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Reviving ancient winemaking: Effects of ceramic vessels and organic coatings in wine production

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A R T I C L E I N F O

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A B S T R A C T

The revival of ancient winemaking techniques using ceramic vessels and organic coatings such as pitch, resin, and beeswax has gained renewed interest among producers seeking distinctive sensory profiles, sustainability, and cultural heritage preservation. This review synthesizes multidisciplinary evidence on the role of ceramic containers and coatings in wine production, integrating archaeological insights with contemporary practices. Ceramic vessels enable micro-oxygenation and thermal stability, influencing phenolic polymerization and wine complexity without introducing exogenous compounds. Organic coatings historically served to waterproof vessels and impart antimicrobial and aromatic properties, with modern applications observed in traditional wines such as Georgian q*vevri*, Portuguese *talha*, Greek *retsina*, and Canary Islands *tea* wines. These techniques have been associated with enhanced poly(phenol) content, unique volatile profiles, and reduced reliance on chemical preservatives. Despite promising findings, research remains fragmented, with gaps in sensory characterization, mineral migration, and coating performance. Addressing these gaps through integrated chemical, microbiological, and sensory studies could transform these heritage practices into scientifically validated strategies for producing high-quality, low-intervention wines.

1. Introduction

Shifts in global priorities, such as health and sustainability, have led to new patterns in food and drink consumption. There has been a growing interest among winemakers and wine consumers in connecting with a bygone era and embracing a lifestyle reminiscent of the past (Buican et al., 2023). Traditional winemaking methods were based on the use of ceramic vessels for fermentation, a practice that dates back to the Neolithic period, around 6000-5000 BC (McGovern, 2013). In contemporary oenology, the term amphorae refers to clay or earthenware vessels used for fermentation, ageing, or storage, a usage that differs from its original archaeological meaning as transport containers not intended for winemaking (Fig. 1a). Throughout this review, the term is employed in its modern oenological sense to denote ceramic vessels used as an alternative to stainless steel or oak.

Recently, several wine producers have been experimenting with fermentation or ageing in amphorae in regions of Austria, Croatia, France, Georgia Italy, Portugal, Slovenia or USA (Picuno, 2016). The use of different types of containers is a technique for winemakers to modulate some of the final characteristics of the wine (Gil i Cortiella et al., 2021). It has been demonstrated that the container affects wine quality, since changes in wine phenolic content, acidity, volatile compounds, mineral composition and yeast activity were observed (Gil i Cortiella et al., 2021; Malfeito-Ferreira et al., 2024).

Besides the influence of the container on winemaking, another aspect that must be considered is the application of different types of coating to the vessels such as resin or pitch. This allows the vessels to be waterproofed, thereby improving preservation of the wine and its specific flavours. The coating also had an effect on wine chemical composition, especially in flavour and preservation properties (Liang et al., 2021; Proestos et al., 2005).

Although previous studies have examined physicochemical and

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sensory attributes (Cabrita et al., 2018; Martins et al., 2018), microbial ecology (Capece et al., 2013), and the effects of resin addition (Liang et al., 2021; Proestos et al., 2005), understanding winemaking practices grounded in ancient traditions remains difficult due to fragmented and heterogeneous data. Existing reviews address vessel influence or the revival of ancient techniques in broad terms, but none provide a focused synthesis of traditional regional wines produced in ceramic vessels with organic coatings. This review fills that gap by integrating archaeological, chemical, microbiological and sensory evidence to clarify how ceramic vessels and organic coatings shape wine composition and quality. In doing so, it links ancient winemaking practices with their documented oenological effects and their relevance for contemporary low-intervention production. By outlining current knowledge alongside remaining research needs, the review offers a concise synthesis of recent advances in this emerging area of wine science.

2. Methods

A narrative literature search was conducted (Scopus, Web of Science, PubMed, Google Scholar) using combinations of "amphora wine", "qvevri", "amphorae", "talha", "retsina", "ceramic vessel", "clay jar", "pitch coating", "beeswax coating", "pine resin", "oxygen transmission rate", "volatile compounds", "polyphenols", "microbiology", "minerals", "sensory". Inclusion: peer-reviewed articles and authoritative books/standards on ceramic vessels or coatings in wine (2000–2025), plus seminal archaeological/analytical references. Exclusion: studies solely on oak/stainless steel without ceramic/coating relevance; purely commercial texts without data. Outcomes were catalogued (chemistry, microbiology, oxygen, minerals, sensory). Due to the high heterogeneity of study designs and outcomes, a statistical summary method was not applicable. A total of 267 records were screened; after removing duplicates and studies not meeting the inclusion criteria, 50 publications were included in the final synthesis.

3. Ceramic vessels in winemaking: historical background and oenological effects

Ceramic vessels have been used for fermenting, ageing and/or transporting wine since the Neolithic period. These containers varied in size, and shape and were found in different sites (Fig. 1a). Depending on the period and culture studied, as well as the geographical area, the ceramic vessels used to produce wine have been referred to by different names, such as Roman *dolia* or Greek *pithoi* (McGovern, 2013) (Fig. 1a). Regardless of the name, ceramic vessels obtained modelling a mixture of clay and degreasant have been the most widely used materials for winemaking over several millennia. Today, this tradition is preserved in examples as the Georgian *qvevri,* the Spanish *tinajas* and the Portuguese *talhas* (Capece et al., 2013; Martins et al., 2018) (Fig. 1b).

From an oenological perspective, ceramic vessels are inherently porous, enabling micro-oxygenation during maturation. This slow oxygen ingress promotes polymerization of anthocyanins and tannins, stabilizing colour and softening astringency (Rossetti & Boselli, 2017; Nevares & Del Alamo-Sanza, 2021). Unlike oak barrels, ceramic does not donate exogenous phenolics or lactones, preserving varietal purity while allowing oxidative reactions that enhance complexity (Rossetti & Boselli, 2017). Also, this controlled oxygen ingress influences yeast metabolism during alcoholic fermentation, which can stimulate the formation of higher alcohols and esters under low-oxygen conditions, thereby contributing to aroma development (Martins et al., 2018).

Oxygen permeability and thermal properties are key factors influencing wine evolution. Earthenware clay vessels fired at low temperatures are highly porous and require coatings (Nevares & Del Alamo-Sanza, 2021). Reported oxygen transmission rates for amphorae (with different earthenware materials and with and without organic coatings) range from 5.38 to 12.57 cm^3/m^2/day, comparable to oak barrels (Nevares & Del Alamo-Sanza, 2018). Thermal inertia is another advantage: ceramic exhibits moderate thermal conductivity (~1.2 W/m·K), buffering temperature fluctuations better than stainless steel but less than concrete (White & Catarino, 2023). This stability supports gradual maturation and clarification.

Compared with stainless steel, ceramic vessels provide controlled micro-oxygenation and greater thermal inertia, while—unlike oak—they do not release exogenous phenolics, allowing oxidative development without wood-derived flavours (Rossetti & Boselli, 2017; Nevares & Del Alamo-Sanza, 2021). Their performance is further shaped by surface treatments. Historically, organic coatings were applied to waterproof vessels, reduce porosity and influence wine chemistry (Colombini, 2009; Boulay, 2012). Understanding how oxygen ingress, coating composition and vessel morphology interact is therefore essential for evaluating the role of ceramics in modern low-intervention winemaking.

4. Organic coatings applied to ceramic vessels

Before glazing was introduced in the Middle Ages, different types of coatings were used to waterproof ceramic vessels. This tradition was

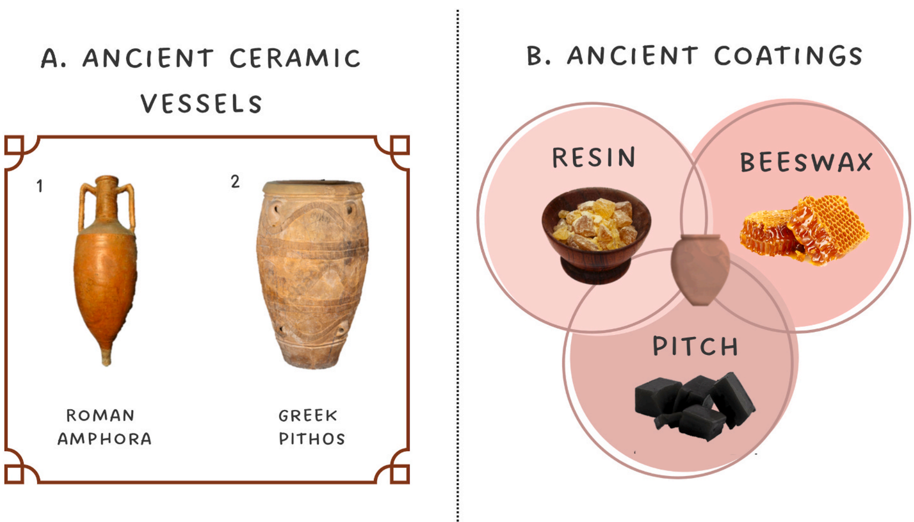

Fig. 1. A) Examples of different types of representative ceramic vessels used in ancient winemaking such as a Roman amphora (1), or Greek pithos (2) (pithos extracted from: heraklionmuseum.gr and amphorae from: britishmuseum.org). B) Most common ancient inner coatings for ceramic vessels in winemaking.

maintained for wine production even after then. In the Western Mediterranean the most common organic coatings were resin or pitch from Pinaceae (Garnier & Pecci, 2021) (Fig. 1b). In other parts of the Mediterranean, such as Greece, beeswax was also used, alone or in combination with resin or pitch to improve their properties (Regert et al., 2003) (Fig. 1b).

4.1. Pitch coating

Pinaceae pitch was the most common product used in the Western Mediterranean, both to coat *dolia* and amphorae (Garnier & Pecci, 2021). It was produced either by heating fresh resin or by distilling pine wood (Colombini, 2009). Chemically, pine pitch is characterised by abietic acid derivatives, and its processing conditions strongly influence the proportion of oxidised diterpenic acids, with higher temperatures and longer heating times increasing their formation (Colombini, 2009). Pitch also exhibits antimicrobial activity that contributes to wine preservation (Izzo et al., 2013). In addition, pitch-derived diterpenes impart resinous and balsamic notes and may interact with wine volatiles during maturation, thereby influencing aromatic development (Colombini et al., 2009; Izzo et al., 2013). Reflecting this long-standing tradition, *talha* wines in Portugal continue to be produced in ceramic vessels internally coated with pine pitch (Cabrita et al., 2018). Overall, pitch provides waterproofing, reduces vessel porosity, and introduces antimicrobial and aroma-active compounds relevant to wine stability and sensory expression.

4.2. Resin coating

The practice of coating wine vessels with resin dates back to antiquity, when pine resin, pitch, or mixtures of both were applied to waterproof clay containers used for storing and transporting wine (McGovern, 2013; Stern et al., 2008). Beyond waterproofing, resin served as a preservative agent, as ancient Greek and Mediterranean cultures recognised its ability to inhibit spoilage through its antimicrobial properties. Resins from species such as pine, larix, and cedar were employed to suppress the activity of undesirable yeasts and bacteria (McGovern, 2013). This effect is attributed partly to terpenes such as α-pinene, which has demonstrated antimicrobial activity and has even been proposed as a potential alternative to sulphur dioxide for controlling bacterial growth and preventing colour degradation (Hou et al., 2020). By limiting oxidation after fermentation, resin coatings helped reduce the risk of acetification (Boulay, 2012). The historical use of resin to preserve and flavour wine underlies the origin of Greek *retsina*. Resin-derived terpenoids not only contribute antimicrobial protection but also act as aroma-active compounds or precursors, shaping the characteristic sensory profile of these wines (Hou et al., 2020; Proestos et al., 2005). Thus, resin coatings function simultaneously as protective barriers, adding antimicrobiological and flavouring substances, affecting wine stability and aromatic composition.

4.3. Beeswax coating

Beeswax was another product used in the waterproofing of ancient vessels devoted to the production and transport of wine, possibly due to its hydrophobic nature. Chemically, beeswax is a complex mixture of saturated and unsaturated n-alkanes, long-chain wax esters, fatty acids, diesters, hydroxyesters and minor components including (poly)phenolic compounds (Evershed et al., 2008). Its composition varies according to bee species and their diet, as wax production is influenced by genetic and nutritional factors (Buchwald et al., 2006). Volatile compounds such as octanal and nonanal, typically associated with fatty and green odours, are among its major aromatic compounds, and can contribute to fresh and citrus notes to the wine (Jackson, 2014; Starowicz et al., 2021). The hydrophobicity of beeswax may also affect the partitioning and release of volatile compounds during fermentation and ageing, subtly modulating aromatic expression (Starowicz et al., 2021). In addition to these sensory effects, beeswax exhibits antimicrobial activity that enhances wine stability (Fratini et al., 2016). These combined properties underpin its continued use as a lining material in traditional *qvevri* vessels.

4.4. Coatings combination

The mentioned coatings could be used individually or in combination. Nevares & Del Alamo-Sanza (2021) studied the differences among beeswax, resin and the combination of these two, in different proportions, on the oxygen permeability of ceramic vessels. It was concluded that, although vessels coated with the three products were all suitable for winemaking, the coating made of 85% of resin and 15% of beeswax showed the best values of oxygen transfer ratio for the maturation of wines.

Overall, coatings influence wine not only by reducing vessel permeability but also through antimicrobial and chemical mechanisms that affect fermentation dynamics and aroma formation (Fratini et al., 2016; Natskoulis et al., 2024). To clarify how ceramic vessels and organic coatings compare with conventional winemaking materials, a summary of their main advantages and disadvantages is provided in Table 1. The combined effects of vessel material and coating composition are best illustrated through the traditional wine styles in which these techniques remain central, providing real-world examples of how ancient practices shape modern wines.

5. Traditional wine styles produced with ceramic vessels or organic coatings

Thanks to designations of origin and heritage protection, several traditional wines have preserved ancient production practices. Among them, *talha*, *qvevri*, *retsina*, and *tea* wines remain the only surviving styles in which ceramic vessels or resin-based materials continue to play an essential role in vinification (Fig. 2) (García-Pérez et al., 2022; Cabrita et al., 2018; Liang et al., 2021). These four wines were selected because they provide complementary case studies for examining how ancient vessel types and organic coatings function under modern production conditions and allow comparison across distinct materials, coatings and fermentation approaches.

Talha and *qvevri* wines rely on pitch and beeswax-coated ceramic vessels, respectively, whereas retsina and tea wines incorporate resin through different container types. Although the latter are not made in ceramic vessels, they offer relevant comparative insights into the historical and functional role of resin and pine-derived materials in wine preservation and flavour development. Table 2 summarises the principal

Table 1
Advantages and disadvantages of ceramic vessels and organic coatings compared with conventional winemaking materials.

Aspect	Advantages	Disadvantages/Limitations
Ceramic Vessels	• Moderate micro-oxygenation similar to oak but without release of exogenous phenolics. • Good thermal inertia during fermentation/ageing. • Can enhance phenolic polymerization and complexity.	• Porosity varies depending on clay and firing. • More difficult to clean and maintain than stainless steel. • Possible mineral migration depending on vessel composition/coating integrity.
Organic Coatings (Pitch, Resin, Beeswax)	• Provide waterproofing to porous vessels. • Contain antimicrobial compounds that improve stability. • Impart distinctive aromatic notes when desired.	• Strong flavour contribution may not suit all wine styles. • Coatings can degrade and require reapplication. • Not ideal when a completely neutral ageing environment is preferred.

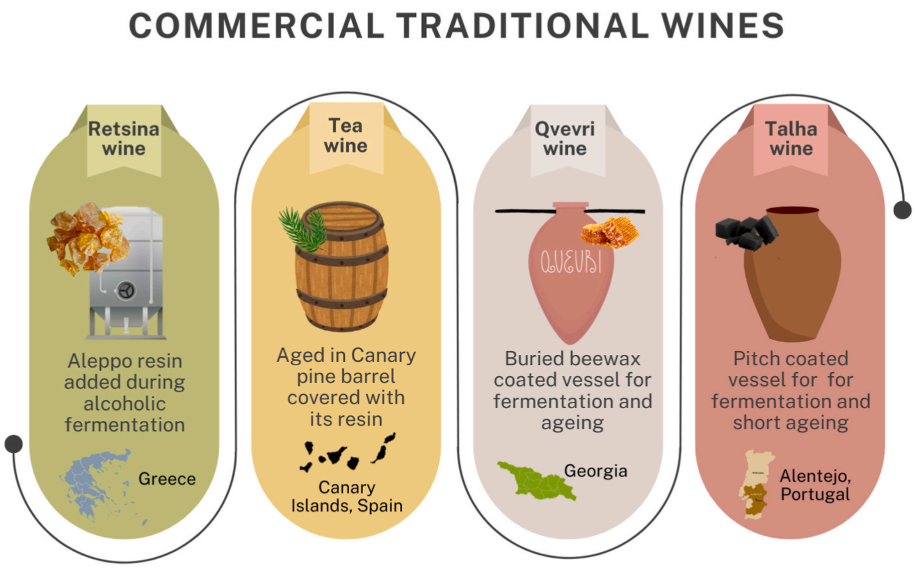

Fig. 2. Geographic origin and key characteristics of four traditional wine styles that remain commercially available today. The figure highlights the production regions and distinctive features of each wine, including vessel type, coating materials, and fermentation practices: *retsina* (Greece), *tea* wine (Canary Islands, Spain), *qvevri* wine (Georgia), and *talha* wine (Alentejo, Portugal).

techniques, vessel types, coatings and associated effects on wine chemistry, microbiology, sensory attributes and mineral composition.

5.1. Qvevri wines (Georgia)

Georgia is one of the birthplaces of winemaking, with its traditional vinification process considered the oldest in the world (McGovern, 2013; Van Limbergen & Komar, 2024). This traditional winemaking method is based on the use of large earthenware vessels called *qvevri*, where both fermentation and ageing take place. *Qvevri* are typically made of clay mixtures rich in minerals that contribute appealing aromas to the wine, particularly astringency, which creates a drying sensation in the mouth (Van Limbergen & Komar, 2024). These vessels are generally coated with beeswax, thus waterproofing them while reducing microbial contamination. During the winemaking process, *qvevri* are buried in the ground to provide natural temperature control (Díaz et al., 2013).

Another unique feature of this process is that both white and red wines are produced with extended skin contact, minimal added chemical agents, and is carried out through spontaneous fermentation (Van Limbergen & Komar, 2024). *Qvevri* wines are sometimes known as orange wines due to their colour. Unlike other orange wines where the colour is due to maceration only, in *qvevri* wines this is due to maceration and the micro-oxidation in the ceramic vessel (Vlasov, 2022).

Nowadays, *qvevri* wines are gaining significant interest worldwide (Vlasov, 2022). In the modern qvevri vinification process (Fig. 3), alcoholic fermentation (AF) occurs spontaneously along with skin maceration, during which the qvevri container remains open. During this stage, punch-downs are performed to keep the solids moist (Fig. 3). After fermentation, the qvevri is sealed with a stone or wooden lid and buried, allowing the wine to age for six to nine months (Fig. 3). Then the wine is racked and either bottled for consumption or transferred to clean *qvevri* for further ageing (Feiring, 2016).

The main scientific interest in relation to *qvevri* wines is the study of their (poly)phenol content (Buican et al., 2023; Garcia-Torres et al., 2021). This traditional method of winemaking has been shown to increase the total (poly)phenol content of *qvevri* white wines. Its content is closer to conventional red wines (1800 to 4000 mg/L) than white wines (170 to 300 mg/L). Likewise, the catechins concentration is significantly higher than other traditional wines (Rossetti & Boselli, 2017). However, this may be partly attributable to the maceration process with the skins, as a correlation has been found between the duration of this process and the phenolic profile of the orange wine (Garcia-Torres et al., 2021). On the other hand, lignans were found to increase in wine using the *qvevri* method compared to fermentation in stainless steel and wood (Dadáková et al., 2021). The lignans with the highest presence in *qvevri* wines were isolariciresinol and syringaresinol.

In terms of typical oenological parameters, the white *qvevri* wines had a higher pH, higher levels of acetic acid and lower levels of titratable acidity and tartaric acid (Diaz et al., 2013; Ieri et al., 2021). Some authors attributed the higher pH to grape maturity, longer maceration (Diaz et al., 2013) or malolactic fermentation (MF), even though this could be linked to other factors. High pH levels make wines more susceptible to oxidation and increase the risk of microbial contamination and spoilage (Jackson, 2014). However, a study analysing defects in Georgian wines found that *qvevri* wines had fewer microbial faults than those produced in other vessels (Vlasov, A. V., 2022)

Microbial ecology and vessel geometry are critical factors in fermentation dynamics. Under spontaneous conditions, *qvevri* vessels have been shown to promote both alcoholic fermentation (AF) and malolactic fermentation (MF) more effectively than stainless steel tanks (Takahashi et al., 2023). This advantage is partly linked to the vessel's pointed shape, which may concentrate microbial cells and enhance fermentation kinetics (Takahashi et al., 2023). These findings align with Malfeito-Ferreira et al. (2024), who also highlighted the influence of vessel geometry on spontaneous fermentation. Nevertheless, many studies still fail to report vessel shape, indicating that this aspect remains underexplored and warrants further systematic research.

Regarding mineral composition, published data showed discrepancies between commercial and experimental wines. Analyses of commercial *qvevri* wines reported mineral profiles largely comparable to conventional wines, with only slightly higher phosphorus levels, likely due to extended skin contact and leaching from grape solids (Díaz et al., 2013). In contrast, controlled laboratory vinification revealed significant differences: wines matured in *qvevri* contained approximately twice the concentrations of manganese (Mn) and iron (Fe) compared to those aged in stainless steel (Takahashi et al., 2023). These elements are involved in redox reactions that promote tannin polymerization (Jackson, 2014) and may contribute to flavour complexity in aged wines. Elemental studies on other amphorae-aged wines, such as Portuguese *talha*, generally reported stable mineral levels within regulatory limits, suggesting that mineral transfer depends on vessel type, coating integrity, and winemaking conditions (Cabrita et al., 2018). Overall,

Table 2
Overview of traditional winemaking techniques using ceramic vessels or resin-based practices, including vessel type, coating material, process highlights, and reported effects on wine composition and sensory profile.

Wine Style	Vessel Type	Organic coating	Winemaking process highlights	Chemical effects	Microbiological effects	Sensory Attributes	Mineral Composition
Qvevri (Georgia)	Ceramic, buried	Beeswax	• Spontaneous AF and MF • Extended skin contact • Buried for temperature control Feiring (2016); Díaz et al. (2013).	• ↑ (Poly)phenols • Higher pH • Lignans present Buican et al. (2023); Dadáková et al. (2021)	• AF and MF enhanced • Fewer microbial faults Takahashi et al. (2023); Vlasov (2022)	• Orange wine style; complex aromas (diethyl succinate, floral notes). Ieri et al. (2021).	• Mixed results: commercial ≈ conventional; lab ↑ Mn and Fe Díaz et al. (2013); Takahashi et al. (2023).
Talha (Portugal)	Ceramic, unburied	Pine pitch	• Spontaneous AF • Low/no SO_2 • Filtered post-fermentation Cabrita et al. (2018); Martins et al. (2018).	• Higher alcohols; volatile phenols Martins et al. (2018).	• Limited data	• Clove/curry notes • Resin nuance Martins et al. (2018).	• Stable • Pitch prevents mineral leaching Cabrita et al. (2018).
Retsina (Greece)	Stainless-steel	Pinaceae resin added to must	• Resin (~1% w/v) during AF • Racked off Proestos et al. (2005); Liang et al. (2021).	• ↑ α-pinene • ↓esters Natskoulis et al. (2024).	• Antimicrobial effect of resin Natskoulis et al. (2024).	• Pine/resin aroma • Bitter almond Buglass (2011); Nakas et al. (2024).	N/A
Tea Wine (La Palma)	Pine heartwood barrels	Pinaceae resin from wood	• Short maceration; ageing in resinous barrels Alonso González et al. (2022).	• ↑ α-terpineol • ↑linalool • ↓ geraniol Alonso González et al. (2022)	• Preservative terpenes Khaleel et al. (2018)	• Lilac, resinous • Less fruity/floral over ageing Alonso González et al. (2022)	N/A

Note: AF = Alcoholic Fermentation; MF = Malolactic Fermentation; OTR = Oxygen Transmission Rate; ↑ = Increase; ↓ = Decrease.

while some evidence points to increased Mn and Fe in clay-based vessels, other studies indicated minimal differences, highlighting the need for further comparative research across amphorae styles.

Finally, sensory characterization of wines produced in ceramic vessels remains limited. Most studies focus on identifying aroma-active compounds such as diethyl succinate and 2-phenylethanol, associated with fruity and floral notes, without conducting sensory analysis (Ieri et al., 2021; Takahashi et al., 2023). These findings suggested potential aromatic contributions rather than confirmed sensory perceptions. Recent research indicates that *qvevri* winemaking may enhance wine complexity and polish tannins (Takahashi et al., 2023), yet systematic sensory trials are still scarce. In summary, *qvevri* wines combine extended maceration with beeswax-lined ceramic vessels, promoting higher (poly)phenol levels, AF, MF, distinctive mineral profiles and sensory complexity.

5.2. *Talha wine (Portugal)*

Talha wines are typical of Alentejo (Portugal) and are still produced using ceramic vessels as in Roman times (Cabrita et al., 2018; Martins et al., 2018). In this vinification technique, destemmed and crushed grapes are fermented in opened large clay vessels with inner pitch coating and without the use of additives. Once fermentation is complete, the carbon dioxide produced by the yeast dissipates, allowing the solid particles to settle at the bottom. The wine is then filtered to eliminate these sediments, typically on November 11th, Saint Martin's Day (Martins et al., 2018). Then it can be either bottled or stored in the same vessels however, since little to no sulphur dioxide is added, its shelf-life is limited (Cabrita et al., 2018).

Talha wines resemble those produced using the traditional "Kakhetian" method in Georgia, with two key differences: in Georgia, the clay vessels are buried, and waterproofing is achieved using beeswax (Capece et al., 2013), while in Alentejo, the vessels are not buried and are internally lined with pine pitch (Cabrita et al., 2018; Martins et al., 2018). Additionally, while amphorae wines in Georgia can be aged, this is not a common practice for Alentejo's amphorae wines. *Talha* wines can be produced from red, white, or a blend of both grape types known as "palhete" wines (Cabrita et al., 2018; Martins et al., 2018).

To date, few studies have characterized these wines, focusing mainly on volatile compounds and mineral content (Cabrita et al., 2018; Martins et al., 2018). Among volatiles, isopentyl alcohol and phenethyl alcohol were found in the highest concentrations (Martins et al., 2018). These higher alcohols, formed by yeast metabolism during alcoholic fermentation, may be elevated due to oxygen transfer through the clay amphorae, which could stimulate yeast activity (Martins et al., 2018). Volatile phenols identified include 4-vinylguaiacol, contributing clove-like aromas, 2,4-di-tert-butylphenol, known for its antioxidant properties, and γ-butyrolactone (Martins et al., 2018). Although no formal sensory panels have evaluated *talha* wines, recent studies indicated consumer acceptance of clay-aged wines (Issa-Issa et al., 2021).

Regarding the study of the mineral content of *talha* wines, it was found that clay vessels do not influence the levels of minerals, as the waterproofing with pine pitch prevents the leaching of minerals into the wine (Cabrita et al., 2018). This implies a good stability of the wine, and the absence of toxicological risks associated with its consumption, in accordance with the OIV recommendation levels (OIV, 2019). Overall, *talha* wines illustrate how pitch-coated ceramic vessels create unique volatile patterns while maintaining mineral stability.

5.3. *Retsina wine (Greece)*

Retsina is a traditional Greek wine with a distinctive herbal and earthy flavour, attributed to the addition of Aleppo pine (*Pinus halepensis*) resin during fermentation (Estreicher, 2002; McGovern, 2013). With a history of more than three millennia, it is now produced mainly in Greece and southern Cyprus using varieties such as Savatiano,

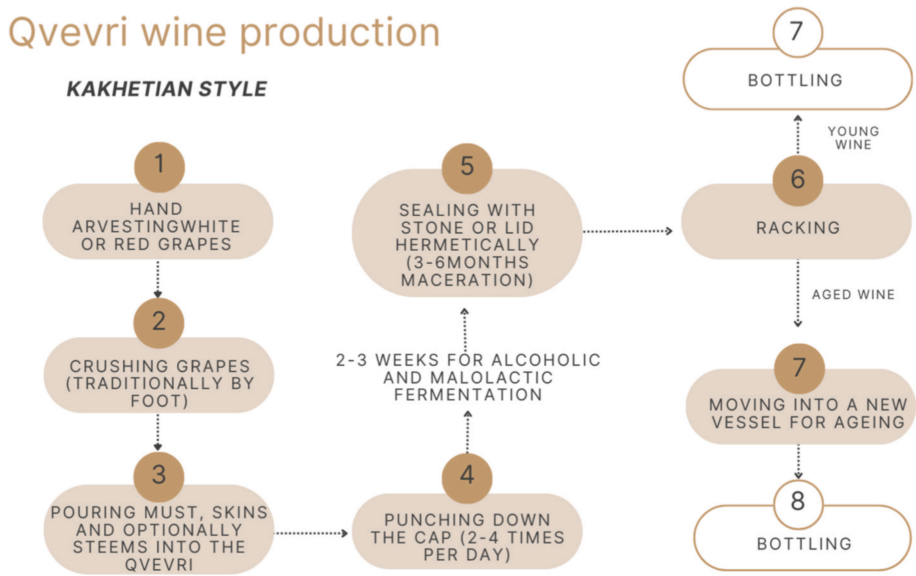

Fig. 3. Workflow of the current *qvevri* wine production process, following the *kakhetian* procedure.

Rhoditis, Athiri and Assyrtiko (Liang et al., 2021). Vinification follows a conventional white-wine process, except for the addition of up to ~1% (w/v) pine resin to the must, which is removed after alcoholic fermentation (Buglass, 2011; Proestos et al., 2005). The resulting wines typically reach 12.0–12.5% (v/v) alcohol and display the characteristic resinous profile associated with this historical practice. Recent analytical studies have examined how resin origin and tapping method influence wine quality (Nakas et al., 2023, 2024; Natskoulis et al., 2024), while others have investigated its sensory characteristics, phenolic composition and biogenic amines (Gougoulias, 2009; Loukou & Zotou, 2003; Proestos et al., 2005).

Regarding the method of extraction of the pine resin, it has been found that when harvested by the natural method (without chemical stimulants), the time of extraction into the must and the choice of the resin collection area are not a quality factor for the wine produced, but rather a matter of style (Nakas et al., 2024). In contrast, when the resin is harvested conventionally (using sulfuric acid as irritating stimulant of the tree), these factors are critical for the resulting quality of the wine (Nakas et al., 2024). The geographical origin of the resin also has no clear effect on the aromatic profile of the wines, while both the harvesting period and the duration of its contact with the wine were the variables that had more significant impact (Nakas et al., 2023).

On the other hand, Natskoulis et al. (2024) demonstrated that the amount of resin added had an effect on the quality of the wine. In fact, the quantity of resin used is proportional to the concentration of α-pinene in wines, and this has consequences at microbial level, since this is an antimicrobial compound. Furthermore, the concentration of esters in the wine, including ethyl decanoate, ethyl caprylate, ethyl caproate, hexyl acetate and ethyl butyrate, tends to decrease with increasing amounts of resin. A lower content of these esters in wines was linked to less fruity and floral aromas (Natskoulis et al., 2024).

Another focus is the sensory analysis of *retsina* wines, as they have a characteristic pine aroma and flavour (Buglass, 2011). Overall, this type of wine features a more complex aromatic profile, characterised by a discernible bitterness and a resinous fragrance (Natskoulis et al., 2024). This is due to their high content of benzaldehyde, which imparts a bitter almond flavour, along with 1-octanol, α-terpineol, terpinen-4-ol, and several polyoxygenated terpenes (Nakas et al., 2024). Additionally specific aromas may also result from certain phenolics, which influence the sensory perception of the wines (Liang et al., 2021; Nakas et al., 2024).

Phenolic compounds seem to be present in greater quantities in this type of resinated white wines compared to traditional wines, due to the additional contribution of the resin. Especially phenolic with the highest concentration were (+)-catechin, *p*-coumaric acid, gallic acid and tyrosol (Proestos et al., 2005). However, in a study analysing the total (poly)phenols in various Greek wines, it was found that *retsina* wine had a lower content than the rest (Gougoulias, 2009). It is important to note that in the latter study, (poly)phenol content was determined using the Folin–Ciocalteu assay, which is not specific to phenolic compounds since the reagent can also be reduced by other nonphenolic substances present in the sample, potentially explaining the observed differences (Raposo et al., 2024). Additionally, Proestos et al. (2005) compared three different *retsina* wines, whereas Gougoulias (2009) analysed only one retsina alongside other commercial traditional wines.

Biogenic amines have also been assessed in Greek wines, including retsina, as they are important indicators of wine quality and safety (Loukou & Zotou, 2003). Histamine and tyramine are among the most relevant compounds, as they originate from microbial decarboxylation of amino acids during alcoholic or malolactic fermentation (Costantini et al., 2019). Loukou and Zotou (2003) reported lower concentrations of biogenic amines, particularly histamine, in retsina compared with other Greek wines, suggesting that the antimicrobial properties of pine resin may help limit their formation. Altogether, retsina demonstrates how resin additions influence wine aroma, microbial stability, and phenolic characteristics.

5.4. *Tea wine (Canary Islands)*

"Tea" refers to the resinous heartwood of the endemic Canarian pine, *Pinus canariensis*, an endemic variety whose characteristics include a greater number of resin canals and higher extractive components than any other pine (Duarte Alonso, 2015). Its characteristics greatly differ from those of *P. halepensis*, whose resin is used in *retsina* winemaking. This resinous heartwood is used to make the barrels in which the wine is aged and stored (Duarte Alonso, 2015). Due to this unique barrelling process, the wines develop resinous flavour tones (Alonso González et al., 2022).

Tea wine is traditionally produced on the island of La Palma (Canary Islands, Spain). It has been recognised as a traditional wine by the Designation of Origin Wines of La Palma (DOVP) since 1993, and they are usually made from a blend of the following white and red grape varieties: Negramoll, Listán Blanco, Prieto, Albillo and Muñeco (García-Pérez, A. et al., 2022). Briefly, the traditional *tea* winemaking process unfolds as follows: grapes are harvested when they reach optimal ripeness. They are crushed using large presses in modern wineries, but it was traditionally trodden by foot. The resulting wine is then transferred either to smaller fermentation tanks or directly into *tea* barrels. Fermentation typically begins in the tanks and lasts several days to weeks. This method involves short maceration, leading to minimal colour and phenolic extraction, which is characteristic of winemaking in the Canary Islands. While some producers do employ racking to clarify the wine, this practice is not widely adopted (Alonso González & Parga-Dans, 2020).

Due to its characteristic sensory profile and the aim of enhancing the value of this traditional production, the research on *tea* wines has focused on the analysis of volatile compounds (Alonso González et al., 2022; Alonso González & Parga-Dans, 2020). The primary contributors to the distinctive aromas of *tea* wine were terpenes derived from the contact with pine resin during fermentation and ageing in the barrels, particularly terpinen-4-ol and α-terpineol (Alonso González et al., 2022; Alonso González & Parga-Dans, 2020). The latter compound is particularly relevant given its multiple applications as antioxidant and health benefits, among others (Khaleel et al., 2018). It supports natural winemaking processes thanks to its preservative properties, which may explain why *tea* wines are well-preserved without developing excessive volatile acidity, while also imparting lilac aromas to the wine (Alonso González et al., 2022; Alonso González & Parga-Dans, 2020). While α-terpineol is naturally found in pine resin, it may be transferred through direct contact with the wine, and the results indicate a clear correlation between higher levels of α-terpineol and longer ageing periods in pine heartwood casks (Alonso González et al., 2022; Alonso González & Parga-Dans, 2020).

Another characteristic volatile compound of *tea* wines was linalool (3,7-dimethyl-1,6-octadien-3-ol) (Alonso González et al., 2022; Alonso González & Parga-Dans, 2020). This monoterpene suggests sensory perceptions of green, floral, and spicy characteristics, such as menthol and aniseed aromas. Even though this compound can be naturally found in grapes, it has been observed that tea barrels contribute to its presence in the finished wine (Alonso González & Parga-Dans, 2020).

Regarding the compounds that decreased during ageing in tea barrels, geraniol stands out (Alonso González et al., 2022). This compound contributes to the floral bouquet of the wines. This reduction can be attributed to its ability to undergo transformation into β-citronellol (King & Richard Dickinson, 2000) which significantly influences the wine's aroma, making it less fruity, floral, and primary (Jackson, 2014).

For all these reasons, although there are few scientific studies on this type of wine, it has been observed that the production process involving contact with Canary pine resin wood results in a unique sensory product that may not require conventional preservatives. In summary, tea wines highlight the strong sensory imprint of Canarian pine heartwood, producing distinctive resinous and floral profiles.

Despite these well-documented traditional practices, several scientific questions remain unresolved, highlighting the need for further research.

6. Research gaps and future perspectives

Traditional winemaking practices using ceramic vessels, such as *talha* and *qvevri*, and ancient coatings like resins have endured for centuries and remain culturally significant. Despite renewed interest, scientific evidence on these methods is still limited. Most research emphasizes volatile profiles, while standardized sensory evaluations are scarce (Takahashi et al., 2023; Vlasov, 2022). Recent studies report distinctive aromatic profiles and consumer acceptance for wines aged in clay vessels (Issa-Issa et al., 2021; Maioli et al., 2022), yet systematic sensory trials are lacking. Comparative studies are needed to determine whether chemical differences translate into perceptible and commercially relevant attributes.

Further gaps include understanding the influence of vessel geometry on spontaneous fermentation and microbial ecology (Malfeito-Ferreira et al., 2024), inconsistencies in mineral migration data (Díaz et al., 2013; Cabrita et al., 2018), and incomplete characterization of oxygen transmission and coating performance (Nevares & Del Alamo-Sanza, 2021). Thermal properties and their impact on maturation speed remain poorly documented, sustainability claims lack empirical validation (White & Catarino, 2023), and the interaction between ceramic ageing and subsequent bottle ageing requires investigation (Ubeda et al., 2022). Addressing these gaps will require integrated research combining chemistry, microbiology, sensory science, and physical modelling to optimize traditional practices for contemporary winemaking. This review consolidates fragmented knowledge and outlines a roadmap for transforming ancient techniques into scientifically validated sustainable strategies for producing distinctive wines.

7. Conclusions

Traditional winemaking practices involving ceramic vessels and organic coatings provide distinctive micro-oxygenation, thermal properties, and antimicrobial effects that influence wine composition and sensory expression. Evidence from *qvevri*, *talha*, *retsina* and *tea* wines shows that these materials can enhance (poly)phenol and terpene profiles, support spontaneous alcoholic and malolactic fermentations, and contribute to characteristic aromatic complexity. By integrating archaeological, chemical, microbiological and sensory findings, this review clarifies how vessel porosity and coating chemistry interact to shape wine characteristics. These insights highlight the relevance of ancient techniques for contemporary low-intervention winemaking. However, key questions remain regarding mineral migration, sensory perception, vessel geometry, coating performance and long-term stability. Future interdisciplinary research is needed to establish standardised methodologies and to fully characterise the oenological potential of these traditional practices.

CRediT authorship contribution statement

Clara Abarca-Rivas: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Marina Corrado:** Writing – review & editing, Validation, Supervision, Conceptualization. **Francesc M. Campins-Machado:** Writing – original draft, Visualization, Investigation. **Anna Vallverdú-Queralt:** Writing – review & editing, Project administration, Funding acquisition. **Rosa M. Lamuela-Raventós:** Writing – review & editing, Project administration, Funding acquisition. **Alessandra Pecci:** Writing – review & editing, Project administration, Funding acquisition.

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Rosa M. Lamuela-Raventos reports a relationship with Cerveceros de España that includes: consulting or advisory. Rosa M. Lamuela-Raventos reports a relationship with UNIDECO that includes: consulting or advisory. Rosa M. Lamuela-Raventos reports a relationship with ADVENTIA PHARMA S.L. that includes: consulting or advisory. Rosa M. Lamuela Raventos reports a relationship with Wine in moderation that includes: consulting or advisory. Rosa M. Lamuela-Raventos reports a relationship with Ecoveritas that includes: consulting or advisory. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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