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Abstract

Background: Withering processes have a strong impact on the phenolic composition of winegrapes and related wines. Even if attention has often been focused on other phenolics, a great number of studies have included phenolic acids because of their quantitative and qualitative modifications during dehydration-withering processes. A systematic review that provides a concise overview of the extensive literature available on this important topic is lacking.

Scope and approach: This review identified 39 articles to answer the research question: *What changes occur in phenolic acids after the withering process of winegrapes?* The expected contribution of this systematic review is to have a full view of the worthwhile recent findings on these often-overlooked compounds to manage the technological process with new awareness and to find eventual weaknesses in this field to highlight new questions and research directions.

Key findings and conclusions: The research yielded useful results for withering and winemaking management. Phenolic acids are well represented in certain special productions to be proposed as markers of wine authenticity. Hydroxycinnamic and hydroxybenzoic acids and their derivatives are often affected differently by the withering process. Their evolution during grape withering is a complex phenomenon that is affected by many varietal and technological variables. In particular, the withering conditions applied and grape genotype play an important role in the changing amounts of phenolic acids, but there is still much to be understood, especially related to the combined effect of both factors through genetic responses to environmental stresses and their respective chemical implications.

Keywords: Phenolic composition; Phenolic acids; Withering process; Grape dehydration; Special wines.

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1. Introduction

The techniques currently utilized in winemaking and grape treatment for wine production are the result of decades of history, experience, and tradition. Scientific research has answered many practical questions, introduced important innovations, and allowed winemakers to manage traditional processes with new awareness.

Among the oenological techniques, the withering of winegrapes is one of the most strongly related to the cultural history and the climate peculiarities of the territories (Mencarelli & Tonutti, 2013). As a consequence, this process may produce wines with very different sensory features: (i) sweet wines, such as the botrytized *Sauternes* and *Tokaj*, the Mediterranean Italian *Passito*, the special icewines from Canada, the traditional wines made from *Pedro Ximénez* sun-dried grapes, or the straw wines called "*Vin de Paille*" and produced in the French Jura region; (ii) reinforced wines, sweet but more alcoholic than conventional wines, produced in territories, such as *Marsala*, where the traditional wines were historically added with alcohol during overseas shipping for the English trade; (iii) fortified wines, dry and full-bodied, such as the *Sforzato* or '*Sfursat'* from the heroic viticulture of Valtellina slopes and the *Amarone* from the Italian Valpolicella region (Kallitsounakis & Catarino, 2020; Scienza, 2013).

The withering process can be conducted on-vine, leaving the grapes on the plant subject to atmospheric phenomena for a long time (e.g., botrytized wine, late harvest wines, or icewines), or off-vine by subjecting the grapes to postharvest dehydration, which may occur outdoors or indoors, under controlled conditions or not (Figueiredo-González et al., 2013a). In recent decades, many authors have extensively studied wines produced from withered grapes because of their cultural and economic relevance, highlighting important changes in berry metabolism throughout the withering process (D'Onofrio et al., 2019; Esmaiili et al., 2007; Zoccatelli et al., 2013).

Polyphenols, which are crucial compounds for wine quality, change during the grape dehydration process (Harrison, 2018; Mencarelli et al., 2010). Several studies have been carried out to better understand the changes in the content and composition of phenolic compounds during the on- or off-vine withering of winegrapes (Corradini & Nicoletti, 2013; Figueiredo-González et al., 2013a; Torchio et al., 2016). These authors highlighted the complexity of the evolution of phenolics over the process, which seems to be the result of a composite balance between synthesis, oxidation/loss, and concentration (Bonghi et al., 2012; De Rosso et al., 2016). This balance varies greatly depending on the genetic features of each cultivar (Zenoni et al., 2016), the ripeness level and mechanical properties of grapes (i.e., skin hardness; Rolle et al., 2009), the different dehydration techniques applied (Costantinou et al., 2018), the management of three important environmental factors (i.e., temperature, humidity, and airflow), and berry weight loss rate (Rolle et al., 2013). Additionally, specific classes of phenolic compounds, although subjected to the same conditions, are not affected in the same manner by the withering process (Toffali et al., 2011).

Phenolic acids are an important fraction of non-flavonoid compounds (Baderschneider & Winterhalter, 2001) present in grapes and wines, which have attracted increasing interest over the past ten years because of their potential health benefits (e.g., antioxidant, antibacterial, antiviral, anticancerogenic, anti-inflammatory, and vasodilatatory actions) (Babbar et al., 2015; Morales-Prieto et al., 2020). Phenolic acids consist predominantly of two subgroups: hydroxycinnamic acids (HCAs) and hydroxybenzoic acids (HBAs), of types C6-C3 and C6-C1, respectively (Monagas et al., 2005). The chemical structures of the most represented phenolic acids and their average contents in the wines are presented in **Table S1**.

HCAs represent the main class of phenolic compounds in white wines and the most represented class of non-flavonoid phenolics in red wines, averaging approximately 130 and 60 mg/L, respectively (Vanzo et al., 2007). They are synthesized through the shikimate pathway from phenylalanine and tyrosine through the action of phenylalanine ammonia lyase (PAL), which is a key enzyme that exhibits a relevant interconnection with the synthesis of other phenolic compounds (Laura et al., 2019). Some of the most represented HCAs are *p*-coumaric, caffeic, ferulic, and sinapic acids. They are usually present in grapes and wines as tartaric acid esters and diesters (HCTAs), such as caftaric acid (caffeoyltartaric acid), coutaric acid (*p*-coumaroyltartaric acid), and fertaric acid (feruloytartaric acid) and rarely as sugar esters (Buiarelli et al., 2010; Ferrandino et al., 2012; Ong &

Nagel, 1978). In grapes, they are mainly located in the pulp and slightly in the skin (Garrido & Borges, 2013). The contents of HCA esters detected in grapes vary greatly for different cultivars; however, caftaric acid is generally the major compound, followed by coutaric and fertaric acids (Waterhouse, 2002). During the fermentation process, the partial hydrolysis of esters occurs, with a reaction rate depending on the pH and presence of specific enzymes, and free HCAs can be released and partially esterified with ethanol, forming HCA ethyl esters (Somers et al., 1987). The oxidation of caftaric acid by grape polyphenol oxidase (PPO) to the corresponding *o*-quinone and subsequent reaction with glutathione through the –SH groups form a stable and colorless compound named GRP (Grape Reaction Product), which plays a key role in the oxidation of other phenolic compounds. This oxidation reaction starts to take place during the crushing and pressing of the grapes, causing must browning (Cheynier et al., 1989a). HCAs and their derivatives are also known to have antimicrobial properties, particularly against the wine spoilage lactic acid bacteria and yeasts (e.g., *Brettanomyces bruxellensis*) (Harris et al., 2010; Sabel et al., 2017; Stivala et al., 2017), increasing cell membrane permeability from wine (Campos et al., 2009) and interfering with the intracellular pH and metabolism (Carmona et al., 2016). The presence of HCAs in wines markedly affects color quality features in different ways: on one hand, they can contribute significantly to the browning of musts due to their oxidation (Cheynier et al., 1989b); on the other hand, they can contribute to the color stabilization of red wines due to the copigmentation effect or participate in the formation of acylated anthocyanins and anthocyanin-derived pigments (i.e., pinotins and portisins) (Bloomfield et al., 2003; He et al., 2012). Therefore, the decrease in the content of coumaroylated anthocyanins during winemaking and aging processes due to hydrolytic and enzymatic reactions can release HCAs in musts and wines (Monagas et al., 2005). In terms of wine mouthfeel qualities, these compounds have been associated with astringency and bitterness perceptions (Garrido & Borges, 2013; Okamura & Watanabe, 1981), but their levels seem not to be perceptible in wine (Vérette et al., 1988). However, some more recent studies have pointed out that "puckering" astringency may be elicited by these compounds and evidenced a synergism on bitterness perception (Gonzalo-Diago et al., 2014; Hufnagel & Hoffman, 2008). Moreover, HCAs were identified as potential volatile precursors of ethyl phenols produced by *Brettanomyces* metabolism, conferring unpleasant flavors to wine (Vanbeneden et al., 2008). In particular, *p*-coumaric, ferulic, and caffeic acids could be enzymatically decarboxylated to vinyl derivatives by a cinnamate decarboxylase and subsequently reduced by a vinylphenol reductase, leading to the typical off-flavors described as “horse sweat,” “medicinal,” “rancid,” and “barnyard” (Malfeito-Ferreira, 2018). While several microorganisms, including *Saccharomyces cerevisiae,* can perform the enzymatic decarboxylation of HCAs, the populations of *Brettanomyces* spp. have a particularly effective activity in the reduction step (Kheir et al., 2013).

HBAs represent a minor component in grapes and wines, averaging approximately 10–20 mg/L in white wines and approximately 70 mg/L in red wines (Waterhouse & Teissedre, 1997; Waterhouse, 2002). Unlike HCAs, HBAs are not phenylpropanoids; they can be synthesized directly from the shikimic acid pathway, even if PAL is not active (Laura et al., 2019). Para-hydroxybenzoic, protocatechuic, vanillic, gallic, and syringic acids are the most abundant HBAs detected (Kallithraka et al., 2009). Among them, gallic acid is considered the most important, as it is the precursor of all hydrolyzable tannins (Nieculescu et al., 2018) and for its relevant antioxidant activity (Kallithraka et al., 2009). HBAs are mainly present in grape skins and pulp as glycosides, but gallic acid can also be extracted from grape seeds in free form through the hydrolysis of tannin galloyl esters or encompassed in condensed tannins (Revilla & Gonzalez-SanJose, 2003; Zou et al., 2002). In wines, HBAs are mostly found in free form (Monagas et al., 2005), even though some authors have also reported ethyl and methyl esters and glucose esters (Baderschneider & Winterhalter, 2001). With regard to sensory contributions, some recent studies have pointed out a synergic astringency effect with other phenols as reported for HCAs, but HBAs showed a higher affinity for salivary proteins than HCAs (Ferrer-Gallego et al., 2014; Ferrer-Gallego et al., 2017). Moreover, Wang et al. (2020) highlighted a relevant matrix effect of phenolic acids on wine aroma modulation, particularly focusing on the interaction between gallic acid and free terpene compounds that inhibits volatile release.

When discussing the outcome of grape withering processes on phenolic compounds, attention is often focused on major molecules, such as anthocyanins and tannins. Nevertheless, many significant changes occur in the phenolic acids. In fact, their evolution throughout the withering process is complex and affected by many variables. Many studies have addressed phenolic acid evolution during grape withering, considering their importance in terms of abundance and wine quality implications; however, a systematic review to summarize these findings is lacking.

Wines made from withered grapes are often identified as unique products of specific, limited geographical areas. Considering their growing interest in competitive and global markets, several studies have tried, through chemical analysis, to define characteristic compounds as quality markers to differentiate these wines from other products. In many cases, the most abundant classes of phenolic compounds that can be used as markers are HBAs or HCAs (Figueiredo-González et al., 2014a; Loizzo et al., 2013; Panceri et al., 2015). The purpose of this paper is to provide an overview of the scientific literature on this challenging topic. The approach used was aimed to focus on the evolution of phenolic acids from both qualitative and quantitative points of view in withered grapes and wines as objectively as possible. The expected contribution of this systematic review is twofold: (i) to have a systematic full view of the worthwhile recent findings to manage the technological process with new awareness, concerning the importance of these compounds, which are often overlooked; (ii) to find eventual research gaps in this field to highlight new questions and research directions.

2. Method

To produce an accurate and concise overview of the extensive literature available on this theme, a systematic review was performed on February 24, 2021, using the procedure based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (Moher et al., 2009).

A protocol was developed to provide explicit, rigorous, and transparent planning proceedings and eligibility criteria for the identification and selection of the studies of interest.

Research question

The review addressed the following close-framed question:

RQ - What changes occur in phenolic acids after the withering process of winegrapes?

The question has been deemed suitable for carrying out a systematic review, with all the PICO key elements specified, as illustrated in **Table 1**.

[Table 1]

Search strategy

The research was performed simultaneously on three digital sources of information: "Scopus" (https://www.scopus.com/), "ScienceDirect" (https://www.sciencedirect.com/), and "Web of Science" (https://webofscience.com/).

An initial list of search terms was developed, including keywords, synonyms, plural/singular forms, and alternative words (**Table 2**).

[Table 2]

The set of terms was used to create the search strings, matching them with Boolean operators. The search strings used for all the selected sources of information are listed in **Table 3**.

[Table 3]

The search fields selected were "all fields,” "find articles with these terms" (i.e., all parts of the documents excluding references), and "all fields" for "Scopus,” "ScienceDirect," and "Web of Science,” respectively. The date range selected focused on articles published "from 2007 to the present".

Selection of relevant studies

This query yielded 16,883 results, which were preliminarily selected and deduplicated. The potentially relevant citations identified were 94, and a two-step screening was carried out.

Step 1: Initial screening The first stage consisted of an initial screening of the retrieved articles based on the Title and Abstract, removing those not related to the evolution of phenolic acids during the withering process of winegrapes.

Step 2: Full-text review and data extraction The full texts of the studies selected in the first stage were then fully reviewed to determine if they were still eligible to undergo data extraction.

The inclusion criteria applied for the article selection were:

- study on the phenolic fraction of withered winegrapes (*Vitis vinifera* L.) and wines;
- focus on phenolic acids;
- evolution of phenolic acids during on-vine and off-vine withering processes and winemaking implications.

The flow diagram of the relevant study selection process, shown in **Figure 1**, allowed to obtain 39 suitable documents.

[Figure 1]

Data extraction, quality assessment, and reporting phase

In the extraction stage, all selected articles were assessed for methodological quality. The main results were collected, described, and critically examined to extract the common trends, comparing the findings regarding winegrapes used for on-vine withering and off-vine natural and controlled withering, genetic-dependent effects toward thermo-hygrometric environmental conditions, and winemaking implications. To produce a synthetic overview of the main findings pointed out by the recent literature (from 2007 to the present) about withering conditions applied, three extraction tables have been elaborated, ordering the studies based on the withering technique. **Table 4** includes the 14 most relevant findings on the modification of phenolic acids over the on-vine winegrape withering process, with most of them regarding the production of ice or botrytized wines. **Table 5** briefly describes the main outcomes of the 18 studies on the off-vine withering process under controlled conditions, while **Table 6** shows a synthesis of the results of the seven studies regarding off-vine natural withering conditions.

[Table 4]

[Table 5]

[Table 6]

3. Results and Discussion

As grape berry composition is affected by several metabolic and physicochemical mechanisms during withering and the findings can vary depending on the withering process, the results were divided into on- and off-vine and the latter further separated under controlled conditions or natural dehydration (**Tables 4**, **5**, and **6**, respectively). This section highlights the different conclusions reported in the selected studies regarding the changes in phenolic acids during the winegrape withering process. The results are discussed in an attempt to understand the causes and establish trends.

3.1. Evolution of phenolic acid content over withering: the result of a complex balance

In all the studies considered, phenolic acids were somehow affected by the withering process, but the analysis of the literature revealed different positions among authors about the balance between concentration, hydrolysis, synthesis, and oxidation/catabolism processes in winegrapes.

Some authors considered the increase in the content of phenolic acids as a consequence of the prevalence of the concentration effect on the degradation reactions. Among these authors, Marquez et al. (2012), assessing grape juice from off-vine dehydration at a constant temperature of 40 °C in Tempranillo and Merlot grapes (**Table 5**), reported a substantial increase in the contents of HBAs and selected HCTAs due to water evaporation and, possibly, the release from solid portions of the grapes during withering, even if some of these compounds were degraded through enzymatic browning reactions. Additionally, Torchio et al. (2016) studied the evolution of phenolic compounds in grape pulp over the off-vine dehydration process at two different controlled temperature conditions (18 and 28 °C) on cultivars Avanà, Chatus, and Nebbiolo (**Table 5**) and concluded that contents of HCTAs increased in withered grapes compared to those of fresh samples significantly for Chatus and Nebbiolo winegrapes These results were probably due to a balance in favor of the concentration effect, as suggested by the findings of Frangipane et al. (2007). Later, to avoid the weight loss variable during the withering process, Frangipane et al. (2012) expressed the content of HCA in Roscetto juice as mg/number of berries (**Table 5**), demonstrating in their experiment how the degradation effect prevailed over the concentration effect. Regarding HBAs, contents of syringic and gallic acids decreased during the withering process when expressed as mg/L juice, in agreement with previous observations on Aleatico grapes (Frangipane et. al, 2007; **Table 5**).

Lukíc et al. (2016) (**Table 4**), focusing on the change in the physicochemical composition of Gewürztraminer wines as a result of late and icewine harvest, hypothesized that the higher amounts of ethyl cinnamates found in these wines could have been due to the concentration effect of HCAs as a consequence of water loss. Accordingly, Panceri et al. (2013) observed an increase in the contents of HCAs (mainly caffeic acid) in Merlot and Cabernet sauvignon grapes (**Table 5**). These authors suggested that off-vine withering under controlled conditions at 7 °C, and low relative humidity could promote the activity of cinnamoyl esterase, similar to that in the maturation of wines in bottles, where HCA esters are hydrolyzed to the free form. However, in the same study, the authors observed a divergence in the HBA amounts for the two grape varieties: Cabernet sauvignon showed an increase in the content of these compounds during withering, whereas Merlot showed a decrease, suggesting a genotype effect rather than a change in the metabolic pathways. More recently, Nievierowski et al. (2021), studying the impact of off-vine withering in a naturally ventilated room on the quality of Merlot grapes, found a significant increase in phenolic acid amounts, both for HBAs and HCAs, particularly for gallic, *p*-hydroxybenzoic, caffeic, and caftaric acids (**Table 6**). Additionally, Constantinou et al. (2017) estimated a sixfold increase in the HCA content and total amounts of HBAs in both traditional Cypriot cultivars Xynisteri and Mavro undergoing an off-vine sun-drying short process (**Table 6**). Interestingly, these authors pointed out some differences among the contents of single HCAs within the subgroup. Many significant changes were observed in individual phenolic compounds in a comprehensive comparative study on Xynisteri grapes (Constantinou et al., 2018), and the increasing trend was common for all phenolic acids, but with different intensities and prevalence of singular compounds within the HBA and HCA classes concerning the various postharvest withering methods tested (**Table 6**). Additionally, the authors interpreted the significant increase in phenolic acid content observed during withering to be higher than that caused by the concentration effect, using four alternative dehydration methods, namely, multiple horizontal wires, multiple vertical pallets, low greenhouse, and hot-air dryer. Serratosa et al. (2008a) also suggested the possibility of an additional increase in the amounts of these compounds in ways other than concentration. Studying Pedro Ximenez grapes withered at temperatures of 40–50 °C (**Table 6**), as in the typical sweet wine production in southern Spanish regions, the authors observed a 188% increase in *p*-hydroxybenzoic acid content, suggesting an additional increase in the amount of these compounds during off-vine sun-drying. However, other phenolic acids (i.e., gallic acid and HCTAs) showed simultaneous degradation, probably due to oxidation or polymerization processes, leading to a final increase lower than expected. In these peculiar conditions of high temperature, several authors have highlighted the occurrence of browning enzymatic reactions involving phenolic acids (Figueiredo-González et al., 2014a; Marquez et al., 2012; Serratosa et al., 2008b). It is assumed that the first step of the PPO enzymatic browning reaction consists of the oxidation of caftaric acid (Serratosa et al., 2011), which is very sensitive to atmospheric variation, particularly related to water stress and UV light (Bellincontro et al., 2009).

Although numerous studies have shown an increase in the contents of phenolic acids, supporting the assumption of the prevalence of the concentration effect or suggesting the possibility of new formation over the withering process, other studies pointed out a decrease in their contents in both on-vine and off-vine, controlled or not, withering conditions. Among the off-vine withering studies (**Table 5**), Negri et al. (2017) found a decrease in amounts of many grape metabolites, including HCTAs, in noble-rot botrytized Garganega grapes, suggesting that they were degraded by fungal metabolism. The loss of phenolic acids in winegrapes infected with noble rot has been reported in other white varieties. A reduction in the content of caftaric acid (–69%) was observed in Chenin blanc grapes (Carbajal-Ida et al., 2016), and of HCAs in skins of botrytized Chardonnay grapes (Hong et al., 2012), probably because of laccase and tyrosinase activities that could be responsible for the oxidation of HCTAs (Dubernet et al., 1977). Nevertheless, in the early stages of the phenylpropanoid pathway during *Botrytis cinerea* infection, increased production of HCAs has been highlighted (Blanco-Ulate et al., 2015; Kallitsounakis et al., 2020). These results confirmed the complexity of the balance that determines the final content of phenolic acids in these special wines.

Piano et al. (2013) observed a very slight increase in the HCTA content in the Piedmontese variety Uvalino undergoing off-vine withering in a room at a constant temperature of 24 °C and relative humidity of 30% (**Table 5**); however, fewer differences were observed in the contents of these compounds in overripened grapes, all during a 21-day withering period. However, Nicoletti et al. (2013) observed a decrease in the contents of phenolic acids during off-vine withering under all the controlled conditions tested on Nebbiolo grapes harvested from vines defoliated at different times (**Table 5**), except for the non-defoliated sample withered at 10 °C, confirming how the agronomic techniques also affect the features of the withered grapes and wines. As a probable explanation for the decrease in the contents of esters of HCAs observed during the off-vine natural withering process of Garnacha tintorera (**Table 6**), Figueiredo-González et al. (2013b) hypothesized the participation of these compounds in degradation reactions owing to their high suitability as substrates in some other types of reactions (e.g., copigmentation or PPO browning), as well as anthocyanin acylation for the free forms, as previously presumed in studies performed on-vine by Ivanova et al. (2011) and off-vine by Toffali et al. (2011) (**Tables 4 and 5**). Nevertheless, lower contents in grapes did not lead to lower contents in the final wines. Rusjan et al. (2017), who studied for the first time the impact of the on-vine cutting of 1-year old canes with fruitful shoots during ripening, –the so-called *double maturation raisonnée* (DMR)– on Merlot grapes (**Table 4**), found the lowest concentration of HCAs in DMR-subjected grape skins when compared to that of the control, despite the presence of high amounts of these compounds in the wine made from those grapes. By contrast, Budić-Leto et al. (2017), in a study on the differentiation between Croatian dessert wine Prošek and dry wines based on phenolic composition (**Table 5**), found significantly lower concentrations of phenolic acids in Prošek dessert wines than in the dry wines.

These heterogeneous results can be explained by several factors: first, it has been shown that the positive or negative final balance of HCAs and HBAs depends on the genotype (Mayén et al., 1997; Zenoni et al., 2016), and several authors have indicated that different varieties subjected to the same withering conditions can be affected differently by the process (Kilmartin et al., 2007; Marquez et al., 2012; Torchio et al., 2016). Additionally, a very important part of the phenomenon explanation is certainly attributable to the different withering conditions applied, both on-vine (Avizcuri-Inac et al. 2018; Mikulic-Petrovsek et al., 2017) and off-vine (Bellincontro et al., 2009; Constantinou et al., 2018; Frangipane et al., 2007; Nicoletti et al., 2013). Furthermore, the rate of weight loss can significantly affect the complex balance dynamics (Bonghi et al., 2012; Mencarelli et al., 2010; Panceri et al., 2015).

3.2. Grape genetic regulation

During withering, berry tissues are metabolically active, and several specific-activated processes may affect the grape compositional features (Rizzini et al., 2009). Several studies have examined the specific changes in gene expression and the complex integration of transcriptomic, metabolomic, and proteomic levels during grape withering (Di Carli et al., 2011; Zamboni et al., 2008; Zamboni et al., 2010). However, little information is available on the weight of genetic regulation in determining the final concentration of phenolic acids in withered grapes. During the study of chemical and biochemical changes in the off-vine process of Aleatico grapes at different temperatures and weight loss rates, Mencarelli et al. (2010) found an upregulation of the expression of PAL gene, which is active at the beginning of the phenolic acid pathway, in berries exposed to temperatures of 10 ° and 20 °C, over dehydration at 10% weight loss. However, transcript abundance of the PAL gene did not correlate well with metabolite abundance. Additionally, Bonghi et al. (2012)

evaluated phenolic compound metabolism and gene expression in the skins of Raboso Piave winegrapes under off-vine controlled withering conditions related to slow and rapid rates of up to 10% and 30% weight loss. These authors highlighted the importance of the complex expression regulation of numerous members of the *Vitis vinifera* L. PAL multigene family as a key step in the multiple physiological responses to environmental stresses. In a comprehensive genetic/metabolomic study, Zenoni et al. (2016) highlighted the complexity of the metabolomic and transcriptomic changes during postharvest dehydration. Even though they found an upregulation of the expression of genes encoding important enzymes that catalyze the earliest steps of phenylpropanoid biosynthesis, the negative or positive final balance of HCAs/HBAs in several winegrape cultivars (Corvina, Sangiovese, Merlot, Syrah, Oseleta, and Cabernet sauvignon) ongoing withering process was genotype-dependent. This balance was negative in Corvina. Furthermore, the six varieties studied were characterized by distinct gene expression profiles and modulation intensities: Corvina berries showed the strongest and fastest response to postharvest withering, whereas Cabernet sauvignon showed the weakest and slowest gene induction. In accordance with these findings, more recently, the same authors assessed two different thermo-hygrometric conditions of off-vine withering with natural or forced airflow on cultivar Corvina and found no significant differences in the accumulation of HCAs/HBAs and their derivatives in response to different environmental stresses (Zenoni et al., 2020).

Regarding the decrease in the concentration of phenolic acids observed by some authors during the grape withering process, a possible explanation could be found from a genetic point of view. In the transcriptomic studies performed by Zamboni et al. (2008) on Corvina winegrapes, the authors described the upregulation of the expression of a chalcone isomerase gene, suggesting the activation of the flavonoid pathway during the withering process, and two tags of polyphenol oxidase, indicating a probable oxidation/polymerization of phenolic compounds. In accordance with the results of Zamboni et al., Di Carli et al. (2011) described an upregulation of the activity of reactive oxygen species (ROS)-scavenging enzymes during the slow withering of Corvina winegrapes. In particular, different trends in ROS accumulation were observed between the veraison and ripening phases, and a decrease in the abundance of PPO involved in browning reactions was observed during withering with respect to the veraison stage. Moreover, as mentioned above, some authors hypothesized that the decrease in the contents of HCAs in the late harvest phase is a result of their functions in some types of reactions such as the synthesis of acylated anthocyanins (Figueiredo-González et al., 2013b; Ivanova et al., 2011; Toffali et al., 2011). Although some genes involved in the first part of anthocyanin acylation mechanisms have been found in transcriptomic studies (Bonpart et al., 2018; Zamboni et al., 2008), further studies are needed to gain a better understanding of the role of genetic regulation in these reactions and their important chemical implications.

3.3. Winemaking implications: extraction and evolution

Qualitative and quantitative evolution of phenolic acids has also been observed during the winemaking of withered grapes. In particular, Marquez et al. (2014) evaluated the antioxidant activity in relation to the phenolic profile during the winemaking of Cabernet sauvignon grapes off-vine withered at a constant temperature of 40 °C and initial relative humidity of 20%. They observed an overall increase in the concentration of HBAs, probably due to the early diffusion from the solid parts of the grapes to their pulp during the withering process and later during subsequent maceration of the skins. The peaks of the amounts of these compounds were observed after 48 h of maceration, as was observed for HCA esters. These results are consistent with those previously reported for Tempranillo and Merlot grapes by Marquez et al. (2012), in which small amounts of HCA esters were present in the final wines, possibly owing to degradation reactions toward free forms and their suitability as substrates for major reactions during maceration.

Few studies have been conducted to evaluate the influence of the grape withering process on the phenolic composition of wines during aging and bottle storage. Figueiredo-González et al. (2014b) studied the phenolic composition of naturally sweet and sweet fortified Garnacha tintorera-based wines during 6 and 12 months of oak aging and observed an increase in the amounts of HBAs and HCAs in both wines. This increase was probably due to release from oak wood and transfer to the wine during the aging period or a consequence of the decrease in the contents of coumaroyl anthocyanin forms to release HCAs. The authors also highlighted a simultaneous decrease in HCTA amounts in the wines, suggesting the occurrence of slow hydrolysis reactions during the aging period. Additionally, the esters could have participated in other reactions such as polymerization or copigmentation with anthocyanins. These findings are in agreement with the previous results reported by Karagiannis et al. (2000), who conducted one of the first studies on this topic on cultivar Muscat lefko grapes from the island of Samos.

Panceri & Bordignon-Luiz (2017) observed an increase in the concentration of phenolic acids (gallic, protocatechuic, *p*-coumaric acids) during 22 months of bottle ageing for Cabernet sauvignon and Merlot wines made from grapes withered under controlled conditions, in accordance with the findings of Issa-Issa et al. (2020) in Fondillón wines made from Monastrell on-vine overripe grapes. The increased availability of free forms of HCAs may result in potential risk for the production of unpleasant flavors because of their suitability as substrates for spoilage microorganisms (Kheir et al., 2013). This possible risk, enhanced by the presence of residual sugars, necessitates rigorous microbiological control by applying appropriate inactivation measures. Nevertheless, wines made from withered grapes are often characterized by higher alcohol content than that of other styles of wine, making the proliferation of spoilage microorganisms more difficult (Malfeito-Ferreira, 2018).

3.4. The case of icewines: a discussed topic

The evolution of phenolic acid content during the production of icewines is a peculiar and often discussed topic. The first study on this issue was conducted by Kilmartin et al. (2007) on the polyphenol composition of Canadian icewines to identify the quality markers of authentic icewines. For example, "Faux" Riesling and Vidal icewines (harvested above –8 °C) had up to 11- and 21-times higher concentrations of total HCAs than those of "Real" icewines (harvested at temperatures of –8 °C or below). These findings agree with those reported by Tian et al. (2009a) who introduced a further kind of "Faux" icewine for cultivar Vidal: a refrigerator-frozen juice, artificially refrigerated at –8 °C, and a concentrated juice made using rotary evaporation at 66 °C. The artificially concentrated juice presented a concentration of phenolic acids 2.1-times higher than that of the refrigerator-frozen juice, and notably, approximately 3.6-times higher than that of naturally frozen juice. These differences were quite preserved in the icewine types produced from them, with little influence from the yeast strain used. Furthermore, the influence of the harvest date on the phenolic acid content of icewines was discussed by the same authors. Kilmartin (2007) pointed out that the earliest harvest dates produced icewines with higher concentrations of HCAs in Riesling and Vidal winegrapes harvested in Canada in 1999, 2000, and 2002, while Tian et al. (2009b) argued that the contents of HBAs and HCAs increased as grape harvest time was delayed to produce icewines from the Vidal variety harvested in China in 2005 and 2006. With regard to the considerations previously made on the influence of withering conditions, it should be recalled that the traditional icewine production technique is an on-vine withering process and is thus subjected to changes due to weather conditions (e.g., freeze-thaw cycles) that could markedly affect the balance of phenolic acids in the berries.

Avizcuri-Inac et al. (2018) focused their efforts on the chemical and sensorial characterization of sweet wines to understand the influence of the dehydration process on the features of several wines made from on-vine withered grapes. The authors analyzed sweet wines obtained by using different varieties and techniques and classified them into three clusters based on the phenolic compound characteristics. The first cluster, characterized by the highest contents of HBAs, HCAs, and other phenolic compounds, such as flavonols, included a late harvest wine and a natural icewine (both involving Tempranillo red grapes). The second cluster, with intermediate amounts of phenolic compounds, included two natural icewines (one from white and one from red grapes), one artificial icewine (from Tempranillo red grapes), and a *supurao* wine (from Tempranillo and Grenache off-vine dehydrated red grapes). The third cluster, which was described by the lowest values of phenolic compounds, particularly for HBAs, included four icewines obtained by grape freezing in the chamber, three produced from white grapes and one from red grapes. Although these findings could have been influenced by variety, environmental and technological factors (such as grape pressing), they show that the extraction and concentration of these compounds produced by freezing winegrapes were lower than those in wines belonging to the other two clusters, produced with more traditional techniques. The concentration of phenolic acids has been associated with the quality and authenticity of icewines (Kilmartin et al., 2007; Tang et al., 2013; Tian et al., 2009a, 2009b). However, new studies are needed to better understand the link between weather conditions and phenolic acid features in the production of these special wines. This alternative approach can be challenging and technically difficult, but will have very useful practical applications, such as a more focused choice of the harvest period.

4. Conclusive remarks and future perspectives

The aim of the present systematic review was to produce a concise overview of the extensive literature available on the evolution of phenolic acids in withering grapes and the wines produced from them. Although phenolic acids are structurally simple molecules, their evolution over the withering process is complex. In most cases, the amount of phenolic acids increased after withering, both at high and low temperatures. However, in some studies, their concentrations decreased or remained almost constant in grapes. In these previous studies, the authors considered a possible cause of the decrease as the high suitability of phenolic acids as substrates for other types of reactions (e.g., copigmentation or PPO browning). Indeed, it is of fundamental importance to remember that the final contents of phenolic compounds in withered grapes and the resulting wines are strongly dependent on the balance between concentration, synthesis, and loss or degradation of these compounds. This balance is particularly evident for phenolic acids in botrytized grapes (reported in section 3.1). Even if at the end of the process the overall balance resulted in the loss of phenolic acids, probably owing to tyrosinase and laccase activities, in the early stages of the phenylpropanoid pathway during *Botrytis cinerea* infection an increased production of HCAs was highlighted. Moreover, HCAs, HBAs, and their derivatives are often affected differently by the withering process, and in some cases, even single compounds within the same class can present different trends. The contents of these compounds are affected by many factors, including genotype and withering conditions. There is still much to understand about the weight of the genetic control of the withering process, and new studies are needed to investigate the berry genetic response to environmental stresses and the related chemical repercussions. In this sense, the modulation of the water loss rate and intensity may be used to increase the concentration of specific compounds. This knowledge can help manage the withering process according to the desired oenological objective.

The winemaking implications are very interesting and well-studied: HBA and HCA ester release seems to start during withering, from the solid parts of the grapes to the pulp, and to continue thereafter during maceration, with a peak after 48 h of skin maceration. The free forms of HCAs tend to increase throughout winemaking and aging. This information may be useful for practical applications, allowing the management of technological processes with improved awareness. On one hand, the increase in the contents of these compounds could involve copigmentation effects, improved antioxidant activity, and health benefits; on the other hand, it may lead to increased risks, such as must browning or off-flavor production, because of their role as substrates for spoilage microorganisms.

Finally, several authors associated the concentration of phenolic acids with a quality and authenticity marker in icewines, but further research should be carried out to better understand the link between the weather/environmental conditions and the phenolic acid features of winegrapes in on-vine withering processes.

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FIGURE CAPTION

Figure 1 –Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram of the study selection process: evolution of phenolic acids in winegrapes undergoing a withering process.

Table 1 – Identification of the question key elements (PICO).

Key element	**Response**
P – population of interest	Phenolic acids of withered winegrape
I – intervention of interest	Withering process
C– comparator	Phenolic acids of fresh winegrape
O– outcome	Changes and evolution of phenolic acids

855 **Table 2 –** List of keywords useful to construct strings with Boolean operators.

Keyword	Synonyms	Plural/singular forms	Alternative words/different spellings
Withering			Dehydration, drying, raisining
Withered grapes		Withered grape	Dehydrated grapes, dried grapes, raisin grapes
Grape	Winegrape	Grapes, winegrapes	
Sweet wines	Passito wines, withered wines, raisin wines,	Sweet wine	Straw wines, Icewines , Reinforced wines, Fortified wines, Dessert wines, Botrytized wines, Marsala, Porto, Sauternes, Tokaji, Sforzato, Sfusat, Amarone, Recioto, Aleatico, Vin Santo, Vin de Paille
Phenolic acids			HCA, HCAs, HCTAs, HBA, HBAs, hydroxycinnamic acids, hydroxycinnamics. hydroxybenzoic acids, hydroxybenzoics

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Table 3 – Search strings used in all the selected sources of information.

Search string	Databases		
	Scopus	ScienceDirect	Web of Science
(phenolic acids) AND (withered grapes)	36	94	3
"phenolic acids" AND "sweet wines"	98	88	2
("phenolic acids") AND ("ice wine" OR "ice wines" OR "icewine" OR "icewines")	47	33	4
("HCAs" OR "HCTAs" OR "hydroxycinnamics") AND ("withering" OR "dehydration" OR "drying" OR "raisining") AND ("grape" OR "winegrape")	54	2115	0
("HCA" OR "hydroxycinnamic" OR "hydroxybenzoic") AND ("withering" OR "withered" OR "raisin" OR "dehydration") AND ("grape" OR "winegrape")	370	717	14
("HBA" OR "HBAs" OR "hydroxybenzoics") AND ("withering" OR "withered" OR "raisin" OR "dehydration") AND ("grape" OR "winegrape")	6	430	0
("HCAs" OR "HCTAa" OR "hydroxyinnamics") AND ("withered" OR "dehydrated" OR "dried" OR "raisin") AND ("grape" OR "winegrape")	56	391	0
("HCA" OR "hydroxycinnamic" OR "hydroxybenzoic") AND ("withered" OR "dehydrated" OR "dried" OR "raisin") AND ("grape" OR "winegrape")	849	2721	14
("HBA" OR "HBAs" OR "hydroxybenzoics") AND ("withered" OR "dehydrated" OR "dried" OR "raisin") AND ("grape" OR "winegrape")	24	1541	0
("phenolic acids") AND ("reinforced" OR "fortified" OR "dessert" OR "straw" OR "botrytized" OR "passito") AND ("wine" OR "wines")	950	976	7
("phenolic acids") AND ("Sauternes" OR "Tokaji" OR "Sforzato" OR "Sfursat" OR "Amarone" OR "Recioto" OR "Aleatico" OR "Vin Santo")	53	44	1
("phenolic acids") AND ("Marsala" OR "Porto" OR "Vin de Paille" OR "sweet wine" OR "withered wine" OR "raisin wine")	1593	861	146
("hydroxycinnamic" OR "HCA" OR "HCTAs" OR "hydroxybenzoic" OR "HBA") AND ("reinforced" OR "fortified" OR "passito") AND "wines"	244	599	6
("hydroxycinnamic" OR "hydroxybenzoic") AND ("Sauternes" OR "Tokaji" OR "Sfursat" OR "Amarone" OR "Recioto" OR "Aleatico" OR "Vin Santo")	38	56	1
("hydroxycinnamic" OR "hydroxybenzoic") AND ("Marsala" OR "Porto" OR "Vin de Paille" OR "sweet wine" OR "withered wine" OR "raisin wine")	810	660	131

Table 4 – Extraction table of the main outcomes on the evolution of phenolic acids in winegrapes during the **On-vine** withering process.

Author, Year	Title/purpose	On-vine/Off-vine withering	Variety	Outcomes/main findings on phenolic acids of withered grapes
Avizcuri-Inac et al. (2018)	Chemical and sensory characterization of sweet wines obtained by different techniques	**On-vine** natural dehydration *vs* **off-vine**	Tempranillo, Grenache, Viura, Cagazal, Riesling Gewürztraminer, Verdil	**Sweet wines obtained using different techniques were classified in three clusters based on phenolic compounds**: the first one was characterized by the **highest contents of HBAs and HCAs**; the second cluster was by **intermediate amounts of phenolic compounds**; and the third, including four artificial icewines, was described by the **lowest amounts of phenolic compounds, particularly HBAs**.
Blanco-Ulate et al. (2015)	Developmental and metabolic plasticity of white-skinned grape berries in response to *Botrytis cinerea* during noble rot	**On-vine:** harvest of grapes with symptoms of noble rot caused by *Botrytis cinerea* strain BcDW1 and other strains present in the field in three different stages of infection	Sémillon	The **increased levels of HCAs derivatives** were probably due to the **activation of** the **shikimate and phenylpropanoid metabolic pathways** by noble rot infection, normally associated with the ripening of red-berry cultivars.
Figueiredo-González et al. (2013a)	Effects on color and phenolic composition of sugar concentration processes in dried-on-or dried-off-vine grapes and their aged or not natural sweet wines.	**On-vine natural withering** vs **Off-vine withering**	All varieties studied in reviewed articles	*Review on the effect of withering on the phenolic composition of grapes and wines*
Hong et al. (2012)	Influence of plant defense system and fungal growth in *Botrytis cinerea*- infected Chardonnay berries	**On-vine:** harvest of botrytized grapes	Chardonnay	Metabolomic investigation revealed a **decrease in the concentration of HCTAs** as ***Botrytis cinerea*** infection increased.
Ivanova et al. (2011)	Identification and changes of polyphenolic compounds in red and white grape varieties grown in R. Macedonia during ripening	**On-vine:** late harvest	Vranec, Smederevka, Merlot, Chardonnay	The **decrease in** the content of **total phenols** in the overripening and late-harvest phase **could be the result of a change in the HCA ester concentration in skins,** due to **oxidation/polymerization reactions** for white and red varieties and the **participation in acetylated anthocyanin synthesis** in red varieties**.**
Kallitsounakis and Catarino (2020)	An overview on botrytized wines	**On-vine:** botrytized wine	All varieties investigated in the reviewed studies	*Review on the different stages of botrytized wine production. The authors provided a section on **HCAs** and their **esters**.*
Kilmartin et al. (2007)	Polyphenol content and browning of Canadian icewines	**On-vine: icewine** production process *vs* **cryogenic extraction method** ("REAL" vs "FAUX" Icewines)	Riesling and Vidal	**Differences** in the amounts of **HCAs were observed** between "REAL" and "FAUX" icewines in 1999-2000 vintages. **The overall concentration of HCAs in "FAUX" icewines was up to 11-times and 21-times higher than that of the "REAL"** Riesling and Vidal icewines, respectively**.** In the 2002 vintage, instead, the authors found relatively high concentrations of **HCAs** both in "REAL" and "FAUX" icewines, probably owing to the matching of the earliest harvest dates in that year.

Author, Year	Title/purpose	On-vine/Off-vine withering	Variety	Outcomes/main findings on phenolic acids of withered grapes
Loizzo et al. (2013)	Phenolics, aroma profile, and in vitro antioxidant activity of Italian dessert Passito wine from Saracena (Italy)	**On-vine:** overripe grapes (Malvasia and Guarnaccia**)** + **Off-vine:** in the typical *cannizza* under the sun, covered during the night (Moscato, not macerated grapes collected few weeks before harvest)	Malvasia, Guarnaccia, and Moscato	**HBAs were the most abundant class of marker phenolic compounds,** particularly **gallic acid,** which showed the highest content (**376.5 mg/L**).
Lukíc et al. (2016)	Changes in physicochemical and volatile aroma compound composition of Gewürztraminer wine as a result of late and ice harvest	**On-vine**: **late harvest** and **icewine** production process	Gewürztraminer	**Higher amounts of HCAs ethyl esters** were found **in late harvest and icewines than those in regular harvest** and of **4-vinylguaiacol in late harvest ones** (but not in icewines), suggesting a **concentration effect of HCAs** in the special wines compared to the control.
Mikulic-Petrovsek et al. (2017)	Effects of partial dehydration techniques on the metabolite composition in 'Refosk' grape berries and wine	**On-vine**: *double maturation raisonnée* (DMR) *vs* **off-vine:** berry partial dehydration in the chamber (PDC: 22–23 °C, 60% relative humidity, and ventilation)	Refosk	Only one HCA compound was detected in grape skins of Refosk (***p*-coumaric acid hexose, 0.72-1.48 mg/100 g dry weight**) and its content **decreased over the withering process**, particularly for PDC-treated berries. Seven HCA derivatives were detected in wines, **caftaric acid being the most abundant (11.43-20.68 mg/L)**. Wines obtained with **PDC-withered grapes showed the highest amounts of HCAs and derivatives compared to those of the DMR wines and the control (1.8 and 1.4-times higher, respectively)**.
Rusjan et al. (2017)	Double maturation raisonnée: the impact of on-vine dehydration on the berry and wine composition of Merlot	**On-vine:** *double maturation raisonnée* (DMR), cutting 1-year old canes with fruitful shoots during berry ripening	Merlot	**A reduction in the contents of HCA and derivatives in DMR grapes** was observed **compared to that of the control**; instead, **a high presence of these compounds** was found **in DMR wines**, in some cases significantly higher than that in control wines.
Tang et al. (2013)	Evaluation of nonvolatile flavor compounds in Vidal icewines from China	**On-vine:** icewine production process	Vidal	**HBAs were the major phenolic acids in icewines**, representing more than 74% of the total amount of the class: **protocatechuic acid (7.43-9.48 mg/L)** showed the highest content and **syringic acid (0.20-0.36 mg/L)** the lowest. As regards **HCAs**, the main compounds were **ferulic (1.07-2.14 mg/L)** and ***p*-coumaric (0.20-1.39 mg/L) acids**. **No significant differences** were found **in phenolic acid concentrations between wines characterized by different pressing levels.**
Tian et al. (2009a)	Comparative study of 11 phenolic acids and five flavan-3-ols in cv. Vidal: impact of natural icewine making versus concentration technology	**On vine:** naturally frozen juice *vs* artificially produced (refrigerator-frozen and concentrated-juice)	Vidal	**The presence and concentration of phenolic acids could differentiate between icewine production methods**. At the end of experimental fermentations, the phenolic acid content **increased by 20% in the wine produced from refrigerator-frozen juice** and **increased by 2.5-2.7 times in the wine from concentrated juice** compared to that of the wine made from naturally frozen juice.
Tian et al. (2009b)	Comparison of phenolic acids and flavan-3-ols during wine fermentation of grapes with different harvest times	**On-vine:** dry wine, semi-sweet wine, icewine with low alcohol levels	Vidal	For the production of icewines, **increased contents of HBAs and HCAs** were observed when grape **harvest time was delayed**.

Table 5 –Extraction table of the main outcomes on the evolution of phenolic acids in winegrapes during the **Off-vine controlled** withering process.

Author, Year	Title/purpose	On-vine/Off-vine withering	Variety	Outcomes/main findings on phenolic acids of withered grapes
Bellincontro et al. (2009)	Study of postharvest water stress of winegrape using non-destructive techniques	**Off-vine:** in perforated plastic trays inside a ventilated small tunnel at different controlled conditions (10 °C with 1.5 m/s airflow; 10 °C with 2.5 m/s airflow; 20 °C with 1.5 m/s airflow. Relative humidity: 45%)	Cesanese	Among the HCAs detected, **caftaric acid was very sensitive to atmosphere variation**. Its content was **368.95**, **513.40,** and **393.28 mg/kg** for grapes withered at 10 °C-1.5 m/s airflow, 10 °C-2.5 m/s airflow, and 20 °C-1.5 m/s airflow, respectively, and in all the cases it was significantly lower than that of the control (644.99 mg/kg).
Bonghi et al. (2012)	Phenol compound metabolism and gene expression in the skin of winegrape berries subjected to partial postharvest dehydration	**Off-vine:** in controlled conditions, slow and rapid rates of up to 10% and 30% weight loss	Raboso Piave	**A slight increase in caffeic acid contents** was observed **in rapidly dehydrated samples at 10% weight loss** and **in *p*-coumaric acid content under slow dehydration at 30% weight loss**. **Reduced content** of **gallic acid** was observed in **rapidly dehydrated samples**. The results obtained on gene expression patterns suggested a complex expression regulation of the **PAL multigene family.**
Budić-Leto et al. (2017)	Differentiation between Croatian dessert wine Prosek and dry wines based on phenolic composition	**Off-vine** with a system for temperature control and ventilation (maximum daily temperature of 40 °C)	Prosek, Plavac, and Posip	Prošek **dessert wines resulted in significantly lower concentrations of HCAs than those of dry wines**.
Frangipane et al. (2007)	Study of phenolic compounds in Aleatico grapes dried in a forced air tunnel	**Off-vine:** in a forced air tunnel with different temperatures (from 15 to 30 °C) throughout 30 days of withering	Aleatico	In the **skin**, ***trans*-caftaric acid** content **increased** at temperatures **between 17 and 23 °C**, but it **declined** when the temperature increased **to 30 °C, evidencing no substantial differences compared to the initial value. In the juice**, ***trans*-caftaric acid content** remained almost constant until midway through the process, after which **its concentration tripled**. Contents of **syringic** and **gallic acids in grape juice**, instead, **decreased during the withering process**.
Frangipane et al. (2012)	Effect of drying process in chamber at controlled temperature on the grape phenolic compounds	**Off-vine**, in a chamber in controlled conditions (18 –21 °C, 68% relative humidity, 1 m/s airspeed) for 16 days	Roscetto	**A slight decrease** in the content of **HCTAs** (expressed as **mg/1000 berries**) was observed in the juice, probably because of **oxidation reactions that occurred during the withering process**. **HBA content showed the largest decrease**.
Marquez et al. (2012)	Colour and phenolic compounds in sweet red wines from Merlot and Tempranillo grapes chamber-dried under controlled conditions	**Off-vine:** in chamber drying under controlled conditions at a constant temperature of 40 °C and initial relative humidity of 30%	Tempranillo and Merlot	**A great increase in HBA and HCTA amounts** was detected **in withered Merlot and Tempranillo grapes.** The concentration of **HBAs increased during the first 24-48 h of maceration, and then no significant differences or slight decrease** were found **in Merlot and Tempranillo, respectively**; moreover, contents of **HCTA esters increased over the first 24 h of maceration and then decreased**.

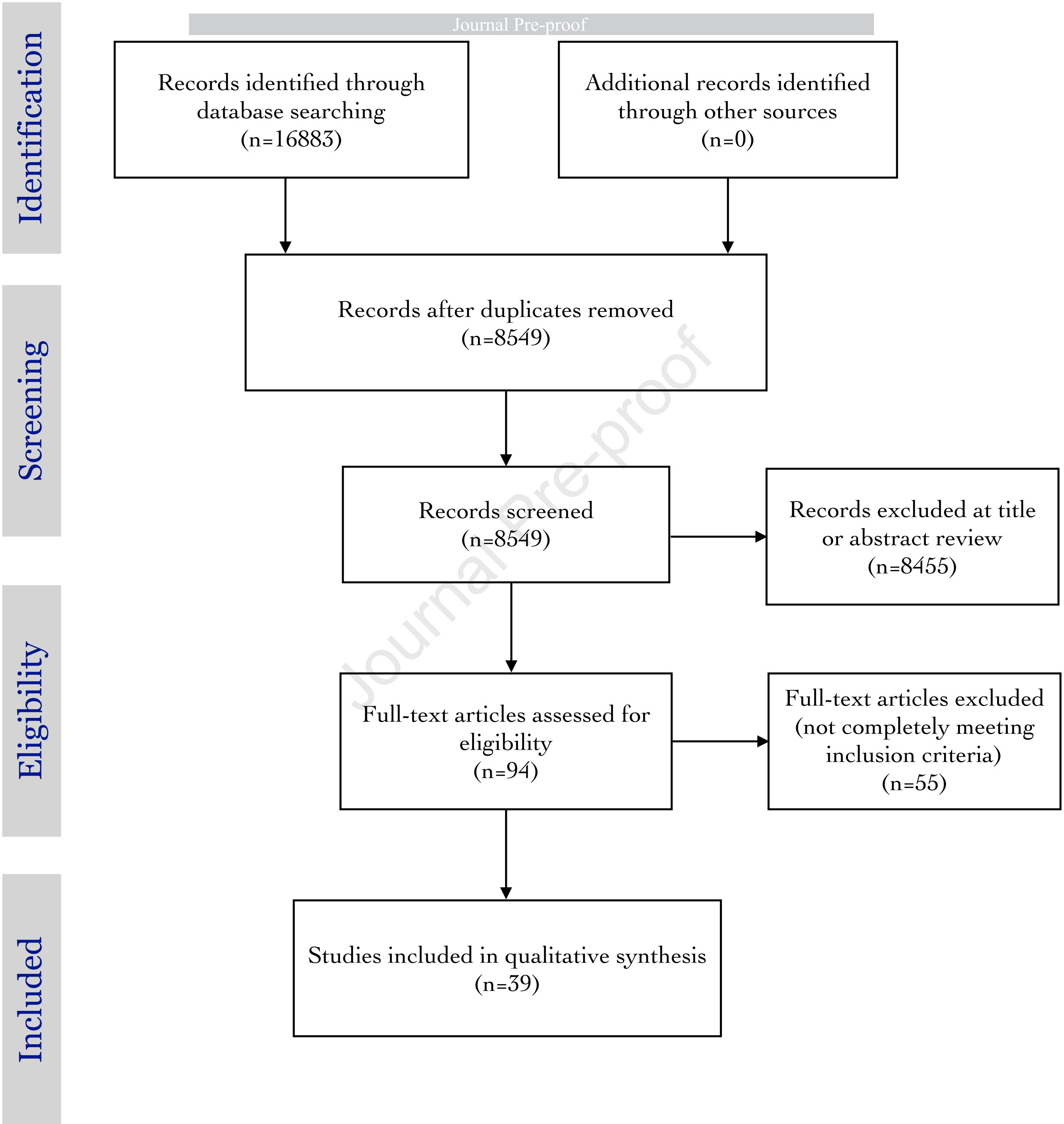
Author, Year	Title/purpose	On-vine/Off-vine withering	Variety	Outcomes/main findings on phenolic acids of withered grapes
Marquez et al. (2014)	Antioxidant activity and phenolic profile changes during the winemaking of Cabernet sauvignon sweet wines	**Off-vine**: in controlled condition at a constant temperature of 40 °C and an initial relative humidity of 20%.	Cabernet sauvignon	**The overall amounts of phenolic acids increased** during off-vine withering and subsequent experimental winemaking**, namely, for HBAs.** The observed increase peaked at **48 h of skin maceration.** Additionally, **contents of HCAs also increased** for all the compounds detected **except for *cis*-fertaric acid, which showed the opposite trend.** Moreover, the evolution of the total amount of phenolic acids was correlated to the **antioxidant activity**.
Mencarelli et al. (2010)	Chemical and biochemical change of healthy phenolic fractions in winegrape by means of postharvest dehydration	**Off-vine**: in different controlled conditions (10, 20, or 30 °C and 30% relative humidity)	Aleatico	**The highest increase in the overall content of phenolic acids (caftaric and coutaric acids) in withered winegrapes was observed at 20 °C and 20% weight loss**, while at 10 °C, the increase was lower, and at 30 °C, it decreased for grapes at 20% and 30% weight loss. **An upregulation in the expression of the PAL gene was detected** in the berries exposed to temperatures of 10 and 20 °C at 10% weight loss. Nevertheless, **transcriptomic abundance did not correlate well with metabolomic abundance**.
Negri et al. (2017)	The induction of noble rot (*Botrytis cinerea*) infection during postharvest withering changes the metabolome of Garganega grapevine berries	**Off-vine:** in perforated plastic boxes in a ventilated withering facility under natural conditions (**17-20 °C, 79% relative humidity**) **until the grapes reached about 30% weight loss**; then half number of plastic boxes were covered **to increase relative humidity (88-94%) to induce noble rot development**, whereas the remaining boxes were maintained at **68-75% relative humidity** for 32 days. The length of the process was 61 days.	Garganega	The authors observed **a decrease in HCTA** concentrations (coutaric, caftaric, and fertaric acids) in ***Botrytis*-induced grapes**, probably owing to **the degradation reactions by fungal metabolism**.
Nicoletti et al. (2013)	Postharvest dehydration of Nebbiolo grapes grown at altitude for *Sfursat* wine production is affected by time of defoliation	**Off-vine:** in controlled-environment rooms (10, 20, or 30 °C; 60% relative humidity; 1 m/s air flow)	Nebbiolo	**During withering, all samples lost phenolic acids** (caftaric and coutaric acids) **except for grapes harvested from not-defoliated vines and withered at 10 °C**, in which the amounts of phenolic acids increased.
Panceri et al. (2013)	Effect of dehydration process on mineral content, phenolic compounds, and antioxidant activity of Cabernet sauvignon and Merlot grapes	**Off-vine:** under controlled conditions of 7 °C, 35% relative humidity, and volumetric airflow of 12 m^3/s (dehydration until 30% and 40% weight loss)	Cabernet sauvignon and Merlot	Among **HBAs** detected, **gallic acid was the predominant** compound in grapes and wines. While **contents of HBAs increased in Cabernet sauvignon**, **a decrease was observed in Merlot grapes**, suggesting an effect induced by genotype. **Increased contents of caffeic acid** in free form were reported **after 40% dehydration for both varieties.**
Panceri et al. (2015)	Effect of grape dehydration under controlled conditions on chemical composition and sensory characteristics of Cabernet sauvignon and Merlot wines	**Off-vine:** under controlled conditions with a constant temperature of 7 °C, 35% relative humidity, and volumetric airflow of 12 m^3/s (dehydration until 30% and 40% weight loss)	Cabernet sauvignon and Merlot	**Total content of HCAs was generally higher only for Merlot wines made from grapes at 30% weight loss** than that of the control wine. **Higher contents of HBAs** were found **in the wines produced from Cabernet sauvignon and Merlot grapes at 30% and 40% weight loss**.

Author, Year	Title/purpose	On-vine/Off-vine withering	Variety	Outcomes/main findings on phenolic acids of withered grapes
Panceri and Bordignon-Luiz (2017)	Impact of grape dehydration process on the phenolic composition of wines during bottle ageing	**Off-vine:** under controlled conditions with a constant temperature of 7 °C, 35% relative humidity, and airflow of 12 m^3/s (dehydration until 30% and 40% weight loss)	Cabernet sauvignon and Merlot	The wines produced from dehydrated grapes evidenced **higher amounts of gallic, protocatechuic, vanillic, and caffeic acids** than that of the control. An increase in the concentration of phenolic acids (gallic, protocatechuic, and *p*-coumaric acids) was observed during 22 months of bottle ageing in all Cabernet sauvignon and Merlot wines made from withered grapes.
Piano et al. (2013)	Focusing on bioactive compounds in Uvalino grapes	**Off-vine:** in a room at a constant temperature of 24 °C and 30% humidity *vs* **On-vine:** not-harvested overripe grapes (control)	Uvalino	**HCTA contents** (caftaric, coutaric, fertaric acids) slightly **increased after 7 days of withering/overripening**, and this increase was maintained up to the 21st day (final point).
Serratosa et al. (2008b)	Drying of Pedro Ximenez grapes in chamber at controlled temperature and with dipping pretreatments	**Off**-vine: at a controlled temperature of 40 and 50 °C *vs.* traditional sun-drying	Pedro Ximenez	An **increase** in the concentration of **gallic acid in the juice from withered grapes** was observed **during the withering process**, **from 2.33 to 7.24 mg/L** at a temperature of 40 °C and **10.2 mg/L** at 50 °C. Similarly, also **HCA concentrations increased by 50% or doubled** after withering at 40 or 50 °C, respectively.
Toffali et al. (2011)	Novel aspects of grape berry ripening and post-harvest withering revealed by untargeted LC-ESI-MS metabolomics analysis	**Off-vine:** in controlled conditions (13-17 °C and about 65% relative humidity)	Corvina	**Anthocyanins acylated with *p*-coumaric acid** started to accumulate after veraison but continued to **increase** thereafter, **during the withering process.** Consequently, **the ratio of non-acylated anthocyanins to coumaroyl anthocyanins fell from 6.4 in ripening and ripe berries to 3.7 in withering and withered berries**.
Torchio et al. (2016)	Influence of different withering conditions on phenolic composition of Avanà, Chatus and Nebbiolo grapes for the production of 'Reinforced' wines	**Off-vine:** different controlled conditions such as slow withering (18 °C, 40% relative humidity, and 0.9 m/s airflow) and fast withering (28 °C, 40% relative humidity and 0.9 m/s airflow)	Avanà, Chatus, Nebbiolo	**The concentration effect due to withering prevailed over the degradation reactions for grape pulp HCTAs** in two varieties out of the three tested, **particularly for Chatus**. These amounts were not influenced by the withering rate.
Zenoni et al. (2016)	Disclosing the molecular basis of the postharvest life of berry in different grapevine genotypes	**Off-vine**: in controlled conditions with gradually decreasing temperature (from 16 ° to 7 °C) and gradually increasing relative humidity (from 55% to 80%)	Corvina, Sangiovese, Merlot, Oseleta, Syrah, and Cabernet sauvignon	The positive or negative **final balance of HCAs/HBAs depended on genotype,** and it was negative in Corvina.

Table 6 –Extraction table of the main outcomes on the evolution of phenolic acids in winegrapes during the **Off-vine natural** withering process.

Author, Year	Title/purpose	On-vine/Off-vine withering	Variety	Outcomes/main findings on phenolic acids of withered grapes
Constantinou et al. (2017)	Metabolic fingerprinting of must obtained from sun-dried grapes of two indigenous Cypriot cultivars destined for the production of 'Commandaria': a protected designation of origin product	**Off-vine:** sun-drying process, during which the grapes were manually turned over periodically. The sun-drying process lasted 10-12 days.	Xynisteri and Mavro	Among phenolic compounds, **HBAs represented the most predominant group in Xynisteri** grapes (62.1% of total phenolics) **and were an important group in Mavro** (42.3%). **Total amounts of HBAs increased in musts of both varieties during sun-drying**. As regards **HCAs and derivatives,** they were the second major group of phenolic compounds, contributing to 25.7% and 39.8% for Xynisteri and Mavro, respectively. During withering, **a six-times increase in their content was observed**, even if the concentration of some **singular compounds** such as caffeic acid dihexoside and fertaric acid isomer **decreased**.
Constantinou et al. (2018)	The impact of postharvest dehydration methods on qualitative attributes and chemical composition of 'Xynisteri' grape must	**Off-vine:** traditional sun-drying method *vs.* alternative dehydration methods (multiple horizontal wires, multiple vertical pallets, low greenhouse, hot-air dryer treatment)	Xynisteri	**Total HBA contents** in musts from grapes withered with multiple horizontal wires, low greenhouse, and hot-air treatments **increased by 1.8-, 2.3- and 2.7-times that of fresh grapes**, respectively. **Traditional sun-drying revealed the lowest effect on HCAs (1.5-times)**, while other **withering methods showed a strong increase (from 1.7 to 6.0 times), which was higher than that of the concentration effect.**
Figueiredo-González et al. (2013b)	Evolution of colour and phenolic compounds during Garnacha Tintorera grape raisining	**Off-vine:** in a room with natural ventilation over 83 days, grapes were placed in a single layer in plastic boxes, turned over, and checked weekly	Garnacha tintorera	The overall concentration of **HCA esters** decreased from **32 to 14 mg/kg of berry during 83 days of withering,** and this decrease began after the 16th day. A **decreasing trend** in HCA esters was observed during withering **for the two isomers**: ***cis*-caftaric** (from 0.38 to 0.07 mg/kg of berry), ***trans*-caftaric** (from 19 to 9.7 mg/kg of berry), ***cis*-coutaric** (from 4.0 to 1.1 mg/kg of berry) and ***trans*-coutaric** (from 9.0 to 3.2 mg/kg of berry).
Figueiredo-González et al. (2014a)	Garnacha-Tintorera based sweet wines: detailed phenolic composition by HPLC/DAD - ESI/MS analysis	**Off-vine**: for naturally sweet wine, in plastic boxes at natural conditions of temperature and humidity	Garnacha tintorera	**The concentration of HBAs was lower in the two sweet wines than that of the dry wine (control), particularly for the fortified one**, mainly driven by the steep decrease in gallic acid content**. HCTAs** and free **HCAs** were present at high concentrations (45 mg/L) in dry base wine, but their presence **decreased** probably **owing to enzymatic browning reactions**.
Figueiredo-González et al. (2014b)	The phenolic chemistry and spectrochemistry of red sweet winemaking and oak-aging	**Off-vine**: in plastic boxes at natural conditions of temperature and humidity *vs.* fortified sweet wine	Garnacha tintorera	An **increase in phenolic acid amounts** was observed **for** both **natural** and **fortified sweet wines during** the **oak-ageing** period of 6 and 12 months. **The concentration of HBAs increased**, starting from 32 and 40 mg/L at the beginning in natural and fortified sweet wines, respectively, and averaging about **50 mg/L in both sweet wines at the end of the ageing**, probably because of the **transfer from the oak wood**. Moreover, **a decreasing trend** was found **in the contents of HCA esters** (caftaric and coutaric acids). The **simultaneous increase of HCA free forms** suggested a **slow hydrolysis** process, but this increase was not proportional to the decrease of the contents of esters.

Author, Year	Title/purpose	On-vine/Off-vine withering	Variety	Outcomes/main findings on phenolic acids of withered grapes
Nievierowski et al. (2021)	Role of partial dehydration in a naturally ventilated room on the mycobiota, ochratoxins, volatile and phenolic composition of Merlot grapes	**Off-vine:** in a naturally ventilated room for 21 days	Merlot	The main differences were observed for **four HBAs** (ethyl gallate, *p*-hydroxybenzoic acid, gallic acid-hexose, and gallic acid) and **two HCAs** (caffeic and caftaric acids). **The amounts of these compounds increased more than two times during withering compared to that of fresh grapes.**
Serratosa et al. (2008a)	Changes in color and phenolic compounds during the raisining of grape cv. Pedro Ximenez (for the production of sweet wines)	**Off-vine**: sun-drying grape raisining on mats in slight hills facing south (40-50 °C) for 7 days	Pedro Ximenez	**The withering process enhanced the concentration of HBAs in grape must**. Particularly, ***p*-hydroxybenzoic acid amount strongly increased by 188%**, suggesting an additional increase by means other than concentration. Meanwhile **the content of gallic acid increased by 33%**, suggesting that this compound can participate in other reactions during the withering process. As regards **HCTAs**, **the amounts of caftaric, coutaric, and fertaric acids increased more for *cis*- isomers than for *trans*-isomers.** These increases were lower than those expected, indicating a **simultaneous degradation of these compounds during withering** that contribute to the typical browning of the sun-dried grapes.


Identification
Screening
Eligibility
Included
Records identified through database searching (n=16883)
Additional records identified through other sources (n=0)
Records after duplicates removed (n=8549)
Records screened (n=8549)
Records excluded at title or abstract review (n=8455)
Full-text articles assessed for eligibility (n=94)
Full-text articles excluded (not completely meeting inclusion criteria) (n=55)
Studies included in qualitative synthesis (n=39)

Highlights

- Phenolic acids are represented by hydroxybenzoic and hydroxycinnamic compounds
- Their evolution during withering involves a complex balance of different processes
- Concentration effect usually prevails in withered grapes increasing their contents
- Withering conditions and genetic regulation are relevant in determining the content
- Phenolic acids have been proposed as authenticity markers for icewines