From Waste to Worth: Wine Lees Composition and Applications in Research and Industry

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Abstract

In oenology, the term “wine lees” refers to the sediment that settles at the bottom of wine containers (e.g., tanks, barrels, or bottles) after fermentation and during the ageing of wine. They consist mainly of biomass from yeast cells –also lactic acid bacteria–, grape solids, and particles of various compositions that precipitate out of wine over time. Wine lees are often used in the ageing process because of their antioxidant properties and the enhancement of the sensory properties of wine. In terms of quantity, wine lees are the second most abundant by-product of winemaking, after grape pomace. Recently, wine lees are increasingly being recognized as a valuable resource within the circular economy, being used for the production of bioactive compounds, biofuels, cosmetics, and organic fertilizers, among others. This approach not only contributes to the sustainability of the wine industry but also reduces the environmental impact of the waste generated during winemaking. This review provides an overview of the properties and potential uses of the wine lees reported to date.

Keywords: review, valorisation, circular economy, by-product, winemaking, bioeconomy

1. Introduction

Winemaking is a multistep process that involves the production of different by-products (Figure 1). From harvested grapes to wine, water waste and other solid residues are generated. Among the solid residues, grape pomace and wine lees are the most abundant (Braga et al., 2002). Wine lees are defined in the Regulation (EU) No 1308/2013 of the European Parliament and of the Council of December 17, 2013, establishing a common organisation of the markets in agricultural products and repealing Council Regulations as: *the residue (a) accumulating in vessels containing wine after fermentation, during storage or after authorised treatment; (b) obtained from filtering or centrifuging the product referred to in (a); (c) accumulating in vessels containing grape must during storage or after authorised treatment; or (d) obtained from filtering or centrifuging the product referred to in (c).* The composition of wine lees largely depends on the type of wine (white or red), the fermentation stage (alcoholic *vs.* malolactic), and the specific oenological practices applied during winemaking. Thus, different types of wine lees can be identified based on their origin.

Wine lees formed after alcoholic fermentation primarily consist of dead *Saccharomyces cerevisiae* yeast cells, grape pulp residues, tartaric acid salts (e.g., potassium bitartrate), proteins, and polysaccharides. Their pH typically ranges from 3.2 to 3.7. These lees are slightly turbid in appearance, usually beige or brown in white wines, and dark purple-red in red wines. Red wine lees contain heavier solids derived from grape skins and seeds, and are particularly rich in polyphenolic compounds. White wine lees are characterized by a lower polyphenol content, a higher tendency for protein precipitation, and the presence of finer suspended particles.

Wine lees from malolactic fermentation, which always follows alcoholic fermentation, are produced in smaller volumes than other lees. They mainly contain dead lactic acid bacteria (such as *Oenococcus oeni*), additional degraded yeast cells from alcoholic fermentation, and bacterial metabolites like diacetyl and lactic acid. These lees are generally more acidic due to lactic acid production and have a slightly lower pH than those formed during alcoholic fermentation.

Tertiary lees, also known as fining or aging lees, accumulate during wine clarification and stabilization processes. These include residues from fining agents (if they are used) employed to improve protein or polyphenol stability in wine, such as bentonite, casein, or egg whites. As a result, these lees may contain varying proportions of fining agent residues along with wine-derived compounds like proteins, polyphenols, polysaccharides, and tartrates. Their composition is highly variable, depending on fining agents used and typically contains less microbial biomass compared to primary and secondary lees. The graphical representation (Figure 1) provides an overview of the various origins of wine lees.

If not differently specified, in the continuation of this review the term “lees” refers to the residue accumulating in vessels containing wine after aging. Ageing on lees consists of keeping the wine for several months in contact with lees that settle at the bottom of the container. Periodical stirring maximizes contact with wine/lees and improves practice outcomes. The positive outcomes of this practice include improvements in the aromatic and gustatory quality of wine, as well as an increase in its physicochemical stability against colloidal precipitation, colour instability, and chemical oxidation (Rigou et al., 2021). During this prolonged contact, lees undergo an autolytic process (Alexandre & Guilloux-Benatier, 2006), where dead yeast cells undergo enzymatic self-degradation, leading to the release of cytoplasmic (proteins, peptides, amino acids, fatty acids, nucleotides) and parietal (mannoproteins, glucans, oligosaccharides) components into the wine (Fornairon-Bonnefond et al., 2003).

It is reported that wine lees can account for approximately 3.5 to 8.5% (w/v) of the used grape mass (Dávila et al., 2017). In this sense, the first works about this aspect, reported that lees and pomace represent the 20% (w/v) of the total volume of the fermented wines (Cantarelli et al., 1964), or that the production of 1 hL of wine, gives from 1.6 kg (Da Ros et al., 2016) to 5.5 kg of liquid lees at 4.5% (v/v) alcohol content (Cabras et al., 1997). Another estimation was performed in Cabras & Angioni (2000), where they estimated that from one kg of grapes 0.65 L of wine, 0.17 kg of cake and 0.055 kg of wine lees are produced.

Wine lees represent a residue with high soluble (Bio-) Chemical Oxygen Demand (COD and BOD)(Ehlinger et al., 1992), low pH, (Sancho-Galán et al., 2020) and moderate alcoholic content when collected after alcoholic fermentation or during wine ageing (Porto et al., 1993). Therefore, wine lees are considered environmental pollutants.

For the past 30 years, the focus of research on wine lees has been to study their contribution to wine quality, in terms of compounds released during ageing in contact with lees and their effects on wine aroma and mouthfeel. Currently, a new area of research is gaining significant attention: exploring innovative ways to repurpose this by-product, effectively giving it a second life (Balmaseda et al., 2024; de Andrade Bulos et al., 2023; De Iseppi et al., 2020; Poulain et al., 2024). However, the revalorisation of wine lees is far from being fully realized or effectively exploited. This is an important point, as the legal framework governs the current use of wine lees once they are produced. In this regard, the previously mentioned Regulation (EU) No. 1308/2013 also regulates the use of wine lees, restricting their application to the production of alcohol, spirits, or *piquette*. Additionally, Directive (EU) 2018/2001 of the European Parliament and of the Council of December 11, 2018, which promotes the use of energy from renewable sources, identifies wine lees as a type of feedstock for producing biogas for transport and advanced biofuels. The application of circular economy principles in winemaking, including the reuse of wine lees, has demonstrated significant reductions in environmental impacts, such as global warming potential and resource depletion, compared to traditional linear production systems (Ncube et al., 2021).

Given their richness in organic matter and high content of bioactive compounds, researchers have explored various promising applications of wine lees over the past decades. According to our research, from years 1939 to the end of 2024 the number of publications with the keyword "wine lees" goes up to about 783 scientific papers indexed on Scopus Database (Figure 2) and we found around 100 patents documents (97 patents from 1899 to 2019) of products related to the use of wine lees (de Andrade Bulos et al., 2023). Overall, there is an increasing trend in the number of publications on this subject (Figure 2A, B), mainly in the fields of Agricultural and Biological Science, Chemistry, Biochemistry, Engineering and Environmental Science (Figure 2C). It is also interesting to note that the leading countries in this subject are Spain, Italy, and France, contributing for the 31%, 16%, and 13% respectively of total publications.

The aim of this review is to summarize the current knowledge on the various uses of wine lees, with a focus on their composition and properties, as well as their applications across different fields, including winemaking, food industry, and energy production systems.

2. Wine lees composition

The composition of wine lees is highly variable, as it strongly depends on the type of grape and yeast used in winemaking, as well as the duration of the ageing process. Lees are primarily composed of a liquid phase rich in ethanol and organic acids, such as lactic or acetic acid (Dávila et al., 2017; Pérez-Serradilla & de Castro, 2008), and a solid phase consisting of microorganisms (mainly yeasts), grape solid particles, and to a lesser extent, tartaric acid, insoluble carbohydrates, phenolic compounds, lignin, proteins, metals, and organic salts. Nonetheless, most of the available information on lees composition is derived from studies examining their contribution to wine composition during ageing. In fact, most studies focus on the impact of lees constituents on wine, while very few studies have analysed their actual composition in lees. Articles reporting the composition of wine lees are summarized in the following paragraphs. Table 1 shows the global composition of wine lees described in various studies. The variability in the obtained data strongly depends on factors such as contact time, autolytic phenomena, and composition of the wine matrix from which the lees were obtained and recovered.

2.1. Polysaccharides

Llaubères et al. (1987) first described that wine was enriched in polysaccharides during alcoholic fermentation and ageing. This work was the first to define mannoproteins as mannans covalently linked to protein residues. The total amount of polysaccharides in white vinification is estimated to be 400 – 500 mg/L (Llaubères et al., 1987), which is the sum of the polysaccharides from grapes and those released by wine lees. The autolysis process that naturally occurs in wine lees determines the increase in polysaccharide and oligosaccharide concentrations of wine, and it depends on the yeast strain (Loira et al., 2013a; Martínez-Lapuente et al., 2018; Moine-Ledoux et al., 1997; Voce et al., 2024).

Particularly, during ageing on lees, the glycosyl residues –arabinose, rhamnose, mannose, and galactose– increase in wine, except for galacturonic acid, which slightly decreases, and glucose and myo-inositol remain at constant concentrations during ageing (Pati et al., 2010). The composition of polysaccharides is dependent on the origin of wine lees (white or red winemaking), ageing time (Pati et al., 2012), and grape variety (Martínez-Lapuente et al., 2018). In this sense, red wine lees present higher arabinose, galactose, and galacturonic acid glycosyl residue polysaccharides than white or rosé wine lees. In addition, polysaccharide concentration can be increased by the resuspension of wine lees, increasing the time of contact with wine or ageing at higher temperatures, which enhances the autolytic process (Llaubères et al., 1987; Loira et al., 2013b).

Apart from the linked sugar residues from polysaccharides, other free sugar residues can be found in wine lees (S. P. Ioannidouet al., 2022), such as glucose and xylose, together with some organic acids, such as succinic and acetic acids. Researchers have found higher concentrations of these compounds in lees from white wine (from Magalouzia cultivar) than in the red variety Grenache. In the same work, the GC-MS technique enabled the detection of various compounds, such as polyols, glycerine (1,2,3-propanetriol), and phenyl alcohols (S. P. Ioannidouet al., 2022).

2.2. Proteins, peptides and amino acids

During ageing of lees, wine is also enriched in proteins, peptides, and amino acids. Proteins constitute approximately the 15% (w/w) of the dry weight of wine lees (Gómez et al., 2004). Yeast intracellular proteases and carboxypeptidases are responsible for the release of these nitrogen-related compounds (Moreno-Arribas et al., 1996; M. Sato et al., 1997) in a yeast strain-dependent manner (Perrot et al., 2002). During autolysis, the dry weight of the lees decreases, while total amino acids, free amino acids, and extracellular proteins increase (Perrot et al., 2002), creating a significantly different amino acid profile in long-term-aged wines (Sartor et al., 2021). In general, the protein concentration in wine seems to be constant at approximately 15 mg/L (Luguera et al., 1998); however, this is due to the equilibrium between protein release and protein degradation during autolysis. Rowe et al. (2010) investigated the origin of these released proteins and observed that the initial proteins originated from the cytosol, followed by those from the cell wall. Furthermore, cytosolic proteins degrade over extended periods of ageing, whereas proteins derived from the cell wall remain stable.

Peptides are released from lees and degraded during wine ageing because of the spontaneous action of yeast enzymes. Not only are peptides released, but proteins are also hydrolysed into shorter peptide fragments (Moreno-Arribas et al., 1996). Protease activity was detected after six months of storage (Moreno-Arribas et al., 1996; M. Sato et al., 1997), even when the enzymatic activity was higher at the beginning. De Iseppi, Rocca, et al. (2024) observed a rapid increase in peptide concentration during the first two months of wine aging on lees, followed by a stabilization phase in which the overall concentration was maintained, while peptide diversity decreased. Most of the peptides identified were derived from yeast proteins associated with glycolysis and stress response mechanisms.

2.3. Lipids

Approximately the 5% of the dry weight of wine lees is composed of lipids that originate from both grape seeds and yeast cell walls (Gómez et al., 2004). Among them, the most abundant lipids were sterols (25.2%), glycolipids (18.2%), and sterol esters (15.9%). In addition, fatty acids (11.2%) are primarily composed of 16- and 18-carbon chains, which correlates with the origin of yeast-derived fatty acids in wine lees. Gómez et al. (2004) reported that lees from sherry wine contain palmitic acid (C16:0), linoleic acid (C18:2), and stearic acid (C18:0). In addition, the origin of wine lees (Sancho-Galán et al., 2020), whether white, rosé, or red winemaking, significantly influences their fatty acid composition, as observed for wine lipid composition (Balmaseda et al., 2021).

2.4. Polyphenols

The polyphenolic composition of wine lees is highly dependent on the grape cultivar, degree of maturity, geographical origin, vinification process, and duration of maceration/extraction (Zhijing et al., 2018). Additionally, within the diverse family of phenolic compounds, it is noteworthy that specific compounds are uniquely associated with different wine by-products. In this regard, Costa-Pérez et al. (2023) identified 59 phenolic compounds exclusive to wine lees, distinguishing them from those found in other by-products.

As an example, the total polyphenolic index for a red Pinot Noir wine lees vary from 17.3 ± 0.4 to 40.9 ± 1.6 mg/g of dry matter, that is higher than the same variety in rosé vinification (from 9.8 ± 0.2 to 10.5 ± 0.5 mg/g of dry matter), or for white wine lees (from 3.1 ± 0.2 to 10.3 ± 0.4 mg/g of dry matter)(Zhijing et al., 2018). Interestingly, the same authors reported no significant differences between rosé wine lees with different maceration durations (Zhijing et al., 2018). In contrast, the time of wine lees collection seems to modify their composition. Recently, Giacobbo et al. (2019) showed that wine lees collected from the first racking had higher solid matter concentrations but less phenolic amounts in comparison to lees obtained from the second racking. Specifically, wine lees from the second racking had approximately 700 mg/kg (lees dry matter) of anthocyanins and 3300 mg/kg of phenolic compounds, whereas those from the first racking had approximately 400 mg/kg of anthocyanins and 1600 mg/kg of phenolic compounds. Similarly, Bustamante et al. (2008) reported that wine lees can contain between 1.9 and 16.3 g of polyphenols/ kg (lees dry matters) depending on the wine type and winemaking practices.

Delgado de La Torre et al. (2015a, 2015b) showed a complex phenolic composition in wine lees, in which the most abundant phenolic compounds were flavonoids. The polyphenols in wine lees are adsorbed from wine on yeast cell walls during winemaking (Salmon et al., 2002). However, polyphenols are more likely to be found in wine than in wine lees (Devi & Anu-Appaiah, 2020).

Mazauric & Salmon (2005) analysed of the remnant polyphenols in wine after ageing indicated that some polyphenols can be adsorbed on the surface of yeast lees following biphasic kinetics. An initial and rapid fixation is followed by a slow, constant, and saturating fixation that reaches its maximum after approximately 1 week. Very few monomeric phenolic compounds remained adsorbed on yeast lees, and no preferential adsorption of low- or high-polymeric-size tannins occurred. The remnant condensed tannins in the wine contained fewer epigallocatechin units than the initial tannins, indicating that polar condensed tannins were preferentially adsorbed on yeast lees. Conversely, the efficiency of anthocyanin adsorption onto yeast lees is unrelated to its polarity. According to Vasserot et al. (2003), anthocyanin adsorption by yeast lees occurs slowly and incompletely, likely because of diffusion limitations. Regardless of the yeast lees concentration, the amount of anthocyanin adsorbed increased linearly with the initial anthocyanin concentration, indicating no saturation of the adsorbent. This suggests that the adsorption process is governed by a partition equilibrium between the anthocyanins adsorbed on the yeast walls and those remaining in the solution. This equilibrium is unstable and can quickly shift toward desorption or additional adsorption with changes in the anthocyanin concentration in the medium, implying that the interactions between anthocyanins and yeast walls are likely weak. Some studies have determined that up to 26 anthocyanins are present in lees samples (Jara-Palacios, 2019). Recently, López-Fernández-Sobrino, Soliz-Rueda, et al. (2021) and Romero-Díez et al. (2018) observed that malvidin-3-glucoside was found to be the most abundant compound in wine lees. Masino et al. (2008) observed that catechin can easily be adsorbed by wine lees, representing the 50 – 62% of the total terminal units of proanthocyanidins extracted from lees (Zhijing et al., 2018). Epicatechin and epigallocatechin were also found in lees, with a predominance in red wine lees. Moreover, low trans-resveratrol, *cis* and *trans*-resveratrol-3-glucoside concentrations can be detected in wine lees (Del Barrio-Galán et al., 2012).

2.7. Microelements

The most abundant microelements in winemaking byproducts (grape pomace, grape stems, and wine lees) are potassium (K), sodium (Na), magnesium (Mg), phosphorus (P), and calcium (Ca) (Bica et al., 2020a). In a recent paper, Sancho-Galán et al. (2020) did a complete study of the microelements of three different, where wine lees were classified according to the type of winemaking of origin (Table 2).

In the case of wine lees, the proportion of these elements was lower than that of other byproducts. For example, for K, the amount found in lees represents only 3% (w/w) of the total, while in marc and wine represents 27% and 70%, respectively (Bica et al., 2020). In addition, the microelement composition of wine lees appears to be very heterogeneous, as pointed by Bustamante et al. (2008) when analysing the composition of 12 wine lees coming from different wineries. Viticultural and oenological practices have a strong impact on microelement composition, mainly because of the use of phytosanitary treatments. According to Suhaj & Koreńovská (2006) the Chromium (Cr) (0.2 mg/kg of dry matter) and the Tin (Sn) (0.12 mg/kg of dry matter) are more likely found minerals in wine lees, whereas others as Cobalt (Co), Lithium (Li), and Vanadium (V) are more homogeneously found in all the wine by-products. Ca and Mg are also more likely found in wine lees, but more abundant in press cake.

3. Oenological properties of wine lees

Ageing on lees is beneficial for the chemical and sensory properties of wine (Fornairon-Bonnefond et al., 2001). This practice helps improve the structure, roundness, and body of wines (Alexandre, 2022), while also reducing their astringency and bitterness (Del Barrio-Galán, Pérez-Magariño, & Ortega-Heras, 2011). The following paragraphs discuss various studies on wine ageing of lees and their impact on wine quality.

3.1. Impact of ageing on lees on chemical stability of wine

The role of mannoproteins from wine lees in the chemical stability of wine was well reported (Ledoux et al., 1992). These authors demonstrated the impact of ageing on the protein and tartaric stability of white wines. A 32 kDa N-glycosylated mannoprotein, corresponding to an *S. cerevisiae* invertase fragment, was identified to be responsible for this stability. In addition, the presence of lees was not sufficient to increase mannoprotein content, but resuspension of lees by stirring (*bâtonnage*) significantly enhanced the quantity of macromolecules extracted into the wine.

In sparkling wines produced by re-fermentation in bottle (*Champenoise* method), autolysis is a key step and a source of polysaccharides, mannoproteins and proteins, affecting taste, mouthfeel and foam properties of wine (Alexandre & Guilloux-Benatier, 2006; Pons-Mercadé et al., 2022). Pons-Mercadé et al., (2022) studied the autolysis of yeast lees in sparkling wines (Cava) and followed the wines during nine consecutive vintages. This study confirmed that yeast contributes to enriching sparkling wines with key macromolecules, such as polysaccharides and proteins, but in low proportions compared to the usual concentrations found in sparkling wines. While lees release these macromolecules, their concentration does not clearly increase over time (during ageing), likely due to simultaneous removal by other processes, such as adsorption or enzymatic degradation.

3.2. Impact of ageing on lees on wine colour

Lees are known to interact with and adsorb certain phenolic compounds found in wines. This adsorption was mainly due to the presence of yeast cells and their fragments. It has been specifically demonstrated that anthocyanins, the coloured pigments in wine, are adsorbed onto the yeast cell wall (Morata et al., 2005). This phenomenon, which gives them decolorizing ability, was observed by Vasserot & Maujean (1998) during experiments on musts of Pinot Noir from the Champagne region. Other phenolic compounds in wine, such as condensed tannins, are also adsorbed by lees, particularly the more polar condensed tannins. However, very few monomeric phenolic compounds are adsorbed onto yeast cells (Mazauric & Salmon, 2005, 2006; Salmon, 2006).

Depending on the polyphenolic composition, the browning of wine during ageing in contact with lees has been reported by several authors. Ibern-Gomez et al., (2000) studied this phenomenon in sparkling wine made from Macabeo, Xarel·lo, Parellada, and Chardonnay cultivars. The analysed Cavas analysed suffered colour changes during ageing in contact with lees, due to the oxidation of phenolic compounds. Cultivars seem to influence browning: Chardonnay Cavas were the most susceptible to oxidation during ageing. Hydroxycinnamates, were the group of phenols most susceptible to oxidation such as *trans*-caftaric acid, *cis*-caftaric acid, and 2-S-glutathionyl- caftaric acid.

3.3. Impact of wine ageing on lees on sensory properties of wines: aroma and taste

The volatile contribution of wine lees has been studied extensively. It might be easy to relate an enhancement of volatile composition in wines aged in the presence of lees, due to an eventual release of adsorbed volatiles, or even their production by viable yeast cells. Some authors have observed an increase in wine volatile compounds in the presence of lees (Bueno et al., 2006; Masino et al., 2008; Pati et al., 2012b; Pérez-Magariño et al., 2015; Rodríguez-Bencomo et al., 2010) by a general increase in ethyl and lactic esters, higher alcohols, acetic esters, fatty acids, terpenes, and lactones (Bautista et al., 2007; Bueno et al., 2006; Loscos et al., 2009).

Jiménez Moreno & Ancín Azpilicueta (2007) reported the retention of volatile compounds by wine lees during ageing in oaks. The compounds with the highest affinity for lees were eugenol, 4-propylguaiacol, 4-methylguaiacol, furfural, and 5-methylfurfural (smoky and toasted aromas). In addition, their results showed that lees could also bind other compounds important for aroma in aged wine, such as oak lactones (coconut aroma), to a lesser degree. Guaiacol and g-nonalactone were the only compounds that could not be bound by the lees (Jiménez Moreno & Ancín Azpilicueta, 2007).

Karagiannis & Lanaridis (2000) and Lavigne (1995) investigated the effect of white wine conservation conditions on the levels of volatile sulphur compounds (thiols). They found that the amount of these compounds is influenced by whether the wine is stored in barrels or stainless-steel tanks, the duration of contact with lees, and the overall conservation period. Racking wines immediately after alcoholic fermentation and storing them in tanks or barrels does not lead to a reduction in odours within the first two days. In contrast, keeping wines on total lees for the same period significantly increased sulphur compounds (such as H_2S, CS_2, DMS, methanethiol, methional, and their derived compounds), potentially causing olfactory defects (Karagiannis & Lanaridis, 2000). However, aeration can reduce the quantity of these volatile sulphur compounds (Lavigne, 1995). Similar observations concerning ethanethiol and methanethiol have already been reported by Ledoux et al. (1992). With no exception for volatile compounds, the origin of wine lees and the vinification process have a strong impact on the volatiles released in wine. Indeed, it has been found that lees from different yeast strains have varying abilities to release volatile compounds from their precursors (Del Barrio-Galán, Pérez-Magariño, Ortega-Heras, et al., 2011).

Finally, contact between lees and dry wines also influences the release of non-volatile compounds that affect the taste of wine. Certain proteins, peptides, and free amino acids resulting from yeast hydrolysis possess taste properties, such as bitterness, umami, and sweetness (Sirisena et al., 2024). Marchal et al. (2011) demonstrated the contribution of the Hsp12 protein (12 kDa) to the perception of sweetness after yeast autolysis in wine. Other studies have also revealed that certain compounds from yeast can enhance the perception of the intensity of other flavours, known as kokumi substances (Chang et al., 2022). These compounds, present in wines, are partly responsible for some of the properties attributed to ageing on lees.

3.5. Antioxidant properties of lees during ageing

The antioxidant properties of wine lees have been demonstrated, particularly during ageing. Although these properties are often attributed to the content of adsorbed polyphenols (Jara-Palacios, 2019; Morata et al., 2005; Vasserot et al., 1997), these compounds do not necessarily reflect the intrinsic antioxidant potential of lees during wine ageing. Early studies on the antioxidant properties of lees have highlighted their ability to consume oxygen under simulated ageing conditions (Fornairon et al., 1999; Salmon et al., 2000). This oxygen consumption is not related to persistent cell viability but rather results from the involvement of the lipid fraction of lees, particularly sterols and ergosterol (Fornairon-Bonnefond & Salmon, 2003; Salmon, 2006). However, the ability of lees to bind oxygen alone does not fully explain their protective effect against the premature oxidation of aroma in white wines (Ribéreau-Gayon et al., 2006).

During ageing, lees release highly reducing substances that limit oxidative phenomena. In this regard, the research of Dubourdieu & Lavigne-Cruege (2004) highlighted the preservation of significant concentrations of glutathione (GSH) in white wines aged on lees. This peptide, with antioxidant properties, is present in grapes and is also released by yeast after alcoholic fermentation. Its content in wine is related to pressing conditions as well as the yeast strain responsible for fermentation, with concentrations sometimes below the quantification threshold, and in some cases, reaching up to 70 mg/L after fermentation (Fracassetti et al., 2011; Kritzinger et al., 2013). The role of glutathione in protecting the aroma of white wine is well established (Lavigne et al., 2007). More specifically, during ageing on lees, glutathione helps prevent the detrimental effects of oxidation on wine aroma (Lavigne et al., 2007; Ribéreau-Gayon et al., 2006). Its free sulfhydryl group (-SH) provides reducing and nucleophilic properties, which are thought to be responsible for its protective effect against oxidation chain reactions (Kritzinger et al., 2013). That is why, some yeast extract derivates are used in winemaking to protect wine from oxidation. However, De Iseppi, Curioni, et al. (2024) demonstrated that wine lees exhibit an antioxidant activity comparable to extracts obtained from the same yeast strain grown under optimal conditions in lab, highlighting their potential as an alternative to commercial antioxidant products. Interestingly, wine lees retain their antioxidant properties even after extraction and oxidation, whereas a model flavonoid solution loses them, indicating that these properties are not solely attributable to flavonoids, but also to another compounds (Ye et al., 2023).

Moreover, yeast autolysis leads to the release of cell wall constituents such as glucans and mannoproteins (Fornairon-Bonnefond et al., 2001). These mannoproteins are then hydrolysed by the proteases present in the medium (Charpentier & Freyssinet, 1989). The work of Jaehrig et al. (2007) demonstrated that products resulting from hydrolysis of the yeast cell wall possess antioxidant activity. In particular, hydrolysis of mannoproteins and cell wall proteins leads to the release of antioxidant peptides (Jaehrig et al., 2008). Similar results were obtained by Alcaide-Hidalgo et al. (2007), who showed that yeast autolysis under model wine conditions led to the increased release of both hydrophilic and hydrophobic antioxidant peptides. More recently, a study of the antioxidant metabolome of white wines conducted by (Romanet et al., 2023) revealed an increase in sulphur (-S) and nitrogen (-N) compounds in wines aged on lees, likely due to the release of antioxidant peptides.

4. Valorisation of wine lees

The generation of residues or by-products in the production of any food and beverage industry is directly related to quick recycling and residue management. During winemaking the processing of one ton of grapes generates around 0.06 tons of wine lees, that represents the second most important waste (10%) after grape marc (25%) in terms of quantity. Studies on wine lees management have been conducted since the early 90's (Ehlinger et al., 1992). The complexity in composition, and more precisely its high concentrations of Chemical Oxygen Demand (COD) of approximately 30,000 mg/L, suspended solids, polyphenols, heavy metals, and low pH, make wine lees a difficult residue management with high environmental impact as a pollutant (Da Ros, Cavinato, Pavan, et al., 2014; Ehlinger et al., 1992; Montalvo et al., 2020). Thus, the management of wine lees is still being explored, with distillation remaining the primary use. The various stages of winemaking can significantly affect the composition of wine lees, thereby influencing their potential applications (Figure 3). The following paragraphs address the various ways in which lees can be recycled in different sectors (Table 3) by different processing technologies (Figure 5). First, studies on the valorisation of wine lees through distillation and anaerobic digestion will be described, as these are the most common methods of utilization. Next, we present an overview of the valorisation of lees, focusing on the valuable properties of their extracts and exploring the various applications of lees and their extracts across different sectors.

4.1. Distillation of lees

Wine lees can be valorised by recovering their alcohol by distillation, particularly to produce various alcoholic beverages. Here are the general steps of this process: (i) collection of wine lees, (ii) re-fermentation to release more alcohol, and (iii) distillation. Distillation separates volatile compounds, including alcohols, from solid residues. The final product is a distillate, which can be used as a base for various alcoholic beverages.

Depending on the desired final product, distillate can be aged in wooden barrels to develop additional flavours and characteristics. It is worth noting that the quality of the final product depends on many factors, including the quality of the wine lees, fermentation, and distillation processes. Some producers use wine lees as the main ingredient for specific spirits, whereas others combine them with other ingredients to create more complex blends. The reuse of wine lees in distillation can help reduce waste and create unique and interesting spirits. The by-products obtained after distillation (*vinasses*) contain extractable compounds that can be further exploited.

Recently, a pilot-scale solar still was proposed for recovering water from wet wine lees and concentrating the solid fraction enriched in bioactive compounds through solar distillation (Mastoras et al., 2023), representing a promising and sustainable methodology for future applications.

4.2. Anaerobic digestion

Researchers have developed different strategies to anaerobically digest wine lees and other winemaking by-products to obtain less environmentally damaging residues while simultaneously producing energy. Anaerobic digestion is a biological process in which microorganisms break down organic matter, such as waste or biomass, in the absence of oxygen, to produce biogas and digestate. In this context, as a biorefinery is a facility that converts biomass into a variety of valuable products, such as biofuels, chemicals, and materials, aligning with the principles of Circular Economy and guided by Life Cycle Analysis, biorefining wine waste has emerged as a promising approach for transforming wine lees into valuable raw materials (Cortés et al., 2019; Hungría et al., 2021).

The use of wine lees for composting has also been described. The composting process is the natural biological decomposition of organic matter, such as food scraps, yard waste, and agricultural residues, by microorganisms in the presence of oxygen. During this aerobic process, bacteria, fungi, and other decomposers break down organic material into humus, a nutrient-rich substance that can be used to improve soil quality. In 2013, Paradelo et al. (2013) first described the composting process of winery wastes, including spent grape marc and wine lees, in the laboratory for five months. After the process, the initial phytotoxicity decreased rapidly and the pH increased close to neutrality during the first two-three months. The described composting was performed in batch, under mesophilic temperature (20-45°C), not reaching the thermophilic range. Interestingly, the most promising winery by-product for anaerobic digestion are wine lees (Da Ros et al., 2017), with an estimated potential of 0.37 N m^3CH_4/kg volatile solid fed. Indeed, the amount of biogas generated from wine lees digestion is sufficient to cover the management costs and the necessary energy of the production plant (Da Ros et al., 2016; Montalvo et al., 2020b). Therefore, there is an increasing interest of using wine lees in anaerobic digestion, and it has been proposed the co-digestion of waste activated sludge and wine lees as economic advantageous approach, as it could also produce energy as biogas – up to 0.4 N m^3/kg COD fed, 65% CH_4 – (Cavinato et al., 2014). This approach was further developed at the pilot scale, producing similar biogas yields but reaching a thermophilic temperature (Da Ros, Cavinato, Pavan, et al., 2014). Authors observed a good stabilization level and a reduction of 60% of total and volatile solids. In addition, the concentrations of pollutants and heavy metals were significantly reduced even if the raw wine lees presented high concentration of these compounds. Because lees polyphenols have a negative effect on the microbiota during digestion, the removal or extraction of these compounds has been proposed as a pre-treatment to increase biogas yield (Da Ros, Cavinato, Cecchi, et al., 2014; Nikolaidou et al., 2016). Other approaches, such as electro-oxidation and the addition of biochar to the anaerobic digestion of wine lees, have been investigated to increase biogas production (Arenas Sevillano et al., 2020), even if some authors did not show an improvement in biomethane production when adding biochar (Chiappero et al., 2023). Another approach to improve anaerobic digestion using lees was proposed in García Álvaro et al. (2024) and Lanfranchi et al. (2025), in which the addition of microparticles – iron- (magnetite) or carbon(graphite)-based microparticles– shoed increases in methane production of more than a 30%. During the process, microparticles help to mitigate the effects of accumulation of toxic compounds as phenolic compounds, fatty acids, and low pH.

In addition, heavy metals from vine treatments can compromise lees digestion. Therefore, white wine lees from ecological crops appear to be more beneficial for the maintenance of methanogenic archaea (Hungría et al., 2020). Acetate can also be produced by anaerobic digestion from wine lees (red and white) with the endogenous microbiota or inoculating specific microorganisms (Lanfranchi et al., 2025).

Furthermore, wine lees have been used to produce electrical energy in microbial fuel cells (MFC)(Pepe Sciarria et al., 2015). These authors observed that higher yields of electricity were obtained with white wine lees due to the inhibition of electron transfer bacteria attributed to red wine lees polyphenols. Nevertheless, polyphenols from lees can be used for solar energy exploitation. Meneghetti et al., (2020) designed a low-cost photovoltaic device in which polyphenols derived from red wine lees were adsorbed on nanostructured ordered mesoporous titanium dioxide. They obtained a comparable photocurrent density and photovoltage to other organic dye-sensitized solar cells produced with other vegetables and fruits.

Peng et al. (2021) proposed an innovative wine lees-based porous carbon framework for use in symmetrical supercapacitors, achieving a stable voltage window and high energy density. This eco-friendly approach highlights the originality and promise of wine lees valorisation for developing sustainable, high-performance energy storage solutions.

4.3. Extraction of high added value compounds from wine lees

The direct valorisation strategy for a by-product is the extraction and recovery of its high value compounds. Most studies (66%) have concentrated on extracting bioactive compounds from lees obtained after alcoholic fermentation, whereas only 33% have explored lees derived from malolactic fermentation (Melo et al., 2024).

Tartaric acid has traditionally been recovered from wine lees (red or white) mainly after distillation (vinasse). Tartaric acid is an important acidifier used in different applications such as food, beverages, pharmaceuticals, cosmetics, and the chemical industry. Its recovery consists of the first solubilization in liquid from wine lees, followed by a crystallization process, in which tartaric acid is recovered as calcium tartrate (Salgado et al., 2010). The solubilization of tartaric acid is typically performed under acidic conditions in the presence of HCl (Salgado et al., 2010) or H_2SO_4 (Kontogiannopoulos et al., 2017). It can also be extracted with water, thereby avoiding the use of other chemicals (Kontogiannopoulos et al., 2016). After solubilization, solubilized tartaric acid can be further concentrated using nanofiltration (1 kDa molecular weight cut-off threshold) (Kontogiannopoulos et al., 2017), and cation exchange resins (Kontogiannopoulos et al., 2016). Tartaric acid can be also recovered from vinasses in the form of tartaric acid crystals and calcium tartrate. The residual streams generated in this process can be used as economic nutrients to produce xylitol by *Debaryomyces hansenii* (Salgado et al., 2010).

Among the highly valuable compounds of wine lees, phenolic compounds are the most studied and appreciated due to their highly diverse applications. As previously described, the stage at which these lees are generated impact the performance of bioactives compounds extracted. It was highlighted that red lees obtained after malolactic fermentation (Mir-Cerdà et al., 2023; Umsza-Guez et al., 2023) contain higher levels of phenolic acids and anthocyanins compared to red lees collected after alcoholic fermentation (Giacobbo et al. 2019).

The conventional solubilization of phenolic compounds from lees is generally performed in a hydroethanolic solution (mostly between 50-70%, v/v). These studies account for approximately 70 % of the published articles, and in recent years, new extraction techniques have been increasingly studied and applied to wine lees. Among these, ultrasound-assisted extraction is reported in 31 % of the studies, microwave-assisted techniques in 28 %, enzymatic processes in 6 %, membrane separation in 31 %, eutectic solvents in 4 %, supercritical and pressurized fluids in 4 %, and combined methods in 6 % (Melo et al., 2024).

Kopsahelis et al. (2018) reported the importance of pre-treatments in a biorefinery to improve the extraction yields of both polyphenols and tartaric acid. First, ultrasound was proposed as a technique to enhance polyphenol extraction yield (Tao et al., 2014) and antioxidant activity or bioactive related compound extraction (Dujmić et al., 2020) compared to conventional extraction with organic solvents. Microwave-assisted extraction has also been tested as a pre-treatment (Arboleda Meija et al., 2019; Matos et al., 2019), and optimized (Tagkouli et al., 2022) for polyphenol extraction. Other research compared the efficiency of some pre-treatments as in Romero-Díez et al. (2019), where they found that microwave pre-treatment increased the extraction yield, whereas ultrasound had no clear effect. In contrast, Tapia-Quirós et al. (2020) considering investment and operational costs, ultrasound-assisted solid-liquid extraction can be proposed for future scale-up evaluation. Moreover, as an alternative to conventional solvents, other natural deep eutectic solvents (NaDESs) can be used, coupled with ultrasound- assisted extraction (Bosiljkov et al., 2017). Other pre-treatments found in the literature are pressurized liquid extraction (Tapia-Quirós et al., 2020), or ultrasonic and enzymatic assisted extraction (Arboleda Mejia et al., 2020). In this way, ultrasound-assisted extraction using water and ethanol as solvents has been proposed as an efficient method to recover bioactive compounds from wine lees, operating at low temperature (30ºC) and requiring only 15 minutes (De Luca et al., 2023). Other possible strategies compromise the induced lysis by combining mechanical and physical treatments (Cotârleț et al., 2025) or the recovery via non-ionic polymeric resins (Gaglianò et al., 2025). Overall, these innovative extraction methods have demonstrated significantly higher yields compared to conventional techniques like maceration. Among them, ultrasound-assisted extraction stood out as the most effective, particularly when used as a complementary approach, offering superior recovery of bioactive polyphenolic compounds from wine lees due to its ability to disrupt cell walls and enhance solvent penetration (Melo et al., 2024).

Once polyphenols have been extracted, these extracts can be further concentrated using membrane technology. Because these extracts are rich in colloids, an initial clarification step using a microfiltration membrane is recommended (Cassano et al., 2019; Giacobbo et al., 2017), or even filtration through a 2 mm nylon fibber (Arboleda Mejia et al., 2020). Then, green chemistry and circular economy approaches can be used to further concentrate the bioactive compounds. This approach allows the use of water as a solvent, eliminating the need for other, less desirable solvents (Cassano et al., 2019; Tapia-Quirós, Montenegro-Landívar, Reig, et al., 2022). The nanofiltration membranes present a high rejection coefficient for polyphenols; thus, preferably find them in the retentate, which can reach up to 99% of retention for anthocyanins (Cassano et al., 2019b). Cellulose acetate membranes can also exhibit good rejection of phenolic compounds and low sugar levels, enabling their selective separation (Arboleda Mejia et al., 2020). Membrane-based schemes are multifunctional, and their setup can be used to purify different fractions.

Giacobbo et al. (2017) reported a microfiltration membrane followed by nanofiltration to obtain a concentrated solution of red wine lees from second racking with a high antioxidant capacity. Moreover, with the aim of separating polyphenols and polysaccharides, an intermediate ultrafiltration membrane allows their separation, as polysaccharides are retained by the ultrafiltration membrane, and then polyphenols by the nanofiltration membrane, retaining more than the 90% of the total polyphenols (Mejia et al., 2022; Reig-Valor et al., 2024). This has also been reported as a promising result for reverse osmosis, comparable to those obtained with nanofiltration (Tapia-Quirós, Montenegro-Landívar, Reig, et al., 2022). Other configurations include polyvinylidene difluoride membranes in line with ultrafiltration using poly-acrylonitrile and polyether sulfone membranes of 5 and 30 kDa) (Mir-Cerdà et al., 2023). In general, the application of polyphenols extracted from lees is related to the production of antioxidants in different industrial fields (Tapia-Quirós, Montenegro-Landívar, Vecino, et al., 2022).

Gómez et al. (2004) studied and developed a methodology for the characterization of lipids from the lees of sherry wine in food as antioxidants. Lipid content, extractability, and fatty acid composition were determined to evaluate their potential use as food or food additives. The major fraction of lipids from lees of Sherry wine was formed by sterols (about 25%), followed by the glycolipids and sterol esters (18 and 16%, respectively), and the minor fraction corresponded to the phospholipids. Squalene, a natural triterpene largely used in pharmaceuticals (used as a strategy to prevent, control, or treat diseases), was found in wine lees (Naziri et al., 2012). In this study, squalene was extracted using supercritical CO_2 ($scCO_2$) (Naziri et al., 2016) with ultrasonic pre-treatments to increase the extraction yield. Using $scCO_2$, the total squalene content in the extracts was found to be 16.9 g/kg of lees, a value comparable to that obtained using ultrasound-assisted extraction (20.4 g/kg of hexane extract) or a reference method (acid-assisted extraction using organic solvents) (17.6 g/kg). In addition to being a solvent-free process, a key advantage of supercritical extraction over other conventional extraction methods is the lack of oxidation products.

Recently, Winstel et al. (2024) an optimized method was proposed to extract and analyse glutathione (GSH, a tripeptide with high antioxidant activity) from white wine lees recovered after alcoholic fermentation. Using an experiment based on the Box-Behnken design, several parameters, such as the type of solvent, extraction time, and solid–liquid ratio, were optimized. The results showed that the main factor influencing the extraction efficiency was the ethanol concentration. Optimal and sustainable conditions for the highest GSH content were obtained using a water solution containing 10 g/L of lees for 105 min. Similarly, Poulain et al., (2024) showed an optimized method for the extraction of antioxidant compounds from white wine lees (racked after alcoholic fermentation) using subcritical water. Thus, due to the presence of various families of antioxidant compounds (polyphenols, lipids, and peptides), these studies highlight the potential of wine lees as a novel source of antioxidants for applications in food, nutraceuticals, pharmaceuticals, and cosmetic products.

The recovery of yeast cell wall polysaccharides for the extraction of glycol-compounds, such as mannoproteins, could represent another way for valorisation of wine lees. In 1999, Moine-Ledoux & Dubourdieu (1999) isolated a fragment of *S. cerevisiae*'s invertase enzyme (Glucanex®) that is used for protein stabilization of wines. This process was applied at the industrial level to produce a haze-protective additive for winemaking. Recently, wine lees from red and white winemaking have been used as emulsifiers in foods by De Iseppi, Marangon, Lomolino, et al. (2021). In this study, mannoprotein precipitation with ethanol was used to obtain the β-glucan fraction that had a thickening action. In addition, De Iseppi, Marangon, Vincenzi, et al. (2021) showed that with three methods, enzymatic hydrolysis, ultrasonication, and autoclaving, it is possible to efficiently extract glycol compounds. Nevertheless, each method allowed the extraction of glycol-compounds of different natures with different potential applications. Autoclave-derived extracts were more suitable for tartrate stabilization, whereas ultrasonicated and enzymatic methods were more effective in stabilizing the proteins of heat-unstable wines. More specifically, Varelas et al. (2016) extracted ß-glucans from wine lees and recovered as insoluble ß-glucans. This study used a combination of autolysis and hot NaOH treatment to extract β-glucans. The content of β-glucans extracted from red wine lees was found to be lower (29%, w/w) than that extracted from white wine lees (43%, w/w). The difference in extraction yields seems to be linked to the presence of polyphenols in red wine lees, which inhibit endogenous glucanase. Besides, the ß-glucan content can vary from 2.77 to 39.36% depending on the variety and winemaking technology (Chioru 2024).

Another interesting property of wine lees extracts from Japan white grapes of the Niagara variety is their antimicrobial activity. Photo-irradiated aqueous extracts from wine lees generate reactive oxygen species (ROS) at a sufficient concentration to exhibit antimicrobial effects against bacterial species, such as *Staphylococcus aureus* and *Pseudomonas aeruginosa*, or yeasts, such as *Candida albicans* (Tsukada et al., 2016). These wine lees extracts could be an alternative to H_2O_2 in the food industry.

It is worth noting that the wine lees analyzed across the selected studies underwent various pretreatment steps, with sample drying being particularly prominent. Notably, in 50 % of the reviewed works, freeze-drying was employed prior to extraction, leading to markedly higher yields of bioactive compounds when compared to traditional convection drying techniques.

Currently, high-performance liquid chromatography (HPLC) is frequently employed for the analysis of extracted compounds, such as polyphenols or antioxidant peptides like glutathione. However, further research is needed to develop comprehensive analytical methods that can characterize wine lees from various origins and support the selection of appropriate valorisation strategies based on their specific bioactive compound profiles. The development of such precise and standardized techniques would enable a more controlled and targeted use of wine lees in various applications.

4.4. Production of microbial biomass for fermentation

The high nutrient and nitrogen availability of wine lees have been extensively used for microbial propagation and fermentation (Pérez-Bibbins et al., 2015). Researchers have evaluated the potential of wine lees as a nitrogen source in defined media to propagate different lactic acid bacteria (LAB). It was observed that white wine lees, especially after distillation, were the most suitable for the growth of some *Lactobacillus* sp. in a medium containing 100 g/L glucose and 20 g/L wine lees (Bustos et al., 2004a, 2004b). The effect of tartaric acid present in wine lees on the growth of *Lactobacillus pentosus* was also examined. It was concluded that *L. pentosus* could grow with or without tartaric acid and simultaneously produce lactic acid (B. Rivas et al., 2006). The growth of *Lactococcus lactis* commonly used in the dairy industry was also promoted with wine lees as a nitrogen source using distilled wine lees, and the microorganism efficiently produced lactic acid and biosurfactants; thus, wine lees represent an alternative economical culture medium (Rodríguez et al., 2010). Recently, wine lees have been used in culture medium formulation as alternative to commercial yeast extract for *S. cerevisiae* and *Lactiplantibacillus plantarum* growth with diverse but promising results (Kokkinomagoulos & Kandylis, 2024).

Wine alcoholic fermentation can also be promoted with extracts coming from white wine lees. Onetto et al. (2024) showed that the addition of autolysis or enzymatic-treated lees can significantly reduce fermentation duration due to an increase in amino acids and trace elements, supporting its use as an alternative to commercial yeast extracts.

In this regard, Balmaseda et al. (2024) studied the potential application of white wine lees recovered after alcoholic fermentation and wine aging as a stimulating agent for the growth of wine LAB and for promoting malolactic fermentation in red wine. It has been demonstrated that the addition of wine lees can reduce the malolactic fermentation duration in wines with high bacterial populations (> 10^4 cell/mL), and at the same time, enable bacterial growth to perform the total conversion of L-malic acid to L-lactic acid (Balmaseda et al., 2024).

The potential use of wine lees as a nutrient for microalgal production has also been evaluated by several authors. Microalgae are photosynthetic microorganisms that are highly dependent on light and other operating parameters (Wobbe & Remacle, 2015). In this sense, it seems that the use of wine lees as a nitrogen source increases the specific growth rate of *Chlorella sorokiniana*, a species of freshwater green microalgae, by reducing the problems of light shielding observed in photoautotrophic cultures (León-Vaz et al., 2019). Wine lees enabled similar biomass growth of *C. vulgaris*, a dietary supplement or protein-rich food additive in Japan, compared with that obtained in other culture media with glycerol supplementation (Salati et al., 2017), as well as an appropriate lipid composition for microbial biodiesel production (Scarponi et al., 2021). Special attention should be paid to wine lees microbiota that can compromise the fermentation process and inhibit microalgal growth (Veronesi et al., 2020).

Microalgae growth can be enhanced with other wine lees related approaches. Scarponi et al. (2024) proposed a semi-continuous system for microalgae cultivation using the liquid fraction from the anaerobic digestion of wine lees, offering a promising approach for both detoxification of wine lees and sustainable microalgae production. Also, Lanfranchi et al. (2025) used wine lees for anaerobic acetate production that could be coupled with microalgae production.

Various authors have proposed an integrated biorefinery to produce different fermentative products from wine lees (Filippi et al., 2022; S. M. Ioannidou et al., 2022). These authors recuperated ethanol, antioxidants, and tartaric acid, and produced a nutrient-rich hydrolysate that was used for succinic acid production by *Actinobacillus succinogenes*. Fermentations with *A. succinogenes* and *Basfia succiniproducens* were performed with wine lees for the same purpose (Hijosa-Valsero et al., 2022), obtaining high succinic acid yields. Besides, Hernández-Correa et al. (2023) used wine lees as organic load to generate different medium-chain carboxylic acids under bioreactor conditions with fresh bovine rumen fluid. The optimised conditions, with in-line extraction for the recovery of the produced carboxylic acids, allowed a caprylate/caproate ratio of 1.2, with *Eubacterium pyruvativorans* as predominant species.

Other fermentation technologies that have used wine lees as a nutrient source are (i) the production of medium-chain carboxylates (for instance, *n*-caprylate and *n*-caproate) in a reactor microbiome (Hernández-Correa et al., 2023; Kucek et al., 2016), (ii) the production of poly(3-hydroxybutyrate) by *Cupriavidus necator* , *a Gram*-negative soil bacterium (Dimou et al., 2015), (iii) the production of mannitol by *Lactobacillus intermedius* (Hijosa-Valsero et al., 2021; Strong, 2011), (iv) the production of xylitol by *Debaryomyces hansenii* (Pérez-Bibbins, Torrado-Agrasar, Pérez-Rodríguez, et al., 2015; Salgado et al., 2010), (v) the production of laccases for different applications by *Trametes pubescens* or *Pleurotus ostreatus* saprobic fungi, a decomposer of the deadwood of hardwoods (Athanasiou, Gkountela, et al., 2024; Bakratsas et al., 2024; Strong, 2011), or

(vi) the microbial propagation of *Trichoderma viride*, a fungal biofungicide (Zhihui et al., 2008), among others.

5. Use of wine lees in different industries

The potential use of wine lees is not only related to their recycling through different techniques but could also be used in different industries (Figure 4). In this section, these promising and emerging applications are discussed.

5.1 Food

Apart from their evident use in winemaking, other food industries have been interested in using wine lees as ingredients for their products. Their bioactive properties and texture make wine lees an interesting additive for the food industry but also, in the case of red wine lees, as natural colorants for jelly production (Gümüş et al., 2024).

Ice cream was the first product to be investigated. Sharma et al. (2015) studied the effect of wine lees (from Cabernet sauvignon variety) addition on the physicochemical parameters of ice cream. They added different wine lees concentrations, from 0 to 40 g/kg, and observed a dose-dependent decrease in pH and increase in acidity and phenolic composition. Interestingly, intermediate concentrations of wine lees were reported to be the most acceptable by the sensory panel, mainly based on the body of the ice cream. More recently, it was observed that wine lees addition also enhanced nutritional-protein, carbohydrate, phenolic compounds, antioxidant capacity, functional and rheological – water holding capacity, and cheese syneresis or yogurt properties in ice cream production (Sharma & Aglawe, 2022).

In this way, the increase in protein concentration is also interesting for the formulation of other products, such as cereal bars. Some of the ingredients are derived from yeasts; thus, wine lees represent a low-cost and high-value source of various yeast-derived compounds. Indeed, Borges et al. (2021) observed that an increase in the protein concentration in cereal bars with autolysed yeast biomass from wine lees (from *Vitis labrusca* and racked after alcoholic fermentation) was also accepted by a consumer panel.

Red wine lees can be used not only as a protein substitute, but also as a fat replacer in muffin production, where they can effectively replace sunflower oil while improving rheological, textural, and colorimetric properties, as well as pore size and sensory attributes of the final product (Bianchi et al., 2023). Thus, replacing fat concentration in the product, addressing consumers' demands for low-fat foods. This has been also studied by Kaynarca (2024) when using wine lees as alternative to egg proteins in the formulation of low-cost spreadable emulsions. In this regard, sugar content can also be reduced by incorporating dietary fiber, aligning with consumer demand for lower-sugar products. In this context, M. Á. Rivas et al. (2024) proposed the addition of wine lees to tomato sauce, observing an increase in phenolic compounds and improved technological properties, with overall consumer appeal comparable to that of the control sauce.

The antioxidant and pH-lowering activities of red wine lees have also been successfully applied as preservatives in deer burgers. Compared to the conventional preservative sodium ascorbate, red wine lees could increase phenolic compounds and inhibit psychotrophic aerobic bacteria and enterobacteria during storage (Alarcón et al., 2020). In addition, wine lees provided new volatile compounds related to wine, bakery, and raisins (Alarcón et al., 2020). Filippou et al., (2022) applied spray-dried polyphenolic extract to minced bovine meat to retard lipid oxidation.

Another interesting approach in the context of the food industry is the application of polyphenolic compounds recovered from red wine lees and encapsulated with maltodextrin (Ricci et al., 2022). The application of spray-dried micropowder in food could enhance their nutritional value, since encapsulated polyphenols can resist *in vitro* digestion, and thus, be absorbed at the gastrointestinal level. The use of wine lees, owing to their high antioxidant potential, could also enhance food packaging. Incorporating the dry extract of wine lees into chitosan films strengthens their properties and imparts excellent antioxidant activity (Athanasiou, Patila, et al., 2024). In addition, the use of lees in combination with xanthan gum improves the functional properties of the hydrogel, allowing for healthier product formulations (Kamer et al., 2024).

Wine lees have also been incorporated into fresh peach and grape juice preparations (Prieto-Santiago et al., 2024). The authors demonstrated that red wine lees can extend shelf life and enhance the nutritional and antimicrobial properties of the beverage, notably inhibiting *L. monocytogenes*, although other mesophilic microorganisms were not affected. However, the sensory evaluation revealed low acceptance of the juice containing wine lees, highlighting the need for further formulation adjustments.

All studies show that the low pH and high polyphenolic composition of wine lees can be exploited in the food industry, as they can inhibit the growth of spoliating microorganisms, modulate the microbial community, and enhance the antioxidant capacity of the products.

In addition, wine lees can impact the fermentation process of sourdough by enhancing its probiotic properties and modulating the aroma profile of bread (Martín-Garcia, Comas-Basté, et al., 2022; Martín-Garcia, Riu-Aumatell, et al., 2022b, 2022a). They can also be used in the production of biscuits fortified with polyphenols and dietary fibbers, showing a slightly enhanced prebiotic effect (Caponio et al., 2024). In addition, the production of biogenic amines can be reduced by the addition of wine lees or their phenolic extracts as ingredients for fermented foods owing to an observed anti-aminogenic effect (Hernández-Macias et al., 2022). In summary, wine lees can modulate both microbial processes and aromatic profiles (Martín-Garcia, Riu-Aumatell, et al., 2022a).

5.2. Animal feed

The high polyphenolic composition and volatile compounds attached to red wine lees can be exploited in animal feed to improve animal health status or the organoleptic profile of feed. In addition, the high content of polyunsaturated fatty acids is interesting for using wine lees for feeding humans or animals (Gómez et al., 2004).

The addition of red wine lees to ruminant feed can increase the total nitrogen and condensed tannin concentrations, which can also improve digestibility *in vitro* (Molina-Alcaide et al., 2008). Indeed, Y. Sato et al. (2020) observed a wine lees dose-dependent effect on (i) decrease in gas production, (ii) a decrease in dry matter and crude protein digestibility, (iii) an increase in polyphenolic content and radical scavenging ability, and (iv) an increase in the proportion of α-linolenic acid and total polysaturated fatty acids. In addition, the increased proportion of ruminal propionate after feeding and plasma malondialdehyde, an oxidative stress marker, decreased, while phosphorus (P) increased. Overall, these observations indicate improvements in ruminant feeds (Y. Sato et al., 2020).

Fermentation is a process that can add value to feed, as it is usually done for human food. Jin et al. (2016) proposed wine lees as a source of carbohydrates and nutrients as a fermenting fundal substrate to produce fermented products for feeding purposes. Fermentation with some selected fungi, *Aspergillus oryzae* and *Trichoderma reesei* – produced fermented wine lees extract enriched in nutrients, proteins, and digestibility.

Another interesting application of wine lees in animal feed is the modulation of organoleptic characteristics of new nutrient formulations. Câmara et al. (2020) studied the volatiles of different wine lees and related their abundance with different quality and safety attributes of the aquafeed. They concluded that wine lees can be used as additives to improve the organoleptic characteristics (aroma and flavour) as well as the health benefits of fish feed. Indeed, some volatiles are antimicrobial, antioxidant, and antiproliferative agents. Moreover, Martínez-Antequera et al. (2023) also reported a protective effect associated with improved growth and feed efficiency, as well as enhanced antioxidant defence against moderate hypoxia in juvenile *Liza aurata* fed with wine lees.

This aspect of improving the health status was also tested in terms of chicken oxidative status. Animal feed supplemented with wine lees was able to improve antioxidant mechanisms and muscle oxidative stability without a negative impact on immune regulation (Mavrommatis et al., 2021b), which can also improve both organisms and meat oxidative status (Mavrommatis et al., 2021a).

5.3. Soil treatment

Traditionally, wine lees are thrown away, accumulated in soil, and cause soil disequilibrium problems. Therefore, the law limits their use and prohibits the troughing of wine lees to soils. However, research on soil treatment with wine lees has opened a new scenario, in which wine lees can help solve some soil problems. Generally, it seems that wine lees do not change soil pH but increase soil salinity (Bustamante et al., 2007). Soil fertility is one of the most important issues in soil management. In this sense, phosphorus appears an essential micronutrient. Requejo et al. (2016) explored the use of a compost mixture of wine by-products, including wine lees, which increased soil P availability and could be retained in calcareous soils, avoiding contamination risks and being available for much time for crops. Interestingly, increased phosphorus availability was also observed in ruminant plasma fed wine lees, as previously presented (Y.Sato et al., 2020a).

Wine lees have also been studied as biochar in soil remediation. Biochar is an active carbon derived from organic matter when applied to soil. Heavy metal accumulation is an important soil health issue that can affect crop growth and affect the food chain. Wine-lees-derived biochar has been proposed as an adsorbing material in soils contaminated with Pb^{2+} (Zhu et al., 2016). The authors described a large specific surface area and total pore volume with abundant -COOH and -OH radicals on the surface. This biochar has also been applied to soils contaminated with different heavy metals, and a reduction in metal mobility and enhanced plant growth has been observed (Xu et al., 2018). In addition, wine-lees-derived biochar can increase nutrient availability, which also contributes to increased microbial growth and biodiversity (Xu et al., 2017).

5.4. Vermicomposting

Vermicomposting is a biological composting process in which earthworms break down organic matter such as food scraps and plant residues into nutrient-rich compost. This process not only produces new generations of earthworms but also changes the physicochemical composition of the substrate in which they are developing.

Some authors have explored vermicomposting using different winery by-products (Nogales et al., 2005, 2020; Romero et al., 2007). They found that the different tested by-products, including lees after distillation, were suitable for earthworm development, but the growth was not as high as in manure (Nogales et al., 2005). As a result of the growth of earthworms, the solid matter increased in pH and nutrients and reduced the C/N ratio, polyphenols, electrical conductivity, microbial enzymatic activities, and phytotoxicity. Moreover, these solid by-products can be used in fresh form without any intermediate transformation processes (Romero et al., 2007). In summary, this application represents an alternative use for wine lees that generates earthworms and simultaneously reduces residues (Nogales et al., 2020).

5.5. Health and cosmetics

The high phenolic content of red wine lees represents a source of bioactive compounds that can have a strong impact on health. For this reason, the few studies on wine lees valorisation found in the literature are focused on red wine lees, which possess a higher polyphenol content. These studies are quite recent and respond to the aim of industrial by-product valorisation and to the need for bioprospection of natural bioactive compounds. In this sense, research on health is still in its first stage, using cell or animal models, far from real human exploitation. The high polyphenolic content of wine lees can be a source of dietary antioxidants (Landeka Jurčević et al., 2017). The bioactive activities of wine lees have been investigated in various health issues. First, Landeka Jurčević et al. (2017) studied the hypolipidemic and antioxidant properties of wine lees in mice with dietary-induced hypercholesterolemia. They observed that mice fed with wine lees in dietary-induced hypercholesterolemia significantly decreased the total cholesterol concentration in serum by reducing triacylglycerol and low-density lipoproteins (LDL). Only a significant reduction in LDL was observed in normocholesterolemic mice. In addition, the antioxidant activity of the liver was strongly increased in mice fed with wine lees in both diet models (Landeka Jurčević et al., 2017).

Moreover, Fernández-Bedmar et al. (2019) characterized wine lees and investigated the anticarcinogenic effect and DNA methylation in a murine hepatocarcinogenesis model. Their results showed that the phenolic composition of the studied lees was mainly composed of pyrogallol, gallic acid, syringic acid, and catechins in red wine lees. Regarding the anticarcinogenic effects, white wine lees reduced DNA hypermethylation. Additionally, low concentrations of both types of wine lees improved hepatocellular architecture and decreased the mitotic index. When comparing white and red wine lees, white lees appear to exhibit a stronger anticarcinogenic potential than red lees. This behaviour may be attributed to the higher pyrogallol, GAE, and syringic acid contents in white wine lees.

This means that the observed anticarcinogenic and hepatocarcinogenesis prevention is related to white wine lees rather than to red wine lees, which are generally classified as the most beneficial due to their high polyphenolic composition.

The use of wine lees as an antihypertensive compound has also been investigated (López-Fernández-Sobrino et al., 2022). López-Fernández-Sobrino, Soliz-Rueda, et al. (2021) described the antihypertensive effects of the soluble fraction of red wine lees in a murine model. They described potent angiotensin-converting enzyme (ACE) inhibitory activity in three red wine lees, Cabernet Sauvignon, Mazuelo, and Red Grenache, but only C. Sauvignon lees exhibited a blood pressure (BP)-lowering effect. In this sense, the BP-lowering effect was present in lees from the same cultivar collected during different vintages and was related to their highest anthocyanin and flavanol concentrations. The observed antihypertensive was enhanced by an enzyme-assisted hydrolysis with a 57.2% increase in total phenolic compounds, higher and more prolonged than a commercial antihypertensive drug (López-Fernández-Sobrino, Soliz-Rueda, et al., 2021). In addition, the effect was dose-dependent and improved in dried wine lees powder (López-Fernández-Sobrino, Soliz-Rueda, et al., 2021), which was related to an improvement in endothelial functionality (López-Fernández-Sobrino, Margalef, et al., 2021). Interestingly, the antihypertensive effects of dried wine lees are related to specific bioactive peptides with known sequences (Bravo et al., 2022). This observed ACE inhibitory activity can be further increased by fractioning the obtained hydrolysates (Fontana et al., 2025). Besides, Moreira et al. (2024) observed that wine lees from fermentations inoculated with *Starmerella bacillaris* and *S. cerevisiae* were potential good sources of bioactive peptides, mainly with antihypertensive effects. Other potential observed effects of those peptides were: (i) immunomodulatory, (ii) antimicrobial, (iii) anti-obesity effects.

Wine lees uptake has also been related to the modulation of lipid metabolism. Caro et al. (2017) observed in zebrafish model that red wine lees polyphenolic extracts reduced embryos' fat reserve up to 40%, changed lipid metabolism related genes' expression, modulated fatty acid and phospholipid fractions, and reduced in trans fatty acid content, resulting in a highly attractive health property for food innovation.

As stated previously, wine lees can exert prebiotic and probiotic effects by modulating the gut microbiota. A recent study (Martín-Garcia et al., 2022) showed an increase in the relative abundance of probiotic bacteria belonging to the *Lactobacillaceae* family, as well as other potentially probiotic species, such as *Blautia hansenii*, *Roseburia intestinalis*, and *Ruminococcus obeum*, when supplementing a rats' diet with sparkling Cava lees. In contrast, the abundance of certain pathogenic bacteria was reduced, showing a modulating effect on the gut microbiota with dietary supplementation with lees.

The antioxidant capacity of red wine lees extracts has also been tested in terms of antioxidant activity through chemical and cell-based assays, focusing on the inhibition of enzymes relevant to skin ageing, demonstrating their potential use as cosmeceuticals (Matos et al., 2019) in topical application (Gonçalves et al., 2024), or in the prevention of inflammation and oxidative stress (Sánchez-Bravo et al., 2025).

In summary, there is increasing interest in the application of wine lees, with studies focusing on determining the appropriate consumption concentration and testing their suitability in humans to better understand the physiological response in our species.

5.6. Innovative materials

In addition to the previously introduced applications of wine lees, they can be used in the fabrication of innovative materials. Carbon quantum dots (CQDs) are tiny carbon-based nanoparticles with unique fluorescence properties that are used in applications such as bioimaging, sensors, and energy storage because of their low toxicity and stability. Therefore, wine lees have been proposed as a raw material for producing carbon quantum dots (CQDs)(Varisco et al., 2017). In this study, a complete synthetic pathway is discussed, including carbonization of the starting material, screening of the most suitable solvent for the extraction of CQDs from the carbonized mass, and their hydrophobic or hydrophilic functionalization. A smooth scale-up process was achieved. They successfully produced CQDs with a quantum yield (QY) of approximately 6%, a value commonly reported for pure CQDs in literature.

Wine lees have shown strong potential as bio-fillers in biocomposites—materials composed of biodegradable polymers such as poly(butylene adipate-co-terephthalate) (PBAT) and polybutylene succinate (PBS), combined with natural additives (Biagi et al., 2024). These polymers must be filled. In this way, wine lees, when used as fillers, can play a key role in enhancing the properties of fully bio-based materials. These biocomposites present promising potential for agricultural applications, including biodegradable vineyard ties, as well as for sustainable packaging solutions. Besides, wine lees can be used in the formulation of composite edible films in combination with carrageenan with potential application in food packaging (Gumus et al., 2024).

6. Final remarks and future perspectives

Despite being of interest in winemaking, particularly during ageing, due to their ability to release compounds that enhance the organoleptic properties of wine, as well as their chemical and oxidative stability, wine lees have received relatively little attention in terms of comprehensive analysis to determine their overall composition. After winemaking, some of the lees are often treated by distillation for ethanol production (for spirits) or to recover tartaric acid for various purposes. Lees, whether derived from winemaking or distillation, represent a rich organic by-product with numerous applications. The polyphenolic fraction, peptides, and lipids are often studied for their potential to produce antioxidant products for health and food applications, while mannoproteins, owing to their techno-functional properties, are utilized mainly in food and beverages. The nitrogenous fraction plays an important role as a nutrient in animal feed and soil. Studies have also highlighted the interest of nitrogenous matter in lees for the growth of microorganisms, opening the way to targeted biotechnological applications.

Despite their potential industrial utility and high-value components, wine lees have been relatively understudied and underutilized. Certain intrinsic characteristics of lees may affect their suitability for specific applications. Colour compounds, particularly in red wine lees rich, may pose challenges in industries where colour neutrality is preferred, such as in cosmetics or certain food formulations. Additionally, nucleic acids and cell debris present in lees can interfere with biotechnological processes like enzymatic reactions or microbial fermentations, potentially requiring additional purification or pre-treatments steps.

Furthermore, the studies cited and discussed in the manuscript aim to propose innovative valorisation approaches that may lead to future applications. However, many of these investigations remain in vitro or at a preliminary stage and thus do not fully address all the practical limitations. In this context, our review serves as a starting point to highlight the promising potential of wine lees, while encouraging further research toward concrete, real-world applications that can support their sustainable and effective valorisation. Finally, appropriate quantification methods for the analysis of wine lees compounds and the development of sustainable processes for their extraction represent an important challenge for wine lees valorisation, which will contribute to improving the environmental and economic sustainability of the wine industry.

Declaration of competing interest

There are no conflicts of interest to declare.

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Authors contributions

Aitor Balmaseda: Conceptualization, Data curation, formal analysis, Investigation, Methodology, Visualization, Writing – Original Draft Preparation, Writing – review and editing. **Nicolas Rozès**: Validation, Writing-Review, and Editing. **Maria Tiziana Lisanti**: Investigation, Validation, Writing – Review & Editing. **Cristina Reguant**: Investigation, Validation, Writing-Review, and Editing. **Claudia Nioi**: Conceptualization, Formal analysis, Investigation, Writing – Original Draft Preparation, Writing – Review & Editing.

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Figure captions

Figure 0 Graphical abstract

Figure 1 Diagram of white wine production technology highlighting the stages where by-products, particularly wine lees, are generated.

Figure 2 General analysis of the published scientific articles including “wine lees” keywords” from Scopus Database. A. number of publication by year. B. Accumulated number of publications by year. C. Fields of the published articles. The search was done in December 2024.

Figure 3 Winemaking steps influencing the composition of wine lees

Figure 4 Diverse potential application of wine lees and wine lees extracts in different industries for enhancing processes or properties.

Figure 5 Diagram illustrating the potential processes applied to wine lees for the generation of high-value products across diverse applications.