Review

AN OVERVIEW ON MOSCATEL DE SETÚBAL FORTIFIED WINE

REVISÃO: O VINHO GENEROSO MOSCATEL DE SETÚBAL

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SUMMARY

Moscatel de Setúbal is a Protected Designation of Origin (PDO) wine produced in Península de Setúbal wine region, being one of the four Portuguese fortified wines recognized as "Generosos". This wine has unique chemical and sensory characteristics due to the grape variety ('Moscatel de Setúbal', *Vitis vinifera* L.) used in its production, the winemaking process characterised by a long period of maceration of skins and grape berry seeds, and the oxidative ageing. According to the legislation, it must be submitted to a minimum ageing period, traditionally performed in wooden barrels, which plays a crucial role in the increase of its sensory quality. Although highly appreciated and recognized by its quality, scientific knowledge on this wine is still very scarce and limited to the general physicochemical and phenolic composition. This literature review aims to gather the available information about this fortified wine, providing a better understanding on the distinctive profile of Moscatel de Setúbal, and to lay out paths for future. It must be noted that Moscatel de Setúbal Roxo wine made with this grape variety also shares the PDO, but because of its rarity and small produced quantities it is not addressed in this work.

RESUMO

O Moscatel de Setúbal é um vinho com Denominação de Origem Protegida (DOP) produzido na região vitivinícola da Península de Setúbal, sendo um dos quatro vinhos portugueses reconhecidos como "Generosos". Este vinho apresenta características químicas e sensoriais únicas devido à casta ('Moscatel de Setúbal', *Vitis vinifera* L.) usada na sua produção, ao processo de vinificação, caracterizado por um longo período de maceração das películas e graínhas da uva, e ao envelhecimento oxidativo. De acordo com a legislação, esta bebida deve ser submetida a um período mínimo de envelhecimento que tradicionalmente ocorre em barricas de madeira, desempenhando um papel crucial no aprimoramento da sua qualidade sensorial. Embora muito apreciado e reconhecido pela sua qualidade, o conhecimento científico sobre este vinho é ainda muito escasso, limitando-se à composição físico-química geral e à composição fenólica. Esta revisão bibliográfica pretende assim reunir a informação disponível sobre este vinho generoso, proporcionando uma melhor compreensão sobre o perfil distintivo do Moscatel de Setúbal, e identificar possíveis futuras linhas de investigação. De salientar que o Moscatel de Setúbal Roxo, vinho elaborado com esta casta, partilha também a DOP, mas pela sua raridade e pequeno volume de produção não é abordado neste trabalho.

Keywords: Fortified wine – "Generoso", winemaking, post-fermentation maceration, oxidative ageing, physicochemical characteristics.
Palavras-chave: Vinho fortificado - Generoso, vinificação, maceração pós-fermentativa, envelhecimento oxidativo, características físico-químicas.

INTRODUCTION

Moscatel de Setúbal is a Portuguese fortified wine from Península de Setúbal wine region, also classified as "Generoso" – a Portuguese traditional appellation joint with Protected Designation of Origin (PDO) attributed to Porto, Madeira and Carcavelos fortified wines (Decreto-Lei Nº 326/88; Council regulation Nº 491/2009; Commission delegated regulation (EU) Nº 2019/934) as well. Moscatel de Setúbal is the second oldest demarcated region in Portugal, which was created in 1907 and regulated in 1908 (Salvador, 2010). However, its production dates back hundreds of years, with records of its fame dating back to the 13th century (IVV, 2018a).

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This wine is produced with 'Moscatel de Setúbal' grapevine variety, also referred to as 'Moscatel Graúdo' (Almadanim *et al*., 2007), which has been internationally recognized and confirmed to be the same variety as 'Muscat of Alexandria' (*Vitis vinifera* L.) (Lopes *et al*., 1999; JKI, 2024). The traditional appellation Moscatel de Setúbal may only be used when at least 85% of the must used to produce the wine is from this grapevine variety (Portaria Nº 118/2014; IVV, 2018a) which represented, in 2022, 9.3 % of the total vineyard area of the Península de Setúbal wine region (IVV, 2023).

Considered as "Portugal`s national drinking heritage", this fortified wine is distinguished by its characteristic aroma, ageing ability and balance between sugars, alcohol, and acids, exhibiting a golden colour, which has earned it the honour of being called "The sun in the bottle" (IVV, 2018a; CVRPS, 2024) and "The prince of Muscats" (Salvador, 2010). Indeed, exports of fortified wines other than Porto and Madeira, including Moscatel de Setúbal, increased by 20.8% in both volume and value between 2019 and 2023 (IVV, 2023), with growth in exports mainly to France, Belgium, Switzerland, Brazil, and Angola.

Moscatel de Setúbal must comply with the requirements established in the applicable legislation (IVV, 2018a). The related winemaking process implies a particular stage after fortification – maceration involving the wine, skins and seeds for several months (Garcia, 2001; Tredoux and Silva Ferreira, 2012; Portaria Nº 118/2014; Abreu *et al*., 2021). Afterwards, the pressing is carried out and the wine is aged for at least 18 months (Portaria Nº 118/2014). According to the Comissão Vitivinícola Regional da Península de Setúbal (CVRPS), the ageing period is one of the aspects that, in addition to the origin and quality of the vineyards, guaranteed by the PDO Setúbal designation, distinguishes Moscatel de Setúbal from the other wines (CVRPS, 2024).

Ageing conditions play a key role in determining wine`s overall quality (Tao *et al*., 2014; Reboredo-Rodríguez *et al*., 2015; Abreu *et al*., 2021). During this stage, the wine undergoes changes in its chemical composition, which are usually reflected in an improvement on its sensory properties (González-Centeno *et al*., 2016; McCallum *et al*., 2019; Pilet *et al*., 2019; Pfahl *et al*., 2021).

Several factors influence the ageing of wines in contact with wood, including the botanical species used, wood toasting, the number of uses of the barrel (Gómez-Plaza *et al*., 2004), and the humidity and temperature of the room where the barrels are placed during the ageing stage (Garde-Cerdán and Ancín-Azpilicueta, 2006; Del Álamo-Sanza and Nevares, 2019; Zamora, 2019; Abreu *et al*., 2021; White and Catarino, 2023). Evidence exists that wooden barrels, made essentially with oak, promote the release of wood compounds into the wine and a small permeation of oxygen through the wood and the joints between staves (Del Álamo-Sanza and Nevares, 2019). Concerning the sweet fortified wines as Moscatel de Setúbal, ageing occurs traditionally in used barrels, often under variable temperature of storage and partly empty (Garcia, 2001), thus promoting the permeation and diffusion of oxygen, more than the extraction of compounds from the wood (Cutzach *et al*., 2000; Gómez-Plaza *et al*., 2004; Carpena *et al*., 2020). Oxygen contributes to stabilize colour and to reduce astringency, and in some fortified wines it is essential to their quality (Câmara *et al*., 2006; Waterhouse and Laurie, 2006; Gómez-Plaza and Bautista-Ortín, 2019; McCallum *et al*., 2019; Pereira *et al*., 2022).

The wine main substrates for oxygen are phenolic compounds (Singleton, 1987; Gómez-Plaza and Cano-López, 2011; Oliveira *et al*., 2011). These compounds are of outmost importance for wine quality, as they play a crucial role in the sensory properties of the grapes and the wine itself (Garrido and Borges, 2013; Li and Sun, 2017; Pérez-Navarro *et al*., 2020), particularly in terms of colour, astringency and bitterness. They can be classified into flavonoid and non-flavonoid phenols and are found in all grape cluster portions; the flavonoids are present especially in seeds, stems and skins (Jordão and Ricardo-da-Silva, 2019). According to the literature, total phenols content is usually higher in red wines than in white wines due to the winemaking process (Bravo *et al*., 2006; Paixão *et al*., 2007; De Lerma *et al*., 2010; Pereira *et al*., 2013). However, the maceration process increases the phenols content of white wines (Darias-Martín *et al*., 2000; Tian *et al*., 2020) that are subject to oxidative browning through chemical oxidation (Correia *et al*., 2023).

Although oxygen participates in numerous reactions during wine ageing, some compounds are formed independently of oxidative processes. Among these compounds, lactones, ethyl furoate, maltol, and homofuraneol arise through Maillard reactions (Cutzach *et al*., 1999). These reactions, which occurrence is promoted by high amounts of sugars, nitrogen compounds (amino acids and proteins) and high temperature (Ellis, 1959; Moreno *et al*., 2007; Li *et al*., 2008; Tredoux and Silva Ferreira, 2012) are involved in many compounds' production, whether in the absence or in the presence of oxygen (Cutzach *et al*., 1999; Rufián-Henares and Pastoriza, 2016). One of those compounds is 5-hydroxymethylfurfural (5-HMF), an aldehyde that can polymerize with polyphenols, producing brown compounds (Serra-Cayuela *et al*., 2013). These compounds have been identified in Madeira wines subjected to "estufagem", an ageing process where the wines are heated to approximately 45 °C for up to 3 months

(Pereira *et al*., 2011). By this path, as well as by the caramelization of sugars, not only the colour is affected but also the flavour (Francisquini *et al*., 2017; Starowicz and Zieliński, 2019; Shakoor *et al*., 2022).

Several studies concerning Portuguese fortified wines aged under oxidative conditions, namely Madeira (Câmara *et al*., 2004; Alves *et al*., 2005; Câmara *et al*., 2006; Oliveira e Silva *et al*., 2008; Pereira *et al*., 2014; Perestrelo *et al*., 2020; Pereira *et al*., 2022; Perestrelo *et al*., 2023), Porto (Ferreira *et al*., 2005; Moreira and Guedes de Pinho, 2011; Martins *et al*., 2013; Prata-Sena *et al*., 2018; Milheiro *et al*., 2023) and Carcavelos (McCallum *et al*., 2019), highlight the importance of the ageing step in wine quality improvement.

Regarding Moscatel de Setúbal, to the best of available knowledge, studies are still scarce and especially focused on phenolic composition (Bravo *et al*., 2006, 2008; Feliciano *et al*., 2009; Silva, 2011; Silva *et al*., 2014), with only one study involving physicochemical analysis in addition to the general phenolic characterisation (Franco and Singleton, 1984).

The Portuguese research on the flavour of 'Moscatel de Setúbal' grapevine variety is limited to the volatile composition of musts and their derived dry wines (Clímaco, 1978), while several studies on 'Muscat of Alexandria' volatile compounds, from other world regions, can be found in the literature (Stevens *et al*., 1966; Hardy, 1970; Ribéreau-Gayon *et al*., 1975; Gunata *et al*., 1985; Lanaridis *et al*., 2002; Zemni *et al*., 2007; Marinaki *et al*., 2023).

Having in mind the limited scientific knowledge on Moscatel de Setúbal fortified wine, this review aims to bring together the available information about this "Generoso" wine and to identify possible gaps/clues for further research.

History of Moscatel de Setúbal wine

While recognized as PDO in the early twentieth century, it is known that the fame of Moscatel de Setúbal wine dates to the thirteenth century. In the fourteenth century it was already being exported to England – King Richard II was a frequent importer of this wine - as well as King Louis XIV some centuries after, who usually served it at Versailles parties. In the fifteenth and sixteenth centuries, Moscatel de Setúbal travelled on ships during the Portuguese expansion and after that continued travelling to the colonies, often made the round trip (IVV, 2018a). It was realised that these wines, so then called "Roda" or "Torna-Viagem" wines, had their quality increased by the conditions to which they were subjected during the journeys, exposed to the atmospheric elements, such as sun, or submerged in sea water at the bottom of ships. Indeed, in 1908, Brazil became an important destination market for José Maria da Fonseca company, where its wines were recognised by experts. This recognition marked a turning point, as the Brazilian trade route would later be crucial in the creation of the famous "Torna-Viagem" Moscatéis (Salvador, 2010). Therefore, these wines are highly prized at auctions (CVRPS, 2024).

In 1675, there are references to the export of 350 barrels of Moscatel de Setúbal. France may have been the intended destination for the wines, given their chronological alignment with the reign of King Louis XIV. In 1797, it was on the menu of a banquet held for the Sovereign Military Order of Malta, along with other prestigious wines. In 1855, José Maria da Fonseca's Moscatel de Setúbal won a gold medal at the Paris Universal Exhibition. On September 9, 1875, Ferreira Lapa, in his 6th conference on wines, upon concluding his study on Estremadura, referred to "the remarkable and important wine region of Setúbal, the exclusive region of Moscatel, renowned in Europe and well-established in Portugal, where very few names are made". This wine is often described as 'a monument of agricultural art and a national treasure', 'the prince of muscats', and 'the national heritage you drink' (IVV, 2018a).

It should be stressed that hereinafter when only "Moscatel de Setúbal" is mentioned, it refers to the fortified wine.

Península de Setúbal Wine Region and Setúbal PDO

Moscatel de Setúbal is produced in the PDO Setúbal from Península de Setúbal region (Figure 1), which is located on the west coast of Portugal, south of Lisbon, and comprises the councils of Setúbal, Palmela, Montijo and, also, the parish of Castelo, in the county of Sesimbra. The region has two different orographic zones: one mountainous, with altitudes between 100 m and 500 m, formed by the Arrábida, Rasca and S. Luís mountains in the south and south-west, and the mountains of Palmela, S. Francisco and Azeitão, the latter cut by valleys and hills. The other zone is flat, whose altitude varies between 30 m and 100 m, comprising the plains and small valleys of the councils of Palmela and Montijo, stretching across a vast plain along the Sado River (Kullberg *et al*., 2014, IVV, 2018b; CVRPS, 2024).

The climate is predominantly Mediterranean, with two distinct seasons – a hot and dry summer and a relatively cold and rainy winter. Due to its proximity to the Atlantic Ocean, the Tejo (Tagus) and Sado river basins and the mountains and hills, it has low temperature variations and annual rainfall between 400 mm and 500 mm. Soils are sandy-clay or sandy-clay loam, limestone, with slight alkalinity (IVV, 2018b; CVRPS, 2024).

Depending on the vineyard's location, Moscatel de Setúbal grapes tend to be sweeter but less aromatic when grown on flat land, due to the warmer and drier climate. In contrast, when planted on the north-facing hillsides of Arrábida, which are influenced by the Atlantic Ocean, the grapes experience slower and longer ripening, preserving the distinct flavours of the Moscatel variety (Franco and Singleton, 1984; Garcia, 2001; Kullberg *et al*., 2014). As a result, this wine exhibits a better balance between acidity and sweetness (Salvador, 2010; Kullberg *et al*., 2014). Bearing in mind that the traditional appellation Moscatel de Setúbal may only be used when at least 85% of the origin must come from this grapevine variety (Portaria Nº 118/2014), an aromatic variety which quality and regional typicity reflects itself together with climate and soil (Ribéreau-Gayon *et al*., 2006), Moscatel de Setúbal has its full expression in the hillsides of Arrábida (Garcia, 2001; Salvador, 2010). Although other varieties are allowed, namely ‘Antão Vaz’, ‘Arinto’, ‘Fernão-Pires’, ‘Malvasia Fina’, ‘Moscatel Galego Branco’, ‘Rabo de Ovelha’, ‘Roupeiro Branco’, ‘Verdelho’ and ‘Viosinho’ (Portaria Nº 118/2014), according to Salvador (2010) the main producers make this fortified wine exclusively from Moscatel de Setúbal grapevine variety. Regarding Portuguese fortified wines, after Porto and Madeira, Península de Setúbal was the region with the highest declared production (by volume) in the 2023/2024 vintage, with 20872 hL suitable for PDO fortified wines (IVV, 2023), at about 3500 hL more than in the previous vintage (IVV, 2022). It should be highlighted that Moscatel Roxo is included in these numbers but, as previously mentioned, its production is limited (Garcia, 2001; CVRPS, 2024). In addition, both fortified wines (white wine, made from ‘Moscatel de Setúbal’ grapevine variety, and red wine made from ‘Moscatel Roxo de Setúbal’ grapevine variety) may be denominated ‘Setúbal’ when the respective grapevine varieties account for at least 67 % of the must.

Figure 1. Península de Setúbal wine region (A) and Setúbal PDO (B) (adapted from IVV, 2018b).

Moscatel de Setúbal grapevine variety

‘Moscatel de Setúbal’ grapevine variety (Figure 2) also designated as ‘Moscatel Graúdo’, is the same variety as ‘Muscat of Alexandria’ (*Vitis vinifera* L.), which may have its origin in the North of Africa (Lopes *et al*., 1999; Salvador, 2010) or at least in Eastern Mediterranean basin (Crespan and Milani, 2001). The exact moment when this variety was introduced to the Península de Setúbal is unknown. However, this achievement is ascribed to the Phoenicians and Greeks, with the Romans and Arabs greatly promoting viticulture in this Portuguese region (Salvador, 2010; IVV, 2018b). Widespread across the Mediterranean basin, this variety also referred as ‘Moscatel de Málaga’ in Spain, ‘Muscat de Kelibia’ in Tunísia, ‘Angliko’ in Greece, or ‘Zibibbo’ in Italy (Böhm, 2010), has a memorable floral and fruity aroma, being widely used to produce table grapes and raisins (Esteras *et al*., 2019), dry white whites, sparkling and fortified wines (Marinaki *et al.*, 2023) or sweet wines from dehydrated grapes such as Zibibbo, in Italy (Verzera *et al*., 2021), fortified wines as Malaga sweet wines (Moreno-Vigara and García-Mauricio, 2013) or “Passito” and “Moscato di Pantelleria” (Tudisca *et al*., 2013).

In Portugal, the vine-growing area reached 1156 ha in 2022 (IVV, 2022), compared to 700 ha in 2010 (Böhm, 2010).

Regarding Península de Setúbal, this variety is mainly used to produce Moscatel de Setúbal fortified wine (Salvador, 2010).

Currently, the area of 'Moscatel de Setúbal' in Península de Setúbal represents 9.3 % of the region total area (IVV, 2023), being the grapes used for the production of Moscatel de Setúbal wine, but also for the production of dry wines.

Figure 2. 'Moscatel de Setúbal' grape cluster and leaf (photo by Joana Granja-Soares).

'Moscatel de Setúbal' is a variety with late phenological stages, low vigour and average yield, requiring high temperatures and sunlight exposition to achieve adequate sugar content (Eiras-Dias *et al*., 2011). Morphologically, it is characterised by medium-sized, rounded leaves with three lobes. The bunch is large, long, winged, conical, loose and with a long peduncle, while the berries are large, oval, yellowish green, with a medium-thick skin and firm flesh. In terms of oenological potential, this variety is widespread used to produce fortified wine (Verzera *et al*., 2021). Regarding the aroma, the so-called Muscat grape varieties are distinctive, which is attributed to an association of several terpenic compounds namely linalool, citronellol, nerol, geraniol and α-terpineol (Ribéreau-Gayon *et al*., 1975; Aragón-Garcia *et al*., 2021), mainly present in the berry skins (Aragón-García *et al*., 2021; Kamaladdin *et al*., 2023). This variety is also rich in proteins (Waters *et al*., 1992; Mesquita *et al*., 2001), which leads to a high risk of haze in the corresponding wines (Marchal *et al*., 2024).

Winemaking

For Moscatel de Setúbal production, harvest typically occurs when grapes maturation achieves a potential alcoholic strength around 12% vol. - 13% vol., to avoid aroma loss (Garcia, 2001). After harvesting, the grapes are crushed and left to ferment in stainless steel tanks until reaching the desirable sugars level (Garcia, 2001). Wine spirit with an alcoholic strength between 52% vol. and 86% vol. or neutral alcohol of vitivinicultural origin with not less than 96% vol. is then added. It means that the wine will have both significant alcohol and sugar content, that can vary between 16% vol. and 22% vol. and up to 280 g/L or 340 g/L of reducing sugars, respectively, depending on whether the wine is less or more than 20 years old, respectively (Portaria Nº 118/2014). Regarding the wine spirit quality, it must have specific characteristics, which are controlled as defined by IVV (Decreto-Lei Nº 147/98). Analytical control of both wine spirit and the wine is made by the CVRPS (IVV, 2018a; CVRPS, 2024).

According to Franco and Singleton (1984), a single addition of sulphur dioxide, up to about 30 mg/L, depending on grapes sanitary condition, is made before crushing. Currently, the maximum acceptable limit of total sulphur dioxide in this wine is 200 mg/L (IVV, 2018a).

Regarding the vinification process (Figure 3), once alcoholic fermentation is interrupted, a particular stage takes place – a prolonged period of maceration with grape seeds and skins and fortified wine (Tredoux and Silva Ferreira, 2012; Abreu *et al*., 2021). According to Franco and Singleton (1984), this period lasts approximately 5 months. Garcia (2001) indicates a variable duration, which can extend up to 6 months, while in the previous century, it "could last until the next harvest". Indeed, this practice is allowed (Portaria Nº 118/2014; IVV, 2018a) but its length is not regulated. After the maceration period, the wine is separated from the pomace, which is pressed and the obtained liquid from pressing is added to the free running wine (Garcia, 2001; Salvador, 2010). Then, according to the regulations, the wine must be submitted to a minimum ageing period of 18 months (IVV, 2018a), updating the minimum ageing period of two years previously established by Decreto-Lei Nº 13/92 (Portaria Nº 793/2009 updated by Portaria Nº 118/2014). According to the CVRPS (2024), ageing time is one of the aspects that, in addition to the origin and quality of the vineyards, guaranteed by the designation PDO Setúbal, differentiates the Moscatel de Setúbal. The ageing stage can be performed either in stainless steel tanks or in wooden barrels (Garcia, 2001; Salvador, 2010).

For the wines of higher quality, the ageing process is traditionally carried out in used wooden barrels often from species of *Quercus* botanical genus (Garcia, 2001; Salvador, 2010). According to Garcia (2001), these containers are kept partly empty to promote increased oxidation, which is beneficial for the wine's development. However, due to significant evaporation losses, they are semi-filled with a similar wine during the initial years, or with wine spirit when Moscatel is aged for more than ten years. Wooden barrels can be kept both in rooms subjected to low or high thermal amplitudes. In the latter case, wine evolution occurs more rapidly, as has been empirically observed in the "Torna-Viagem" Moscatéis from the José Maria da Fonseca company (Garcia, 2001; Bouça, 2016). This process promotes the development of distinctive volatile compounds that contributes to the characteristic bouquet of Madeira wines subjected to “estufagem” (Oliveira e Silva *et al*., 2008; Pereira *et al*., 2014). Before bottling, the wine is stabilised, filtered and blended with wines from the same vintage to enhance its organoleptic properties (Silva, 2011). After bottling, the wine's evolution is slow and not significant (Garcia, 2001).

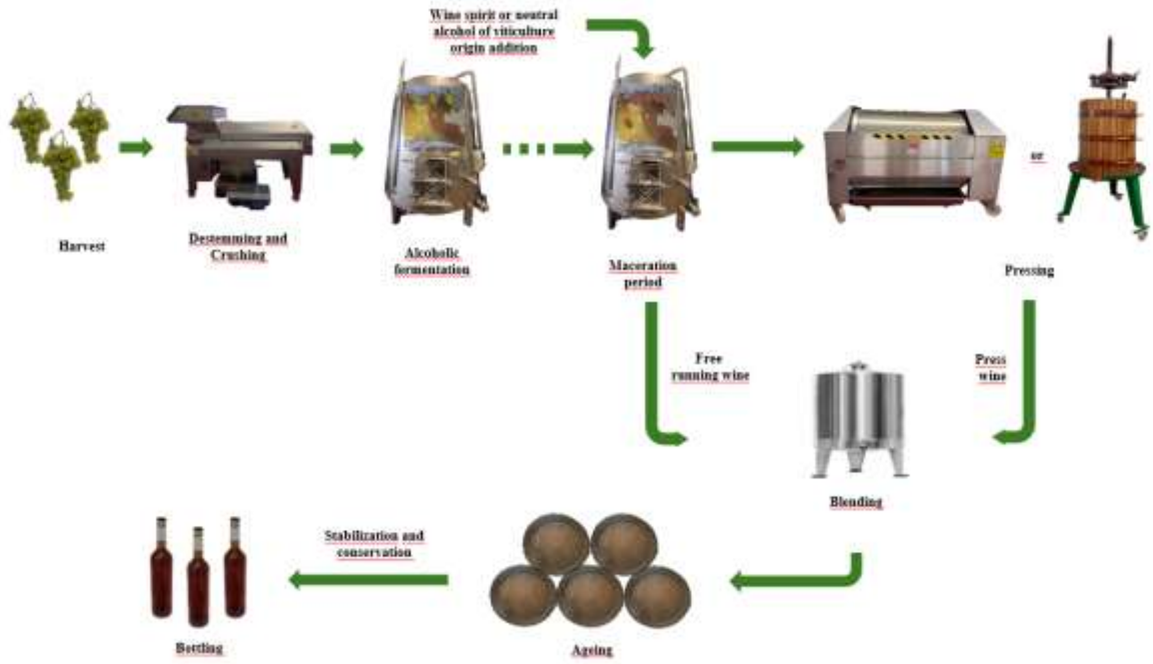

Figure 3. Representative flowchart of Moscatel de Setúbal winemaking.

For trade purposes, the label may indicate or not the vintage year (Portaria Nº 26/2017; Portaria Nº 130/2018; Portaria Nº 325/2019), age indications or other classifications, according to the current legislation (Table I).

Traditional ageing and its influence on Moscatel de Setúbal quality

Wooden ageing is an important step in winemaking recognised for improving beverages quality (Garde-Cerdán and Ancín-Azpilicueta, 2006; Canas *et al*., 2019; Pilet *et al*., 2019; Abreu *et al*., 2021; White and Catarino, 2023). Several phenomena, such as some evaporation of ethanol and water through the wood, a mild permeation of oxygen through the wood and the extraction of volatile compounds and ellagitannins from the wood to the wine, contribute to the improvement observed (Zamora, 2019). However, the wood loses its richness during successive uses, while adsorbing compounds from beverages that have been previously aged in those barrels (Coelho *et al*., 2019). All of these phenomena are influenced by ageing time, wine and wood characteristics (Garde-Cerdán and Ancín-Azpilicueta, 2006) namely the wood species, the wood geographical origin, the part of the trunk selected to give rise to the barrel, the manufacturing process in terms of the seasoning conditions and time/temperature binomial used in the toasting step (Canas, 2017; Gibson and Newsham, 2018), the size of the barrel (Puech, 1984; Feuillat and Keller, 1997; Caldeira *et al*., 2009; Canas and Caldeira, 2015), and also by the temperature and humidity conditions of the cellar (Del Álamo-Sanza and Nevares, 2019).

Wooden barrels (Figure 4) increase fortified wines quality (Ho *et al*., 1999; Cutzach *et al*., 1999, 2000; Gómez-Plaza and Bautista-Ortín, 2019; Silva *et al*., 2014; McCallum *et al*., 2019) giving them the “desirable aged oxidative character” expected by the consumers (Tredoux and Silva Ferreira, 2012). In the 1980`s, oak was, in fact, referred to as "the only wood capable of really improving beverages” (wines and wine spirits) (Chatonnet *et al*., 1989), even if other botanical species are used in the ageing step namely chestnut, acacia and sherry (Martínez-Gil *et al*., 2018; Jordão and Cosme, 2022). Nevertheless, in accordance with the OIV (2025) resolutions and European regulations, only chestnut and oak can be used, with oak by far the most commonly employed species (Belchior *et al*., 2015; Zamora, 2019). Moscatel de Setúbal is aged in wooden barrels of various capacities (ranging from 200 to 1000 litres; Garcia, 2001), which were previously used to age wine or whisky (Salvador, 2010). Furthermore, according to McCallum *et al*. (2019), fortified wines are usually aged in old barrels to reduce the extraction of aroma and flavour compounds from the wood. Thus, fundamentally what happens is oxidative ageing due to the wood's permeability to oxygen. Indeed, as previously mentioned, during ageing the wooden barrels are kept unfilled to promote higher oxidation, being sometimes "semi-filled" with identical wine during the first years, if losses are significant, and with wine spirit to the ones ageing over ten years (Garcia, 2001).

Table I

Classifications of Moscatel de Setúbal

Classification	Description	Legal regulation
5; 10; 15; 20; 25; 30; 35; 40; 50 Years [1]	The wine or wines used in the blend must have at least the indicated ageing period.	Portaria Nº 118/2014; Portaria Nº 346/2015; Aviso Nº 13722/2024/2
Superior [2]	Wines with minimum age of five years with distinct quality demonstrated in sensory evaluation (by the CVRPS tasting chamber)	Portaria Nº 118/2014; IVV, 2018a; Portaria Nº 26/2017; Portaria Nº 130/2018; Portaria Nº 325/2019
Reserva [2]	Wines with an outstanding quality rating obtained in the CVRPS tasting chamber.	Portaria Nº 26/2017; Portaria Nº 130/2018; Portaria Nº 325/2019
Vintage year [3]	Wines made with at least 85 % from grapes of the year to which the indication relates to.	Portaria Nº 26/2017; Portaria Nº 130/2018; Portaria Nº 325/2019

1 - "Indicação"; 2 - "Menção tradicional"; 3 - "Menção específica".

Oxygen is recognized as a paramount factor in winemaking (Cutzach *et al*., 2000; Du Toit *et al*., 2006; Gómez-Plaza and Cano-López, 2011; Anli and Cavuldak, 2012), as it can lead, in appropriate doses, to a sensorial improvement of wines (De Beer *et al*., 2008; Tarko *et al*., 2020), changing their colour, aroma, and flavour (Tarko *et al*., 2020; Pfahl *et al*., 2021; White and Catarino, 2023). It results from the presence of phenolic compounds, which are responsible for wine's quality (Anli and Cavuldak, 2012), and are primarily affected by oxygen (Singleton, 1987; Anli and Cavuldak, 2012). Most white wines do not benefit from oxidation since they have lower phenolic content than red wines (Oliveira *et al*, 2011). However, it was already showed that white wines subjected to maceration have high phenolic content correlated with antioxidant capacity (Ružić *et al*., 2011; Darias-Martín *et al*., 2000; Tian *et al*., 2020), which is the case of the particular vinification process of Moscatel de Setúbal (Feliciano *et al*., 2009). Therefore, it is believed that oxidation plays a fundamental role in improving the quality of this wine, although no studies have yet been conducted in this regard.

Furthermore, wines can be aged both at low temperature ranges warehouses and at warehouses with high temperature differences between summer and winter, in conditions similar to the "canteiro" ageing system for Madeira wine. In the latter case, although the air temperature can range from 5 °C to 40 °C, the wine temperature varies between 10 °C and 25 °C, resulting in a more pronounced evolution of the wine (Cutzach *et al*., 2000; Garcia, 2001; Câmara *et al*., 2004; Pereira *et al*., 2022).

Physicochemical composition

According to the "*Caderno de especificações*" for PDO Setúbal (IVV, 2018a), which is based on legislation - Portaria Nº 239/2012, modified by Portaria Nº 342/2013, Portaria Nº 255/2014, and Portaria Nº 322/2015 - Moscatel de Setúbal wine must fulfil specific analytical requirements (Table II).

As previously mentioned, literature lacks information about physicochemical characteristics of Moscatel de Setúbal wine. An exception is the study of Franco and Singleton (1984), reporting some analytical parameters for wines of different vintages (Table III), being the only known involving physicochemical characterisation of Moscatel de Setúbal. From a total of 75 vintages, 24 wines were selected based primarily on their sensory characteristics, specifically those that were most representative of the wine style under study. Then, a temporal gap of three to four years was kept between the selected vintages to ensure a more uniform chronological distribution for analytical purposes.

Figure 4. Old wooden barrel used for Moscatel de Setúbal ageing (photo by Joana Granja-Soares).

Table II

Mandatory physicochemical characteristics of Moscatel de Setúbal (IVV, 2018a)

Acquired alcoholic strength at 20 ºC (% vol.)	16-22	
Alcoholic strength in natural potency (in must) (% vol.)	≥ 10.0	
Volatile acidity * (g acetic acid/L)	Wines ≤ 10 years	1.5
	Wines ≥ 10 years	1.8
Reducing substances (g inverted sugar/L)	Wines ≤ 20 years	280
	Wines ≥ 20 years	340
Total sulphur dioxide (mg SO_2/L)	<200	

* A tolerance of 20 % is allowed on these limits for unbottled wines in storage.

In general, higher values of sugars content, fixed acidity and volatile acidity are observed in the older wines. As authors pointed out, modifications in the value of each analytical parameter over time, may be due to one or more phenomena such as concentration by evaporation, extraction from the wooden barrel, formation from other wine compounds, precipitation from wine or differences between wines of different vintages. Moreover, wines were aged in barrel with different sizes and wood origins, of unknown number of uses.

Phenolic composition

Wine phenolic compounds mainly come from the grapes and are extracted during the winemaking process. Thus, they are heavily influenced by this stage. They are then modified during ageing, since their content can be enhanced by the wood and the storage conditions (Singleton, 1987; Waterhouse, 2002; Pfahl *et al*., 2021).

Wine owes its intrinsic characteristics not only but especially to phenolic compounds, as they determine sensory attributes such as taste and mouthfeel - bitterness and astringency -, visual - limpidity and colour (Singleton, 1974; Sun *et al.*, 2001; Waterhouse, 2002) and aroma – volatile phenols (Jackson, 2014). Furthermore, they are key elements in wine preservation, as they can act as browning agents and be involved in protein haze development and/or clarification (Waterhouse, 2002; Clarke *et al.*, 2023). Phenolic compounds can be classified as flavonoids and non-flavonoids based on their chemical structure/carbon skeleton. Flavonoids, namely flavonols, flavones, flavanols, isoflavones, and in red grapes anthocyanins, are present in seeds, skins and stems, while non-flavonoids, such as stilbenes, hydroxycinnamic and benzoic acids come mostly from the pulp (Cheynier, 2005; Paixão *et al.*, 2007; Jordão and Ricardo-da-Silva, 2019). In addition, hydrolysable tannins can be found, sourced from wood during ageing step (Waterhouse, 2002) or added during the winemaking process (OIV, 2025). White wines winemaking usually does not include maceration process that leads to a high extraction from the solid grape constituents. Typically, and due to the ripeness stage and winemaking process, red wines usually show higher levels of total phenols, as well as in flavonoids content (Mattivi *et al*., 2006;

Paixão *et al.*, 2007; Jackson, 2014). Therefore, Moscatel de Setúbal is expected to exhibit phenolic levels approximate to those of red wines or at least higher than white wines due to the maceration period (Ružić *et al.*, 2011), the addition of wine spirit, which enhances extraction through ethanol (Ribéreau-Gayon *et al.*, 2006; Setford *et al.*, 2017), and the influence of wooden ageing (Feliciano *et al.*, 2009).

Table III

Time of barrel ageing, vintage, sugars, fixed and volatile acidity of 24 Moscatel de Setúbal wines from 1902 to 1980 (adapted from Franco and Singleton, 1984)

Years in barrel	Vintage	Sugars (g/L)	Fixed acidity (g tartaric acid/L)	Volatile acidity (g acetic acid/L)
0	1980	125.0	3.73	0.20
0	1979	105.0	3.77	0.45
5	1974	145.0	2.98	0.72
8	1971	145.0	4.42	0.48
11	1968	145.0	3.88	0.57
15	1964	181.0	4.41	1.11
19	1960	161.0	3.65	1.29
24	1955	209.0	3.62	0.87
28	1951	195.0	4.41	0.87
32	1947	205.0	4.79	1.05
36	1943	215.0	4.41	0.98
41	1938	254.0	4.63	1.29
46	1933	214.0	4.70	1.35
50	1929	244.0	5.04	1.68
52	1927	238.0	4.89	1.50
56	1923	340.0	3.55	1.68
59	1920	317.0	6.77	162
62	1917	417.0	9.13	1.35
65	1914	377.0	7.79	1.65
67	1912	347.0	8.02	1.83
69	1910	355.0	8.04	2.13
71	1908	405.0	8.94	1.77
74	1905	417.0	9.47	1.68
77	1902	389.0	9.85	1.77

In 1984, Franco and Singleton, using spectrophotometric methods, found higher amounts of both total phenolic compounds and non-flavonoids in the oldest wines, in a series of wines with different ages. In those wines, non-flavonoids represented more than half of the total phenols, except for the youngest ones, who have just been placed in wooden barrels (< 1 year). The authors hypothesized that the highest extraction from the wood was due to the fact that non-flavonoids mostly derive from the oak, and older wines were stored in smaller barrels than the younger wines. This fact, along with the evaporation over time, likely increased the extraction due to the surface-to-volume ratio, which is higher in smaller barrels (Table IV). Bravo *et al.*, (2006) studied Moscatel de Setúbal wines from different producers, and determined total phenolic content ranging between 0.4 g and 1.7 g of gallic acid per litre, and identified some compounds, such as catechin, epicatechin, piceid and quercetin glycosides and phenolic acids (gallic, protocatechuic and caffeic), by Liquid Chromatography-Mass Spectrometry (LC-MS). Both the chromatographic profile and the evolution of phenolic content followed a similar trend for each producer, increasing once the press wine was added to the free-running wine. Bravo *et al.*, (2008) determined by LC-MS the concentration of *trans*-resveratrol, a stilbene found to decrease during the winemaking process (Bravo *et al*., 2008). Feliciano *et al*. (2009) studied the total phenolic and flavonoid contents and antioxidant capacities of Moscatel de Setúbal, highlighting the effect of vintage and winemaking in the final wine. Silva *et al*. (2014) developed a model to estimate total phenolic and flavonoids content of Moscatel de Setúbal by Fourier Transform Infrared-Attenuated Total Reflectance (FTIR-ATR). In the two latest studies, the authors concluded that Moscatel de Setúbal has significant antioxidant capacity. However, they also observed high variability between producers and even within the same producer, which they assigned to differences in maceration time and maturation temperature.

Table IV

Time of barrel ageing, vintage, total phenols and non-flavonoid phenols of 24 Moscatel de Setúbal wines from 1902 to 1980 (adapted from Franco and Singleton, 1984)

Years in barrel	Vintage	Total phenols (mg GAE/L)	Non-flavonoid phenols (mg GAE/L)
0	1980	457.0	147.0
0	1979	557.0	136.0
5	1974	417.0	228.0
8	1971	649.0	343.0
11	1968	434.0	247.0
15	1964	506.0	358.0
19	1960	467.0	309.0
24	1955	622.0	388.0
28	1951	624.0	373.0
32	1947	666.0	400.0
36	1943	770.0	502.0
41	1938	718.0	473.0
46	1933	785.0	496.0
50	1929	818.0	496.0
52	1927	795.0	512.0
56	1923	1481.0	791.0
59	1920	1372.0	643.0
62	1917	1736.0	837.0
65	1914	1517.0	759.0
67	1912	1651.0	854.0
69	1910	1739.0	946.0
71	1908	1810.0	975.0
74	1905	2130.0	1212.0
77	1902	1978.0	1092.0

Volatile Composition

Wine aroma is a primary attribute in its quality assessment (Bordiga *et al*., 2013; Aleixandre-Tudo *et al*., 2015). Several factors influence the volatile composition, comprising the grapevine variety(ies), viticultural practices, environmental conditions, grape ripeness state (Alves *et al*., 2005), alcoholic fermentation, and ageing conditions, such as temperature and humidity of storage (Abreu *et al*., 2021), and oxygen exposure (Cosme *et al*., 2019).

The aroma profile of wine, likewise other beverages, is shaped by a variety of volatile compounds, including those with minimal odorant impact (Ryan *et al*., 2008). Being one of the most aromatic grapevine varieties, 'Muscat of Alexandria' aroma has always drawn attention. Both grapes and wines are characterised by a sweet floral Muscat aroma, resulting from the combination of several terpenic compounds, including linalool, citronellol, nerol, geraniol, α-terpineol and alcohols (Stevens *et al.*, 1966; Ribéreau-Gayon *et al.*, 1975; Clímaco, 1978; Aragón-Garcia *et al*., 2021). These terpenoids occur in free and glycosidically bound forms, the latter being found mainly in grape skin, with considerable aromatic potential (Gunata *et al*., 1985; Jackson, 2014).

Due to its exuberant and distinctive aroma, several studies have been conducted to better understand how to maximize the flavour potential of 'Muscat of Alexandria'. In particular, a study on the identification of 41 free and 28 bound compounds in Muscat of Alexandria, using Gas Chromatography and Gas Chromatography-Mass Spectrometry (GC and GC-MS) revealed that the concentration of these compounds increased with skin contact in dry wines (Cabaroglu and Canbas, 2002). The influence of two different grape freezing techniques on the wine aroma was determined by Ruiz-Rodríguez *et al*. (2020). Ultrasound techniques were found to promote the release of terpenic compounds from the solid parts of grapes (Aragón-Garcia *et al*., 2021). Furthermore, 109 volatile compounds and their kinetics were studied in 'Muscat of Alexandria' musts during fermentation (Marinaki *et al*., 2023).

After fortification, Moscatel de Setúbal remains in maceration for a long period of time. The addition of neutral alcohol to stop fermentation influences the flavour thresholds of the wine compounds, affecting minimally the flavour of the product (Rogerson and De Freitas, 2002). However, wine spirit even freshly distilled has a pool of volatile compounds, such as aldehydes (Awad *et al*., 2017; Caldeira *et al*., 2021), influencing the final characteristics of the product, and are likely a factor that increases diversity in Moscatel de Setúbal.

Oxidative ageing provides also specific characteristics, already investigated in other wines, such as Porto (Vilela *et al*., 2020), Madeira (Pereira *et al*., 2011) or Jerez (Chaves *et al*., 2007), namely described as "madeirized" in the case of sweet fortified white wines (Cutzach *et al*., 2000). Among volatile compounds, sotolon (3-hydroxy-4,5-dimethyl-2(5H)-furanone) seems to play a key role in the typical aroma of Madeira wine (Câmara *et al*., 2004, 2006; Oliveira e Silva *et al*., 2008; Pereira *et al*., 2022; Perestrelo *et al*., 2023) and Porto Tawny wines (Ferreira *et al*., 2005). Sotolon is described as having nutty and spicy aroma (Prata-Sena *et al*., 2018) and its formation depends on oxygen and temperature (Martins *et al*., 2013).

To the best of the authors' knowledge, there are no studies on the volatile profile of Moscatel de Setúbal fortified wine.

Sensory characteristics

Moscatel de Setúbal must comply with the requirements established in the CVRPS internal regulations regarding colour, clarity, aroma and flavour, and according to the respective PDO Setúbal specifications (IVV, 2018a). In terms of colour, this wine is described as showing, before ageing, a dark yellow colour with occasional greenish reflections. Over time, the ageing process leads to a modification in colour, shifting to an orange-golden hue, amber, topaz, sometimes achieving a dark brown colour (Garcia, 2001; Salvador, 2010). Probably this non-enzymatic browning is a phenomenon arising from the Maillard reactions that occurs during ageing (Starowicz and Zieliński, 2019). These reactions involve a reducing sugar and an amino acid (Moreno *et al*., 2007; Francisquini *et al*., 2017; Starowicz and Zieliński, 2019), which are compounds widely available in this wine.

The aroma of sweet fortified wines submitted to thermal treatment is associated with Maillard reactions (Cutzach *et al*., 1999) and with caramelisation of sugars (Oliveira *et al*., 2011). Young Moscatel de Setúbal wines are characterised by their fruity and floral notes, with typical aromas including orange blossom and linden, with hints of honey, dates and orange (IVV, 2018a). Silva (2011) highlighted that Moscatel de Setúbal exhibit primary aromas of linden, apple, and quince, accented by floral hints. This combination creates "exuberant" wines, with a powerful, honeyed flavour, that is commonly much appreciated by consumers (Bravo *et al*., 2006). These wines are also noted for their "unprecedent acidity" (CVRPS, 2024). Older wines feature hints of dried fruits, like walnuts, hazelnuts, and raisins, along with spices and sour cherry and fig jams, with more complex notes of coffee and chocolate found in more aged ones (CVRPS, 2024). Garcia (2001) also mentions tea, bitter orange and cinnamon, along with complexity and persistence.

The older and Superior versions also reveal a velvety texture (CVRPS, 2024). Indeed, higher temperatures promote proanthocyanidins precipitation and depolymerisation, thereby increasing the wine`s mouthfeel sensation more rapidly (Jordão and Ricardo-da-Silva, 2019). Likewise, the oxidative ageing contributes to reduce astringency. According to Garcia (2001), due to the high degree of oxidation that occurs during wood ageing, these wines undergo minimal evolution after bottling — a behaviour commonly observed in other oxidatively aged fortified wines.

CONCLUDING REMARKS

Moscatel de Setúbal fortified wine is unique due to its winemaking process and ageing. The permitted variability in maceration time and ageing conditions allows to predict high diversity of wine characteristics. This diversity is of great interest to consumers, oenologists, and winemakers.

The long period of maceration promotes extraction of phenolic compounds, proteins and polysaccharides from grape skins to wine, most probably increasing the levels of these compounds in it, thus increasing the risk of physicochemical instability. This is another interesting aspect related to this fortified wine that requires a better understanding.

Given these considerations, a more detailed understanding of the influence of the vinification process on the chemical composition of the wine is essential to allow for potential adjustments in winemaking steps. Additionally, increasing knowledge about the oxidative ageing of this wine, considering factors such as ageing conditions and length, and their impact on the wine's physicochemical composition, phenolic profile, volatile constituents, and sensory properties is of paramount importance. For the latest purposes, future work on this wine could evolve NMR profiling and untargeted metabolomics for key markers identification. In addition, other analytical approaches like GC-MS and descriptive sensory analysis would be crucial for gaining a better understanding of its volatile profile. Enhancing the scientific knowledge about this wine is essential to ensure the recognition of its quality.

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