tests, triangle tests, descriptive analysis, consumer and expert preferences, rate-all-that-apply, and rating/scoring systems (Table 2). The variety of methodologies employed in these studies hindered the possibility of conducting a comprehensive meta-analysis due to the diverse nature of the findings. However, these findings are still valuable for identifying potential trends or overarching conclusions that could inform future winemaking practices. By dissecting and analysing these results, we aim to provide insights that can assist winemakers in making informed decisions regarding this practice.

1. Descriptive analysis results

Descriptive analysis is a sensory evaluation method that is often used to characterise the flavour and aroma profiles of the wine (Diago *et al.*, 2010; Macfarlane, 2017). It can be a comprehensive tool that can also help relate results to consumer acceptance and instrumental measures, such as GC-MS. This method involves training judges to identify and describe sensory attributes, refining a list of descriptors, and conducting tests to evaluate taste, mouthfeel, and aroma characteristics (Bowen *et al.*, 2016; Bruwer *et al.*, 2011; Chapman *et al.*, 2004). This method is labour-intensive for both researchers and participants and training methods can vary widely between studies, but it still provides valuable insight into discerning differences in wines.

Out of the studies that examined wine sensory attributes, ten studies employed descriptive analysis to assess the impact of cluster thinning (CT) on wine quality. Among these ten studies, four reported positive effects of cluster thinning on various sensory parameters of wine (Bowen *et al.*, 2016; Bubola *et al.*, 2023; Roberts *et al.*, 2007). Bowen *et al.* (2016) reported improved sensory characteristics in ice wine resulting from cluster thinning. They referenced (Reynolds *et al.*, 2007) to support their claim that cluster thinning enhances overall wine quality in Chardonnay Musqué. However, it is important to clarify that this interpretation is misleading. Reynolds *et al.* (2007) actually found minimal sensory differences among wines subjected to different viticultural treatments, suggesting that any impact of cluster thinning on sensory attributes was overshadowed by variations introduced by different yeast treatments.

The findings of Bowen *et al.* (2016) are in line with those of Bubola *et al.* (2023), who studied Merlot wines and observed enhanced sensory quality, including increased aroma intensity, body, and overall quality, despite higher alcohol content. Notably, this improvement in wine quality did not correspond to significant changes in berry phenolic composition, indicating that alterations in wine composition were not directly mirrored in the berries. This finding is noteworthy given the extensive body of literature on the effects of cluster thinning on berry composition. Surprisingly, studies including Bubola *et al.* (2023) have shown that viticultural practices sometimes do not significantly change anthocyanin concentrations in berries, yet they do result in a notable increase in anthocyanins in the final wines (Kemp *et al.*, 2011). This contrasts with the findings of Avizcuri-Inac *et al.* (2013), who observed that cluster thinning led to reduced herbaceous attributes but increased astringency, bitterness, and fruit and flower aromas, aligning with higher concentrations of anthocyanins and flavanols in the wine composition.

Roberts *et al.* (2007) noticed that wines from thinned vines, especially those thinned at veraison, were characterised by higher overall quality, muscat, and floral aromas and flavours, as determined through sensory evaluation, concluding that cluster thinning significantly influenced the sensory profile of their wines. However, relying on data from a single vintage may limit the generalisability of the findings, as variations between growing seasons can significantly impact grape and wine characteristics.

The other six articles that used descriptive analysis for their wine quality analysis found negative or variable impacts from cluster thinning on wine quality. Studies that were conducted in cooler climates, such as Reynolds and Wardle (1989) and Reynolds *et al.* (2007) on Chardonnay Musqué, reported minor changes in sensory attributes despite changes affecting the wine composition from cluster thinning. Variability in sensory outcomes was also observed across different grape varieties. De Bei (2022) found contrasting effects of cluster thinning on Semillon versus Shiraz wines. Semillon showed little change in wine quality, while Shiraz showed improved sensory attributes post-thinning.

Interestingly, there could be differences in vineyard management practices, such as pruning intensity or vine balance, that could be influencing the sensory impact of cluster thinning. Studies like Chapman *et al.* (2004) found that pruning interventions may have a more pronounced effect on sensory attributes compared to cluster thinning alone. Roberts *et al.* (2007) noted that sensory characteristics were more affected by these treatments than by cluster thinning, indicating potential interactions and complexities in wine production practices. Several studies mentioned the influence of oenological treatments, such as yeast strain selection or enzyme use, on wine sensory properties (Bubola *et al.*, 2023; Suklje *et al.*, 2022).

2. Wine rating (wine scoring) results

The method of "wine scoring" or "wine rating" in sensory analysis measures wine quality by evaluating sensory characteristics like aroma intensity, flavour intensity, balance, and overall quality (Fertel, 2011; Sinton *et al.*, 1978; Sun *et al.*, 2012). Statistical analyses like ANOVA are then used to interpret the results and determine significant differences in sensory ratings among wines. Wine rating as a sensory analysis method does face challenges in ensuring consistency and objectivity with factors like panellist experience, the training required for each panellist, and the sample size (Cicchetti & Cicchetti, 2009).

Three studies used wine scoring to determine wine quality which also found positive results from using cluster thinning to enhance wine quality. It was Bravdo *et al.* (1984) and Naor *et al.* (2002) that observed moderate cluster thinning led to improved wine quality, such as increased colour intensity, better flavour harmony, and enhanced aroma profiles. Naor *et al.* (2002) specifically found that wine sensory evaluation scores increased with decreasing crop load. A more recent study from Turkey, conducted by Tahmaz in 2023, reported similar findings. This study demonstrated significant improvements in the chemical and sensory profiles of Syrah wines using cluster thinning and leaf removal combinations. Interestingly, Tahmaz (2023) used the same tasting scale as the previous two studies but explicitly mentioned a sample size of 20 tasters, which was not specified in the earlier studies.

The choice of grape variety also played a crucial role in the outcomes. For instance, two white wine varieties were studied: Naor *et al.* (2002) examined Sauvignon blanc and observed positive effects of cluster thinning on sensory evaluations, whereas van Schalkwyk (1995) found no improvement in Chardonnay quality with cluster thinning, deeming the practice economically unviable.

Similarly, Škrab *et al.* (2021) investigated the impact of cluster thinning on Ribolla Gialla sparkling wines grown in a warm climate and found that tasters preferred non-CT wines. van Schalkwyk (1995) also reported a preference for non-thinned wines in their study on white wine from a warm climate. In such regions, where cluster thinning may lead to advanced grape maturation, the practice might not be necessary for grape varieties intended for sparkling wine production. van Schalkwyk (1995) even suggested that grapes harvested from cluster thinning could still be used for sparkling wine production. This example underscores how cluster thinning may not be essential for grapes destined for sparkling wines, where high acidity is typically desired in the grapes to achieve the desired characteristics of sparkling wines.

The varying degrees of cluster thinning severity across these five studies may explain their different outcomes. In **Škrab** *et al.* (2021) study on sparkling wines, they employed a lighter cluster thinning approach, thinning only around 20 % of the grapes per vine. The inconsistency in their findings could be attributed to this lighter-thinning practice. In contrast, studies by Naor *et al.* (2002) and Bravado *et al.* (1984) involved cluster thinning of approximately 30 % or 60 % of the grapes, and they found that moderate thinning led to the most preferred wines compared to lighter thinning. Similarly, Tahmaz (2023) reported that cluster thinning of 50 % of the grapes resulted in higher wine quality scores favouring cluster-thinned (CT) wines.

From these studies, it appears that moderate cluster thinning, often near 50 %, tends to yield more positive effects on wine scoring than other thinning severities. The grape variety also plays a crucial role in white wine varieties, especially those intended for sparkling wines, and does not seem to benefit from cluster thinning. Additionally, climate influences the effectiveness of cluster thinning. In hot climates, where vines are more vigorous, cluster thinning has a more pronounced effect compared to warm or cool climates. The influence of climate on cluster thinning will be explored further in this review.

3. Consumer and expert preference test results

The consumer preference test method for evaluating wine quality has both benefits and drawbacks. One benefit is its ability to measure the actual preferences of the target audience, as most wine consumers are not experts. Additionally, this method allows for the collection of a wider range of data from a larger sample size, compared to expert scores which require rigorous training and often involve small sample sizes. However, a drawback of this method is the difficulty in creating predictive models based on consumer data, likely due to consumers' inability to base their preferences on objective descriptive attributes (Hopfer & Heymann, 2014). In this review, four papers were identified in the literature that used either consumer and/or expert preference testing to determine wine quality changes from CT. All four of these papers found either non-significant improvements in quality or a preference for non-CT wines (Essary, 2021; McDonnell, 2011; Preszler, 2012; Reeve *et al.*, 2018).

The only study among these conducted in a cool climate found that experts preferred wines from non-CT vines (Preszler, 2012). While the study noted that CT enhanced soluble solids accumulation in grapes, typically associated with advanced ripening and potentially higher wine quality, the sensory trials revealed different aromatic attributes and lower likability ratings for wines from lower cropped vines compared to those from higher crop levels. This suggests that although CT can improve certain aspects of grape maturity, it does not necessarily lead to higher wine quality as perceived by consumers. Similar findings were reported by Reeve *et al.* (2018), conducted in a warm climate, where consumer likability rankings sometimes favoured non-CT wines.

In Essary (2021), cluster thinning (CT) had mixed effects on wine quality. Consumers preferred CT wines for their appearance and colour but not for their aroma. Additionally, the study found that wines from combined CT treatments with two-bud pruning were the most preferred. However, there was no significant difference in preference between wines from two-bud pruning alone and those from two-bud pruning combined with CT. Conversely, McDonnell (2011) did not observe a strong consumer preference for CT wines. Despite changes in grape composition due to CT, these did not translate into a noticeable preference among consumers.

4. Triangular sensory analysis test results

The triangular sensory analysis method is a discrimination test that is used to determine whether there are perceivable differences between two wine samples. In this method, participants are presented with three samples, two of which are identical and one that is different, and they are asked to identify the odd one out (Fertel, 2011). This methodology was used in three studies examining the impact of CT on wine quality. While one study found no discernible impact from CT (Fertel, 2011), the other two studies identified a significant and discernible difference between the control wines and those subjected to CT (Gil-Munoz *et al.*, 2009; Rutan *et al.*, 2018).

Each of these studies focused on a different red wine variety. Fertel (2011) found that only 12 out of 25 tasters correctly identified wines made from thinned Cabernet-Sauvignon vines, statistically indicating that the wines were indistinguishable. Notably, this is the only study among the three that describes the training the tasters underwent before

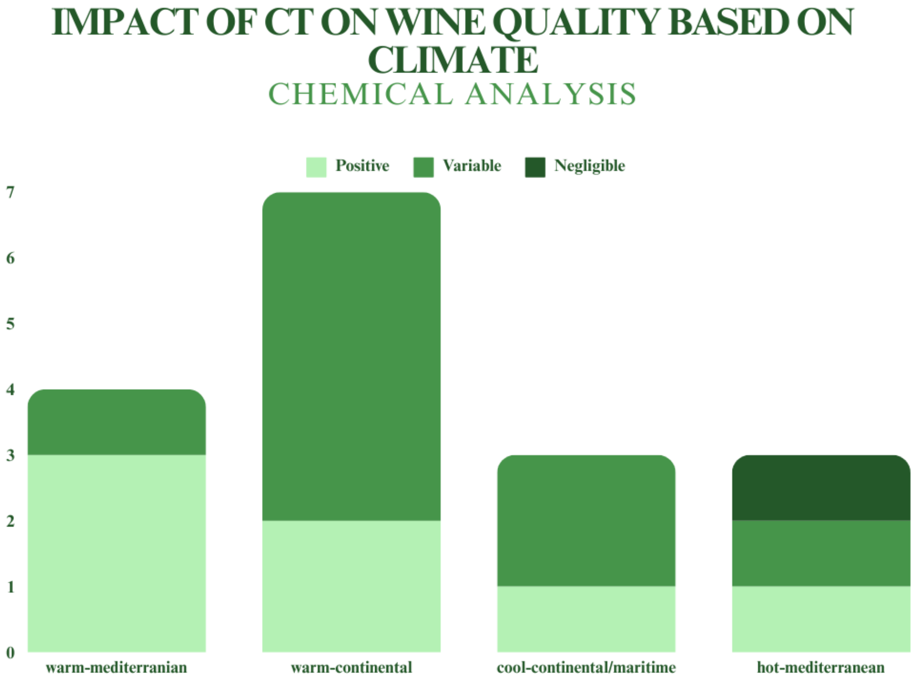

FIGURE 1. Trends in climate type for chemical analysis.

participating in the experiment. Gil-Munoz *et al.* (2009) and Rutan *et al.* (2018) did not indicate that any of their tasters received training before participating in the triangular tests, with sample sizes of 24 and 15 tasters, respectively. Both studies concluded that tasters could distinguish between the control sample and the CT sample. Interestingly, Fertel (2011) was the only study conducted in a hot climate. This climatic difference could be a confounding factor that contributed to the effectiveness of CT in improving wine quality.

CLUSTER THINNING SEVERITY AND ITS EFFECTS ON WINE SENSORY QUALITY

The severity of cluster thinning has a notable influence on the sensory attributes of wine, though its effects are not always linear or consistent across varieties and climates. Studies have shown that moderate thinning, typically around 30–50 %, can enhance specific sensory qualities such as fruitiness, body, and overall aroma intensity (Avizcuri-Inac *et al.*, 2013; Bowen *et al.*, 2016; Bubola *et al.*, 2023; Gil *et al.*, 2013; Naor *et al.*, 2002; Tahmaz, 2023). Another study showed more severe thinning beyond 50 % often leads to diminishing returns in sensory improvements with moderate thinning being sufficient to enhance sensory quality (Rutan *et al.*, 2018). However, King *et al.* (2012) reported that severe thinning increased total phenolics in both study years, while moderate thinning increased phenolics for only one of the years. This suggests that while moderate CT is likely to enhance sensory aspects, its effectiveness and the need to be more severely thin is contingent on other viticultural factors such as vine balance and seasonal variation.

TABLE 3. Trend of results by climate type for chemical analysis.

Climate type	Positive effect on phenolics/volatile compounds	Varying effects on phenolics/volatile compounds	No effect on phenolics/volatile compounds
Warm-Mediterranean	Bubola *et al.* (2011) Martínez-Lüscher *et al.* (2023) Mucalo *et al.* (2022)	Alba *et al.* (2022)	
Warm-continental	Rescic *et al.* (2015) Rutan *et al.* (2018)	Feng (2014) Karoglan *et al.* (2014) Vilanova *et al.* (2020)	Cojocaru *et al.* (2018) Gil *et al.* (2013)
Cool-continental/maritime	Prajitna *et al.* (2007)	Gonzalez-Neves (2002) Suklje *et al.* (2022)	
Hot-Mediterranean	Condurso *et al.* (2016)	Tahmaz (2023)	Bravdo *et al.* (1985)

CLIMATE TRENDS IN CLUSTER THINNING WINE CHEMICAL ANALYSIS

When examining the impact of cluster thinning on a wine's chemical composition, an interesting pattern emerges (Table 3 and Figure 1). Most studies investigating the effects of CT on chemical parameters, such as polyphenol and aromatic composition, were conducted in warm climates. Specifically, five studies were categorised as warm-Mediterranean, seven as warm-continental, four as cool-continental, and three as hot-Mediterranean. The following section will discuss the important role climate plays in the effectiveness of cluster thinning and the overarching patterns that emerged from the existing literature.

To re-emphasise, the impact of climate on the studies included in this review is only undergoing a narrative analysis. This approach is necessitated by the significant variability in data from studies examining the effects of cluster thinning on a wine's chemical composition. A previous meta-analysis on the impact of cluster thinning on grape composition has quantitatively analysed whether climate factors such as growing degree days (GDD) or precipitation influence the effects of cluster thinning on grape parameters (Vanderweide *et al.*, 2024). They concluded that climate variables did not have a significant impact on the changes in grape chemical parameters due to cluster thinning. However, our focus on narratively analysing the literature allows for the inclusion of a broader range of studies. This enables us to draw overarching conclusions by categorising the studies based on the climate of the study location and interpreting if there is a pattern in the literature.

In warm-Mediterranean climates, three studies reported positive effects of cluster thinning (CT) on wine composition (Bubola *et al.*, 2011; Martinez-Luscher & Kurtural, 2023; Mucalo *et al.*, 2022), while two studies found variable effects (Alba *et al.*, 2022; Bubola *et al.*, 2017b). Compared to other climate classifications, studies conducted in warm-Mediterranean climates demonstrated the highest percentage of positive/variable outcomes, with no studies indicating any effects from CT. In contrast, studies from the other three climate classifications (continental, hot, and cool) predominantly showed variable to no effects, with only a few reporting positive outcomes.

Research conducted in warm-continental climates often demonstrates variable to negative effects on the chemical composition of wine. For instance, Feng (2014) observed that cluster thinning had inconsistent impacts on grape and wine volatile compositions, with significant variations noted over three seasons. These findings align closely with those of Vilanova *et al.* (2020), who also performed GC-MS analyses on wines from cluster-thinned grapes and reported variable effects on the volatile composition across different seasons.

Two studies employing HPLC analysis on cluster-thinned wines yielded conflicting results. Karoglan *et al.* (2014) found that cluster thinning significantly increased trans-resveratrol levels in wines, whereas Gil-Munoz *et* al. (2009) observed no such increase. Notably, both studies focused on Cabernet-Sauvignon and were conducted within the same climate classification. A crucial distinction between the two studies is that Gil-Munoz *et al.* (2009) specified the severity of cluster thinning, whereas Karoglan *et al.* (2014) did not. This suggests that the effectiveness of cluster thinning in enhancing resveratrol content in wine may be influenced by the severity of the thinning process. Cluster thinning (CT) at the pea-size stage has been shown to enhance the phenolic content of grapes, corroborating findings from previous studies (Diago *et al.*, 2010; Rescic *et al.*, 2015) that align with those of Karoglan *et al.* (2014).

Three studies examined the effects of CT on wine quality in cool climate conditions. Despite being conducted two decades apart, two of these studies had similar conclusions that the impact of CT on wine quality appears to be influenced by the timing of the intervention and prevailing environmental conditions (Gonzalez-Neves *et al.*, 2002; Suklje *et al.*, 2022). These studies did not consistently observe significant differences in wine phenolics or varietal volatiles across seasons. However, another study conducted in a comparable climate with similar CT severity reported a consistently positive effect on wine phenolics (Prajitna *et al.*, 2007). This study focused on a hybrid grape variety, which may account for the discrepancies observed between this study and the previous two.

In hot-Mediterranean climates, three studies have focused on wine composition and the effects of CT on the profile of a wine. Two recent articles found that CT enhanced phenolic content and significantly improved the chemical and sensory profiles of 'Syrah' wines (Condurso *et al.*, 2016; Tahmaz, 2023). Conversely, one study on Cabernet-Sauvignon claimed that cluster thinning reduced wine quality compared to the control (Bravdo *et al.*, 1985).

Overall, the trend suggests that CT is slightly more effective in warm Mediterranean climates. This could be due to the phenomenon observed by Poni *et al.* (2023) where climates prone to producing overcropped vines experience a greater benefit from cluster thinning than those that are not overcropped. This aligns with previous literature indicating that moderate thinning, as opposed to severe CT, is the most beneficial severity for cluster thinning (Bravdo *et al.*, 1984; Rutan *et al.*, 2018; Vanderweide *et al.*, 2024). In cool climates, overcropping is particularly unlikely due to slower vine growth and ripening. Warm-continental climates yielded more variable results compared to Mediterranean climates, but still showed positive outcomes. The wide variability in environmental conditions across these studies likely contributes to the differing results. In hot climates, where wines can easily become overripe and excessive temperatures can inhibit photosynthesis beyond 40 degrees Celsius, grapevines may not benefit from cluster thinning as much (Greer & Weedon, 2012; Jiang *et al.*, 2017; Luo *et al.*, 2011; Venios *et al.*, 2020; Zhang *et al.*, 2018).

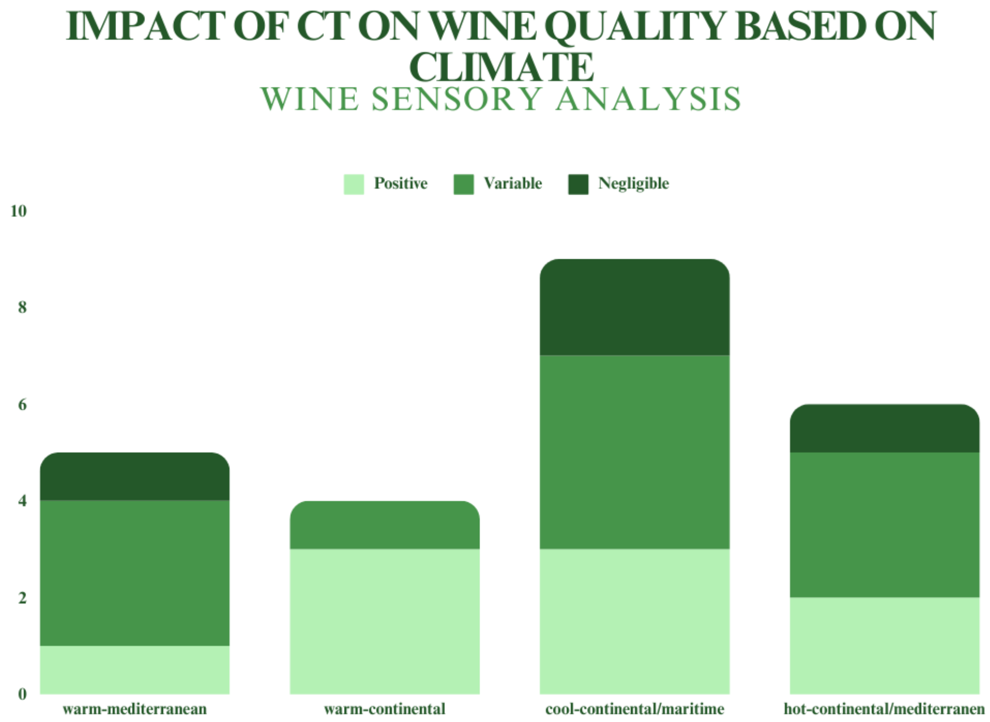

FIGURE 2. Trend of results by climate type for sensory analysis.

CLIMATE TRENDS IN WINE SENSORY ANALYSIS

A consistent pattern emerges in studies examining the sensory aspects of wine quality through various sensory analysis methods (Figure 2). It appears sensory analysis frequently reveals that tasters are highly variable in their ability to detect differences between wines in relation to CT (Table 4). There is no apparent difference between climate types regarding the effectiveness of CT.

Studies using sensory analysis to assess wine quality differences suggest that changes in the phenolic composition of grapes do not necessarily result in changes in wine composition (Bowen *et al.*, 2016; Bubola *et al.*, 2023; Kemp *et al.*, 2011). Sometimes, sensory analysis shows no preference for CT wines over the control (McDonel, 2011), even when there is a significant difference in the wine's phenolic composition. Conversely, one study found a significant increase in wine phenolic concentration due to CT, despite no increase in the grapes (Bubola *et al.*, 2023). This underscores the importance of sensory analysis in evaluating the benefits of CT, as relying solely on grape compositional changes can misrepresent wine quality differences due to CT.

TABLE 4. Trend of results by climate type for sensory analysis.

Climate type	Increased wine quality overall	Varying effect on wine quality overall	Negative effect on wine quality overall
Warm-Mediterranean	Bubola *et al.* (2023)	De Bei (2022)	
		McDonnell (2011)	
		Ough and Nagaoka (1984)	
Warm-continental	Rutan *et al.* (2018)	Avizcuri-Inac *et al.* (2013)	Gil *et al.* (2009)
		Diago *et al.* (2010)	
Cool-continental/maritime	Bowen *et al.* 2016	Macfarlane (2017)	Prezler (2012)
	Roberts *et al.* (2007)	Mawdsley (2019)	Reynolds and Wardle (1989)
	Sun *et al.* (2012)*	Reynolds *et al.* (2007)	
Hot-continental/Mediterranean	Naor *et al.* (2002)	Bravdo *et al.* (1984)	Van Schalkwyk (1995)
	Tahmaz (2023)	Essary (2021)	
		Fertel (2011)	

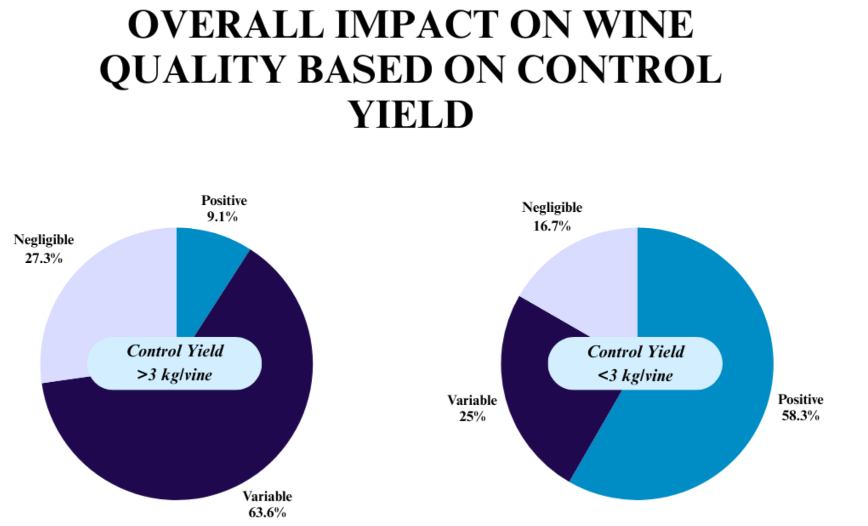

FIGURE 3. Overall impact on wine quality based on control yield.

The variability in sensory analysis methods, such as sample size, expertise level, and training protocol, complicates determining CT's true effect on wine quality concerning sensory preferences. However, eleven (half) of the sensory studies reviewed found that tasters could discern differences between wines at variable times (Avizcuri-Inac *et al.*, 2013; Bravdo *et al.*, 1984; De Bei *et al.*, 2022; Diago *et al.*, 2010; Essary, 2021; Fertel, 2011; Macfarlane, 2017; Mawdsley, 2019; McDonnell, 2011; Ough & Nagaoka, 1984; Roberts *et al.*, 2007), with an additional eleven studies showing conclusively positive or negative results from CT. Specifically, seven studies found tasters preferred CT wines (Bowen *et al.*, 2016; Bubola *et al.*, 2023; Naor *et al.*, 2002; Roberts *et al.*, 2007; Rutan *et al.*, 2018; Sun *et al.*, 2012; Tahmaz, 2023), while four studies found a preference for non-CT wines (Gil-Munoz *et al.*, 2009; Preszler, 2012; Reynolds & Wardle, 1989; van Schalkwyk *et al.*, 1995). Thus, more than half of the studies in this review reported variable to positive results from CT. This observed trend as well as the tendency for warmer climates to experience more positive effects from CT should help winemakers make more informed decisions on whether to implement CT or not.

EFFECT OF A VINEYARD'S INITIAL YIELD ON THE IMPACT OF CLUSTER THINNING

The impact of cluster thinning (CT) can vary due to multiple factors, including vineyard location, seasonal climate conditions, grape variety, and the severity of thinning applied. An additional, and perhaps underexplored, variable is the initial crop load per vine, measured in kilograms per vine (kg/vine). Despite its potential importance, there appears to be limited research specifically addressing the role of initial crop load in moderating the effects of CT on wine quality. To date, no published studies have compared the impact of CT on high-yielding vineyards versus already low-yielding vineyards, controlling for other factors such as cultivar, pruning practices, climate, and irrigation regimes.

This study sought to fill that gap by categorising experimental vineyards into two groups based on initial crop load: high-yielding (> 3 kg/vine) and moderate/low-yielding (< 3 kg/vine). A crop load of 3 kg/vine was selected as a threshold based on comparative data from viticultural regions such as California and Europe. In regions like Burgundy and Bordeaux, maximum permitted yields range from 35 to 60 hl/ha, equating to approximately 2.5 to 3.5 kg per vine, depending on vine density (Denig, 2023; Hubble, 2017; Karlsson, 2022; Denig, 2023; Hubble, 2017; Karlsson, 2022).

The included studies were then categorised based on their reported impact of CT on wine quality as positive, variable, or negligible. Of the 23 studies that disclosed data on initial yield per vine, 11 were classified as high-yielding and 12 as moderate/low-yielding. Among the high-yielding vineyards, 10 studies reported either no effect or a variable effect from CT, whereas only 5 of the moderate/low-yielding studies reported similar outcomes (Figure 3). This suggests that high-yielding vineyards may benefit less from CT than moderate-yielding vineyards. However, it is important to note that the studies included in this comparison varied in methodology, climate, and grape variety. Despite these differences, the findings highlight an area of viticultural research that warrants further exploration, particularly regarding the underlying mechanisms that may influence the effectiveness of CT in improving wine quality.

ECONOMIC IMPACT OF CLUSTER THINNING

The consensus on the economic viability of CT for vineyards is that CT is not feasible for many vineyards.

Sun *et al.* (2012), discuss the economic implications of cluster thinning, highlighting that higher grape prices would be necessary to compensate for lost yields and additional production costs associated with cluster and shoot thinning. Despite the economic impact of reduced yield found by Condurso *et al.* (2016), they concluded that the overall improvement in wine quality, particularly in aroma and colour compounds, makes cluster thinning a viable option in the Mediterranean climate. This conclusion contrasts with that of Karoglan *et al.* (2014), who raise concerns about the economic feasibility of cluster thinning due to the higher grape prices needed to compensate for yield loss and additional production costs. Their results show reduced yields with CT but do not provide a detailed economic analysis to fully support this claim.

McDonnell (2011) reached a similar conclusion, highlighting that the financial costs associated with CT outweigh the sensory benefits, as the practice did not significantly enhance wine quality to justify a higher bottle price or price per ton. Another study supporting the view that CT is not economically feasible even included the increased revenue from selling the thinned grapes to make sparkling or low-alcohol wines (van Schalkwyk *et al.*, 1995). One study, focusing on verjus production using CT grapes, found that the practice could be financially profitable if the grapes were sold for verjus production and the final harvest sale price significantly increased (Marbach *et al.*, 2023). Lastly, the most detailed economic analysis of CT comes from Preszler (2012), who introduced a new analytical model demonstrating how growers can determine their required price at a given yield to compensate for losses. However, when considering the willingness to pay determined through their consumer research, the substantial price increases necessary to offset losses from CT were not deemed feasible.

CONCLUSION

Based on the comprehensive narrative systematic review, several conclusions can be drawn regarding the impact of CT on wine quality. This review highlights that CT can influence wine quality by affecting sensory attributes, volatile compounds, and polyphenol content. However, the extent of its impact varies widely based on several factors, including grape variety, vineyard location, climatic conditions, and the timing and severity of thinning interventions. The sensory analysis revealed that CT generally enhances the aromatic complexity and flavour profile of wines, contributing to greater depth and richness. Studies employing GC-MS consistently demonstrated that CT alters the volatile composition, leading to more desirable aroma characteristics. Similarly, HPLC analyses showed that CT can increase polyphenol content, improving the wine's colour intensity.

Despite these benefits, the economic feasibility of CT remains contentious. The practice often results in reduced yields, which necessitates higher grape prices to offset the loss. While some studies, such as those conducted in Mediterranean climates, found that the improvement in wine quality might justify higher costs, other research, particularly in regions with different climatic conditions, questioned its overall viability.

In conclusion, while CT can be a valuable tool for enhancing wine quality, its implementation must be carefully considered in the context of specific vineyard conditions and economic constraints. Future research should focus on refining CT techniques to maximise quality improvements while minimising economic drawbacks. This review provides a detailed synthesis of current knowledge, offering practical guidance for viticulturists aiming to optimise CT practices for superior wine production.

ACKNOWLEDGEMENTS

I would like to express my gratitude to the College of Agriculture and Life Sciences for their generous support. The horticulture department scholarships provided essential funding that enabled the performance of this research. Their support has been invaluable to the success of this study.

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