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REVIEW

Effects of whole cluster and carbonic maceration techniques on the chemical and sensory characteristics of red wines

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Abstract – The objective of this study is to investigate the effects of whole cluster (WC) and carbonic maceration (CM) techniques on red wine production, aiming to understand how these winemaking practices influence phenolic composition, color intensity, tannin structure, and aromatic profile. Based on the principles of wine chemistry and microbiology, the study emphasizes the role of phenolic compounds, anthocyanins, tannins, and volatile compounds, as well as the impact of grape stems during fermentation. An integrative literature review was conducted, gathering original research and recent reviews, with data organized in a comparative table and critically analysed. Results indicate that both techniques significantly affect the chemical and sensory characteristics of wines. WC tends to produce more structured and astringent wines with greater aging potential, whereas CM yields lighter, fruitier wines, sometimes with lower alcohol content. Effects vary according to grape cultivar and vinification conditions, and studies on Brazilian grape cultivars remain limited. Implications include the diversification of enological styles, enhancement of regional identity, and encouragement of further national research. The study contributes by consolidating available scientific knowledge and highlighting perspectives for improving the competitiveness and quality of Brazilian wines.

Keywords: Whole cluster. Carbonic maceration. Red wine. Phenolic composition. Sensory analysis. Enology.

Efeitos das técnicas de *whole cluster* e maceração carbônica nas características químicas e sensoriais de vinhos tintos

Resumo – O objetivo deste estudo é investigar os efeitos das técnicas de *whole cluster* (WC) e maceração carbônica (CM) na produção de vinhos tintos, buscando compreender como esses métodos influenciam a composição fenólica, a intensidade de cor, a estrutura dos taninos e o perfil aromático. Fundamentado nos princípios da química e da microbiologia do vinho, o trabalho destaca o papel dos compostos fenólicos, antocianinas, taninos e voláteis, bem como o impacto da presença dos engaços durante a fermentação. Realizou-se uma revisão integrativa da literatura, reunindo pesquisas originais e artigos recentes de revisão, com organização dos dados em tabela comparativa e análise crítica. Os resultados indicam que ambas as técnicas afetam de forma significativa as características químicas e sensoriais dos vinhos. A WC tende a originar vinhos mais estruturados e adstringentes, com maior potencial de envelhecimento, enquanto a MC resulta em vinhos mais leves, frutados e, em alguns casos, com menor teor alcoólico. Os efeitos variam conforme a cultivar e as condições de vinificação, sendo ainda escassos os estudos com variedades brasileiras. As implicações incluem a diversificação dos estilos enológicos, a valorização da identidade regional e o estímulo a novas pesquisas nacionais.

Palavras-chave: *Whole cluster*. Maceração carbônica. Vinho tinto. Composição fenólica. Análise sensorial. Enologia.

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Introduction

Alcoholic fermentation is a biochemical process carried out under anaerobic conditions, in which the sugars present in grape must are converted into ethanol and carbon dioxide (CO_2) by the action of yeasts, mainly *Saccharomyces cerevisiae* (Gonzalez; Morales, 2022). With recent technological advances and the growing demand for wines with distinctive sensory profiles, alternative winemaking methods have gained increasing attention. Among these, whole cluster (WC) fermentation and carbonic maceration (CM) stand out as practices capable of significantly influencing wine quality (Jackson, 2020; González-Arenzana *et al.*, 2020).

The use of whole grape clusters was historically common in winemaking. However, with the introduction of mechanical destemming in the late 19th century, this approach was largely replaced to avoid the extraction of undesirable compounds (Ribéreau-Gayon *et al.,* 2021). Recently, whole cluster fermentation techniques have been re-evaluated as strategies capable of intensifying tannin structure and increasing the aromatic complexity of wines (Luzzini *et al.,* 2025).

WC fermentation may involve between 10 % and 100 % whole cluster inclusion, adjusted according to grape cultivar, desired wine style, and winemaking practices. CM, in turn, consists of fermenting whole clusters in a sealed environment saturated with CO_2, promoting intracellular fermentation in the berries, which can enhance volatile compound extraction and yield more intense coloration. This approach also allows for modulation of tannin extraction and stabilization of aromatic precursors, which can significantly influence the resulting wine's mouthfeel and aging potential (Godden, 2018; Tong *et al.,* 2023).

Both techniques require strict temperature and maceration time control, being especially indicated for cultivars such as Pinot Noir and Syrah, which have softer tannins (Day *et al.,* 2020). Conversely, cultivars such as Cabernet Sauvignon, with naturally high levels of 3-isobutyl-2-methoxypyrazine (IBMP) - a compound linked to intense herbaceous aromas - may not benefit from these approaches (Godden, 2018).

Given this context, the present study aims to consolidate technical and scientific knowledge by highlighting the transformations induced by WC and CM techniques on phenolic compounds, volatile composition, tannin structure, color, and the sensory profile of red wines. In addition, this review seeks to provide insights that stimulate further research, particularly on Brazilian wines, to deepen the understanding of the mechanisms involved and to promote innovation in regional winemaking.

Materials and Methods

This integrative review aimed to compile and critically analyse the scientific literature on the application of whole cluster (WC) and carbonic maceration (CM) techniques in red wine production. The literature search was conducted in the Web of Science, Scopus, ScienceDirect, SciELO, and CAPES Periodicals databases using combinations of the keywords "whole cluster fermentation", "whole bunch fermentation", "carbonic maceration", "stem contact fermentation", "wine phenolic composition", and "wine aroma profile". Original research articles and review papers were considered, prioritizing studies published between 2020 and 2025, although earlier relevant publications were also included. Articles were included when they reported chemical or sensory effects associated with WC or CM techniques in red wine production, whereas studies that did not address these aspects or lacked sufficient methodological description were excluded. A total of 42 publications were initially

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identified, of which 21 met the inclusion criteria and were selected for qualitative analysis, while additional classical references were used for conceptual support. The extracted information was organized into a comparative table and critically discussed. This review contributes by synthesizing recent scientific evidence on WC and CM techniques and by identifying current research trends and knowledge gaps, particularly regarding their application under Brazilian winemaking conditions.

Phenolic composition of grapes and stems

Grape clusters consist of berries (fruits) and the stem, which supports them (Fig. 1). The stem is composed of the peduncle (main stalk that connects the cluster to the vine) and pedicels (small stalks that attach the berries to lateral branches). The berries are made up of skin, pulp, and seeds. The skin is rich in phenolic and aromatic compounds; the pulp contains water, sugars, and tartaric acid; and the seeds concentrate tannins (Leão, 2021; Ribéreau-Gayon *et al.,* 2021).

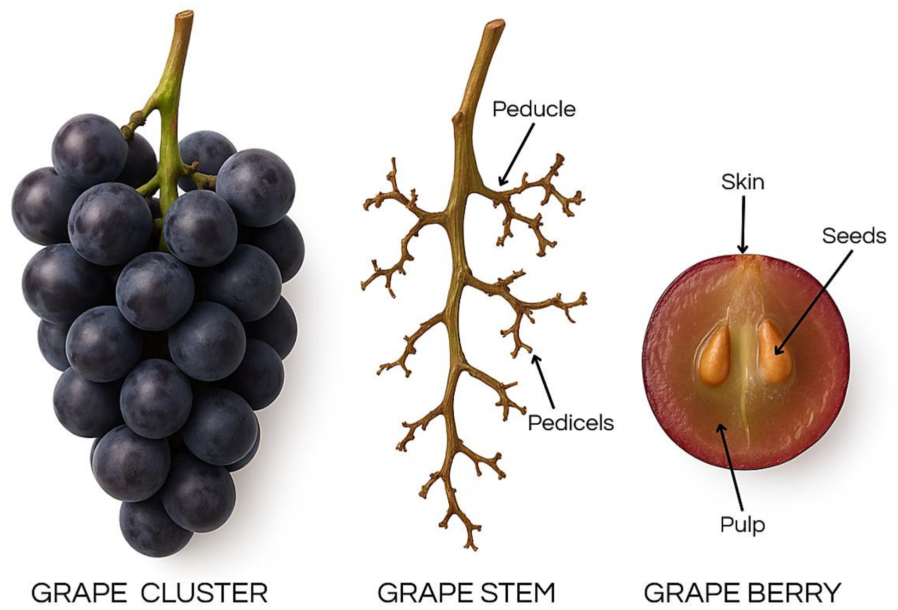

Figure 1. Structural composition of grape cluster, stems and berries.

Grapes contain a wide variety of compounds that contribute to the color, structure, and oxidative stability of wines. These compounds are divided into flavonoids (anthocyanins, flavonols, and flavanols) and non-flavonoids (phenolic acids and stilbenes). Anthocyanins, mainly concentrated in the skins, provide color to red wines, while flavanols, predominantly found in seeds, contribute to astringency (Ribéreau-Gayon *et al.,* 2021; Kumar; Tian; Harrison, 2022). In terms of distribution, the skin shows the highest total phenolic content (142.75 to 483.39 mg/L), followed by the seeds; the pulp contains significantly lower amounts (86.50 to 146.32 mg/L) (Stahl, 2011).

Stems are composed mainly of water (55-80 %) and have a lignocellulosic structure with cellulose, hemicellulose, and lignin, giving them adsorptive potential (Blackford *et al.,* 2021). They concentrate volatile compounds such as IBMP, hexanal, geraniol,

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and methyl salicylate, which are associated with vegetal, floral, and menthol notes. The phenolic composition of stems includes flavonoids, hydrolyzable tannins, pectins, and soluble inorganic salts (Marchante *et al.,* 2019; Kosińska-Cagnazzo *et al.,* 2020).

The application of bioactive extracts obtained from skins and stems was evaluated by Casquete *et al*. (2021), as an alternative to sulfur dioxide (SO_2) use. Stem extracts showed higher total phenolic content and greater *in vitro* antioxidant activity. Furthermore, both extracts demonstrated selective antimicrobial action, with lower inhibition of yeasts, which may favor the fermentation process.

Proanthocyanidins (or condensed tannins), present in seeds, skins, and stems, play an important role in sensory perception, particularly in astringency. This sensation results from the formation of complexes between tannins and salivary proteins, leading to contraction of the oral mucosa. Interaction with salivary amylase intensifies the sensation of dryness, a characteristic of wines with high tannin concentrations (Blackford *et al.,* 2021).

Principles of WC and CM techniques

The WC technique involves the inclusion of entire grape clusters, including stems, in the fermentation process. Grapes may be crushed or kept intact, allowing partial carbonic maceration to occur within whole berries. This technique facilitates the extraction of tannins from stems and the formation of volatile compounds that contribute to the aromatic diversity of wine (Tesniere; Flanzy, 2011).

The presence of stems in the must can accelerate the onset of alcoholic fermentation and reduce residual sugar content, possibly due to increased oxygenation promoted by the porous structure of the stalks, which favours yeast development. In addition, stems act as thermal buffers, helping to stabilize must temperature during fermentation. However, when stems are insufficiently lignified or still green, they may intensify vegetal characteristics, compromising the aromatic typicity of the wine (Casassa *et al.,* 2021).

Renowned producers such as Domaine de la Romanée-Conti (Burgundy) and Sine Qua Non (California) use the WC technique to enhance the tannic and aromatic structure of cultivars such as Pinot Noir, Syrah, and Grenache. In Brazil, the practice has been adopted by some wineries, particularly for cultivars with more delicate tannins such as Syrah and Pinot Noir (Scheeren, 2023).

The CM process, in turn, consists of fermenting whole grape clusters in sealed tanks saturated with CO_2, creating an anaerobic environment. Under these conditions, intracellular fermentation occurs in the berries, with partial conversion of sugars and malic acid into ethanol and other metabolites by endogenous enzymes. When the alcohol content reaches approximately 2 %, the berries rupture and release their juice, which then undergoes conventional alcoholic fermentation (Tesniere; Flanzy, 2011; Maicas, 2021).

This method can produce wines with intense coloration attributed to higher anthocyanin content, as well as elevated levels of catechins and proanthocyanidins. The sensory profile is characterized by floral and fruity notes, associated with increased levels of terpenes, esters, and compounds such as ethyl cinnamate (fruity aroma) and benzaldehyde (bitter almond aroma). In addition, reductions in C6 alcohols and aldehydes, linked to undesirable herbaceous aromas, have been reported (González-Arenzana *et al.,* 2020). Beyond aroma-related effects, wines produced by CM may exhibit lower alcohol content, not as a direct consequence of alcoholic fermentation, but rather due to intracellular grape metabolism under anaerobic

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conditions, which slightly reduces the pool of fermentable sugars available for ethanol production (Gutiérrez *et al.,* 2023).

Results and Discussion

The CM and WC techniques can variably influence the chemical and sensory properties of wines. The main comparative data are summarized in Table 1.

Day *et al.* (2020) investigated the impact of including whole and partially crushed clusters (75 % to 100 %) in Shiraz and Pinot Noir cultivars wines. The results revealed an increase in color intensity, a greater expression of dark fruit aromas, and a significant elevation in IBMP concentrations in both cultivars. For Shiraz cultivar, a direct correlation was observed between WC proportion and tannin levels, accompanied by a greater perception of astringency. These results indicate that increasing WC proportions enhances phenolic extraction from both berries and stems, which is directly reflected in a firmer tannin structure and heightened tactile perception, often perceived sensorially as increased astringency (Waterhouse; Sacks; Jeffery, 2024). Tannin concentrations ranged from 596.00 to 1360.00 mg/L, values higher than those reported by Watrelot (2021) for wines produced by traditional methods (48.00 to 831.00 mg/L).

The use of WC in hybrid wines was investigated by Gapinski, Horton and Watrelot (2023). Samples with 50 % inclusion exhibited significant increases in tannins (from 1.00 to 1.50 g/L) and anthocyanins, while maintaining color intensity after four months of aging. Sensorially, these wines were preferred by evaluators due to their greater complexity and balance of body and texture. According to Kumar, Tian and Harrison (2022), the tannin/anthocyanin ratio may be critical for color stability as well as for promoting the solubility and retention of tannins during wine aging. Such sensory preference is likely associated with a balanced tannin/anthocyanin ratio, which contributes to improved mouthfeel integration and color stability during early aging.

Casassa *et al.* (2021) evaluated the effects of WC and dried stems (DS) additions in Pinot Noir cultivar over two vintages (2016 and 2017). Both practices increased wine pH and volatile acidity (VA). The most pronounced values were pH (from 3.31 to 3.60) and VA (from 0.79 to 1.12 g/L) in 100 % WC during the 2017 vintage. From a sensory perspective, elevated pH and volatile acidity levels may modulate freshness perception and enhance the expression of herbaceous and astringent attributes, particularly in wines produced with high WC proportions (Jackson, 2020). Although oxygen exposure contributes to increased VA through the stimulation of acetic bacteria, it is not the sole mechanism involved. According to Waterhouse, Sacks and Jeffery (2024), potassium and calcium extraction from stems promote potassium bitartrate precipitation, altering the acid-base equilibrium and leading to increased wine pH. The inclusion of DS also resulted in marked increases in tannin content (up to 137 %), contributing to wines with more pronounced fruity, herbaceous, and astringent sensory notes.

In the study by Li *et al.* (2025), the effects of stem-contact fermentation were evaluated in Cabernet Sauvignon and Merlot cultivars. The results showed increases in pH and total phenols, anthocyanins, and tannins. From a compositional and varietal perspective, Watrelotm, Heymann and Waterhouse (2020) identified that the tannins of the Cabernet Sauvignon cultivar are drier and more persistent than those of the Pinot Noir cultivar due to their higher molecular weight. According to these authors, WC wines are sensorially described as fruit-forward yet structurally more assertive, with increased tannin persistence, dryness, and a more

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pronounced astringency. A slight reduction in alcohol content (from 13.00 % to 12.60 %) was also noted, an effect associated with the water content present in stems, which may be released during maceration (Blackford *et al.,* 2021). Similarly, Gutiérrez *et al.* (2023) reported alcohol reductions of up to 4 %, depending on the winemaking conditions and the cultivar used.

González-Arenzana *et al.* (2020) found that Tempranillo wines produced by CM showed higher color intensity, increased phenolic content, and improved aromatic quality, with notable increases in esters, acetates, and vitamins A and B. In contrast, Portu *et al.* (2023), comparing CM with traditional vinification in Tempranillo and Graciano cultivars, observed lower color intensity and reduced anthocyanin and flavonoid concentrations in CM wines. These contrasting outcomes are likely related to grape composition and specific vinification conditions, which strongly influence phenolic extraction and aroma development during CM. According to general enological principles, such compositional variability is associated with differences in structural perception, mouthfeel intensity, and overall balance among wines (Jackson, 2020).

In Brazil, studies addressing the application of CM remain limited. Souza *et al.* (2017), analysing unconventional methods applied to the Touriga Nacional cultivar in the Vale do Submédio São Francisco, reported that CM resulted in wines with lower color intensity, reduced alcohol content, total polyphenol index, anthocyanins, and total phenolic compounds compared to other vinification approaches. Similarly, Rizzon *et al.* (1999) described the production of less structured wines obtained through CM. This sensory profile is consistent with reduced phenolic extraction, resulting in wines with lower body, softer tannin structure, and shorter palate persistence. Additionally, Bertagnolli *et al.* (2007) observed reductions in *trans*-resveratrol levels, suggesting that the CO_2 rich atmosphere limits the extraction of compounds present in the grape skins and seeds.

Overall, CM demonstrates a strong capacity to modulate both the chemical composition and sensory profile of red wines, although its effects are highly dependent on grape cultivar and vinification conditions. As reported in the studies discussed above, CM may promote enhanced aromatic expression, particularly fruity and fermentative notes, while also being associated with reduced phenolic extraction, resulting in wines with lighter body, lower color intensity, softer tannin structure, and reduced palate persistence when compared to conventionally vinified wines. This variability highlights the complexity of CM and reinforces the need for context-specific evaluations (González-Arenzana *et al*., 2020; Portu *et al*., 2023; Souza *et al*., 2017).

The scarcity of recent studies conducted under Brazilian conditions reveals an important research gap, as grape cultivars and winemaking environments in Brazil differ substantially from those traditionally studied in European contexts. Brazilian viticulture includes a high proportion of hybrid and American grape varieties, as well as cultivars developed by national breeding programs, which often exhibit distinct phenolic profiles compared to classic *Vitis vinifera* cultivars (Silva *et al.,* 2022). In addition, warm and subtropical climates, along with viticultural practices such as double pruning used to optimize fruit ripening, may significantly influence grape composition and wine quality (Maniero *et al*., 2025). These factors reinforce the importance of further investigations to better understand the chemical–sensory relationships associated with alternative vinification techniques under

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Brazilian winemaking conditions.

Table 1. Chemical and sensory parameters of red wines produced by WC and CM methods.

Cultivars/Region	Treatments	Results	References
Pinot Noir, Shiraz/ Australia	Control (destemmed) and WC crushed at 25 %, 50 %, 75 % and 100 %.	Pinot Noir and Shiraz cultivars: ↑color; ↑herbaceous compounds; dark fruit aroma; ↑IBMP (5.50 ng/L). Shiraz cultivars: ↑tannins (596.00 to 1360.00 mg/L).	Day *et al.,* 2020
Frontenac, Marquette/USA	Control (destemmed) and WC at 25 % and 50 %.	↑tannins (1.00 → 1.50 g/L); ↑anthocyanins (highest at 50 % WC); sensory preference and aging potential for 50 % WC.	Gapinski; Horton; Watrelot, 2023
Pinot Noir/ USA	Control (destemmed), WC at 50 %, 100 % and stem addition.	↑pH (3.31 → 3.60 for 100 % WC in 2017); ↑VA (0.79 → 1.12 g/L for 100 % WC in 2017); tannins in 2016: ↑68 % (50 % WC), ↑100 % (100 % WC), and ↑90 % (DS); in 2017: ↑61 % (50 % WC), ↑123 % (100 % WC), and ↑137 % (DS). Vegetal aromas.	Casassa *et al.,* 2021
Cabernet Sauvignon, Merlot/China	Control (destemmed), 10 %, 20 % WC.	↑total polyphenols (1.523 →1.862 mg/L); ↓alcohol content (13.60 % →13.00 %); ↑fruit and tannin perception.	Li *et al.,* 2025
Tempranillo/ Spain	CM vs. traditional vinification.	↑CI (9.45 vs. 8.36); ↑TPI (55.13 vs. 51.57); (2.14 vs. 1.91); ↑total tannins (2.67 vs. 2.49 g/L); ↑esters (1.80 vs. 1.61 mg/L); ↑acetates (3.11 vs. 1.29 mg/L); ↑vitamin A (2.76 vs. 2.13 mg/L) and B (2.00 vs. 1.50 mg/L).	González-Arenzana *et al.,* 2020
Touriga Nacional/ Brazil	CM, cold pre-fermentation maceration and thermovinification.	↓IC (7.37); ↓alcohol content (9.52 %); ↓TPI (<40); ↓anthocyanins (110.63 mg/L); ↓total phenolic compounds (1271.58 mg/L).	Souza *et al.,* 2017

Units = ng/L: nanogram per liter; mg/L: milligram per liter; g/L: gram per liter. Acronyms = VA: volatile acidity; DS: dried stems; IC: color intensity; TPI: total polyphenol index; WC: whole cluster; CM: carbonic maceration; vs.: versus.

Conclusion

Whole cluster and carbonic maceration techniques exert significant effects on the phenolic composition and sensory profile of wines, promoting increases in color intensity, tannin concentration, and aromatic complexity, with responses strongly dependent on grape cultivar and specific winemaking conditions. WC generally produces wines with greater structural

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integrity and tannin content, exhibiting enhanced astringency and aging potential, whereas CM often yields lighter, fruit-forward wines with lower alcohol levels and may result in reduced tannin and anthocyanin extraction under specific conditions. Nevertheless, there is a marked scarcity of recent studies applying these techniques to Brazilian wines, underscoring the need for further research, particularly involving grape cultivars adapted to the national context. Collectively, these findings provide evidence-based insights for winemakers seeking to diversify wine styles and optimize vinification strategies according to grape cultivar and regional conditions.

Conflict of Interest

The authors declare that the research was conducted in the absence of any potential conflicts of interest.

Ethical Statements

The authors confirm that the ethical guidelines adopted by the journal were followed by this work, and all authors agree with the submission, content and transfer of the publication rights of the article to the journal. They also declare that the work has not been previously published nor is it being considered for publication in another journal.

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