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Winery Wastewater Treatment Technologies: Current Trends and Future Perspective

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The water footprint of wineries is typically more than 1 L water/L wine. In the European context, this annually equals to over a hundred million hectoliters of water, most of which eventually become wastewater. The winery wastewater is known to have high organic loads, most frequently quantified by chemical oxygen demand (COD). Particularly during the vintage season, the discharge of winery wastewater with extreme COD values can paralyze municipal wastewater treatment plants. As a result, the treatment plants pose strict limits on wastewater parameters. This forces wineries to either transport the wastewater to specialized facilities capable of handling the wastewater extremities, or invest into their own wastewater treatment plant. Since wine has been historically produced by small wineries, either option economically challenge these often family-owned companies. This work reflects the need for robust wastewater treatment technologies that would be able to handle winery wastewater parameters' fluctuations throughout the year and the abovementioned peaks. The technologies are categorized into physicochemical, biological, membrane, advanced oxidation and combined processes. There are a number of treatment methods that have shown a COD removal rate of over 90 %. However, they significantly vary in size, process flexibility and maintenance difficulty. Some alternative processes are also critically evaluated in the context of circular economy and water reuse, which can further improve the process economy for small- and medium-sized wineries.

1. Introduction

The wine industry is related to a great use of natural resources, particularly land and water (Zacharof, 2017). The overall water footprint of wine production is estimated to be as high as 1,000 L per 1 L of wine (Bolzonella et al., 2019). The vast majority of the value belongs to wine growing, while only around 1 % of the footprint is represented by processing in wineries (Ene et al., 2013). Even though this fraction might appear small, virtually all of the water used in wineries is contaminated to a different extent, resulting in a significant wastewater production of approximately 1–4 L per 1 L of wine (Zacharof, 2017).

World wine production was estimated to be 25,000 ML in 2021 (International Organisation of Vine and Wine, 2021). Given the abovementioned specific wastewater production, this translates into a global winery wastewater (WWW) production of 25,000–100,000 ML.

A majority of the global wine production takes place in Europe, with the EU member states producing some 14,700 ML in 2021, a year heavily impacted by adverse weather events, and averaging at 16,500 ML over the last 5 years (European Comission, 2021a). Although the production volume is likely to remain stable, the market shift towards a higher share of PDO (Protected Designation of Origin), PGI (Protected Geographical Indication) and organic wines is expected (European Comission, 2021b). These types of wine are often associated with small- to medium-sized wineries, therefore this segment's increasing importance is to be expected, which can potentially initiate a shift in the WWW treatment approach towards more intensive, compact and cost-effective equipment.

Among the market evolution, there is a number of environmental, sustainability and legislation reasons to research and improve WWW treatment. Historically, the WWW has been applied to soil (Bolzonella et al., 2019).

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While this concept has been re-engineered and is still applied in the form of crop irrigation in some parts of the world such as South Africa (Howell and Myburgh, 2018) or Australia (Laurenson et al., 2012), it leads to a gradual decline of soil and is not feasible in Europe because of strict wastewater limits, for instance, Council Directive 91/271/EEC (European Council, 1991) and its amendments.

There is a large number of reviews published in the last decade, either covering the WWW treatment technologies holistically (Ioannou et al., 2015), or focusing on a certain category of the technologies such as biological (Bolzonella et al., 2019), advanced oxidation (Davididou and Frontistis, 2021) or wetlands (Masi et al., 2015). Those sources provide an excellent and deep insight into virtually all the WWW treatment options available nowadays. However, they almost exclusively focus on WW discharge into environments such as surface waters and meeting the disposal limits in a specific region. Thus far, research efforts to increase water reuse in the wine making industry has been limited.

On the EU level, it is estimated that 20 % to 40 % of water is wasted and that water efficiency could be improved by 40 % merely by technological improvements (European Comission, 2011). This issue has already been reflected in the 2020 Circular economy action plan, which encourages a) water reuse and efficiency in agriculture and industrial processes, b) sustainable application of nutrients, c) stimulation of markets for recovered nutrients (European Commission, 2020). More specific legislation steps have already been taken in this area, with the water reuse regulation proposed in 2018 and becoming effective in 2023 to address the worsening water scarcity and droughts in Europe (European Comission, 2018). While the topic of WWW treatment has already shown increased popularity since around 2005 when the publication activity approximately tripled (Ioannou et al., 2015), this additional pressure and legislative framework makes the issue extremely topical.

The goal of this work is to evaluate the information available in the literature according to a) the European perspective, b) circular economy and water reuse ideas, c) future predictions.

2. Winery Wastewater Characterization

Winery wastewater (WWW) is mostly acidic, phytotoxic, with high oxygen demand and bactericidal phenols (Zacharof, 2017). Figure 1 shows a block diagram of the wine-making process. First, grapes are crushed and destemmed – this takes place either in a winery or at a vineyard. To prevent oxidation, SO_2 or an alternative sulfur-based agent is added before pressing and fermentation, a biological process of converting sugars to ethanol. The following step of clarification and stabilization removes wine turbidity, harmonizes the taste and improves shelf life. Before the final step of bottling, wine may or may not be aged to improve its quality.

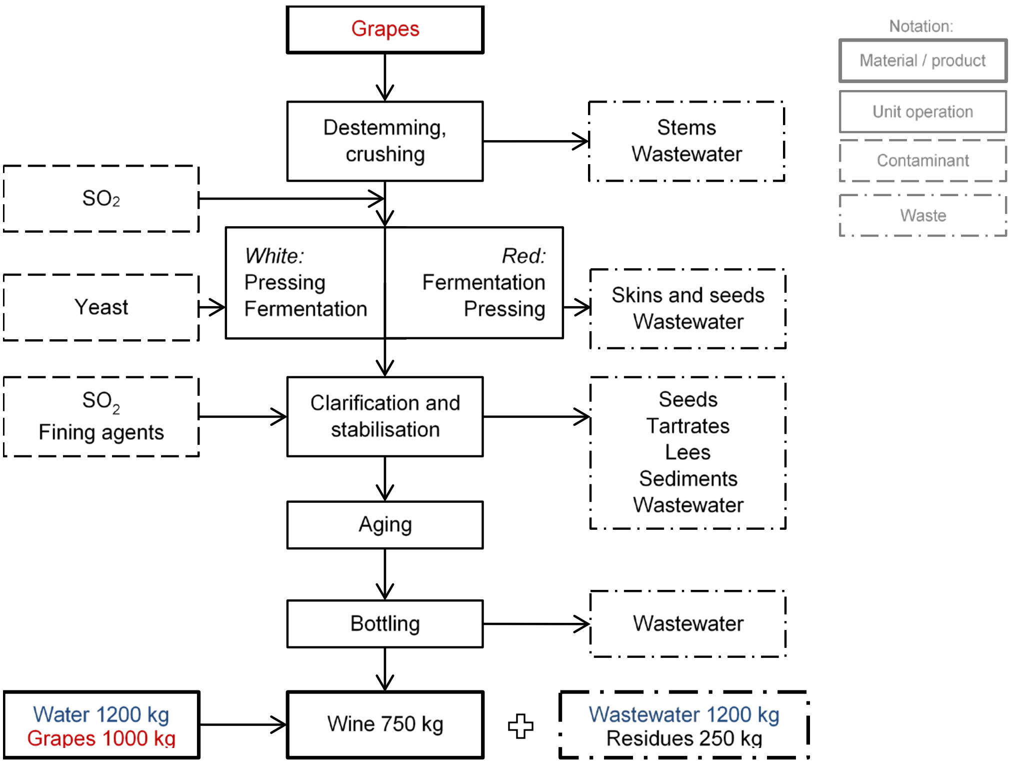

Figure 1: A winery mass balance with respect to waste and its different sources

Figure 1 puts emphasis on mass balance and the fact that wastewater and other forms of waste are produced in most of the unit operations, resulting in approximately 2 kg waste/L wine, 75 % of which is winery wastewater (Jia et al., 2018). The composition and volume of WWW is extremely variable between different wineries as well as through a year within one winery (Mosse et al., 2011).
A particularly problematic period is the vintage (crush) season, which can be responsible for a majority of wastewater production (Lofrano and Meric, 2016) and also affects the concentrations of organics, for instance, ethanol is the main contaminant in the non-crush period, whereas a significant amount of grape sugars is generated during the vintage season (Mader et al., 2022). Apart from the crushing as the most contributing step of WWW production (~50 %), the operations of (intermediate) product transfer, cleaning (particularly equipment rinsing) and bottling produce significant amounts of water with typical shares of 25, 14 and 8 %, respectively (Lofrano and Meric, 2016).
A complete WWW composition analysis is difficult to obtain, with time-consuming and costly methods of high-performance liquid chromatography (HPLC) and gas chromatography combined with mass spectrometry (GC-MS) being the most pronounced methods for this task and requiring highly qualified personnel (Mosse et al., 2011). For this reason, there is a very limited number of publications providing specific concentrations such as (Malandra et al., 2003), revealing a wide range of sugars, alcohols, organic acids, esters and polyphenolic components. Besides these organic compounds, WWW is also known to contain inorganics, most concentrated of which are typically sodium (from cleaning agents) and potassium (from grapes and/or cleaning agents) (Laurenson et al., 2012).
While elemental analyses are crucial to track some persistent contaminants and micropollutants in WWW, there are other wastewater metrics that are the key to selecting a suitable WWW treatment technology, e.g. chemical oxygen demand (COD) and suspended solids (SS) (Kyzas et al., 2016). The pH value also has a significant impact on basically all WWW treatment technologies (Ioannou et al., 2015); nevertheless, it can and often is controlled within a treatment facility (Lofrano and Meric, 2016). All three parameters, however, show significant seasonal fluctuations described on the previous page. COD is reported to be in the wide range of 320–49,105 mg/L (Ioannou et al., 2015) and some authors mention values as high as 296,119 mg/L (Mosse et al., 2011).
Biochemical oxygen demand during the period of 5 days (BOD_5), correlating with biodegradability of contaminants, is similarly fluctuating and typically around a half of the COD value (Ioannou et al., 2015). The mean pH value of 5 makes average WWW acidic, yet it can increase to values as high as 12, mostly due to hydroxides (NaOH, KOH) as the most popular cleaning agents in wineries (Mosse et al., 2011).
This extreme variability puts significant pressure on designing a flexible technology, robust enough to handle the high organic load, possessing a wide enough turndown ratio to deal with the peak values, yet not overdesigned with respect to the usual operation. The next chapter focuses on this challenge.

3. Winery Wastewater Treatment Technologies

Winery wastewater (WWW) treatment technologies are typically divided into four categories: a) physicochemical processes, b) biological processes, c) advanced oxidation processes, d) membrane processes.

Table 1 Selected WWW treatment methods reported to have high efficiencies among their category

Category	Methods	COD removal	Source
a) Physicochemical	-precipitation -sedimentation -coagulation -electrocoagulation	9 % 20-40 % ~35 % (73 % with chitosan) 47 %	(Ioannou et al., 2015)
b) Biological	Aerobic -membrane bioreactor -conventional activated sludge process Anaerobic -anaerobic sequencing batch reactor	 94–97 % 98 % 80–97 %	(Bolzonella et al., 2019)
c) Advanced oxidation	-TiO_2-based -sulfate radical-based -Fe-based -Ozone-based	84 % 79 % (96 % after evaporation) 93 % (98 % after air stripping) 30 %	(Davididou and Frontistis, 2021)
d) Membrane	-reverse osmosis	97 %	(Ioannou et al., 2015)

COD removal is the most common measurement of how efficient a WWW treatment technology is. COD is typically the limiting factor for effluent discharge to aquatic environments. Table 1 shows an overview of the different options for the WWW treatment.
The physicochemical methods excel with their simplicity; however, the limited COD removal makes them suitable only for as WWW pretreatment. Unlike some following methods, they are efficient at removing solids, both suspended (sedimentation, coagulation) and non-suspended (precipitation).
The biological treatment is a mature technology widespread over municipal as well as industrial wastewater treatment. While the biological methods provide high organic load removals, they require relatively long residence times associated with extensive equipment. The aerobic methods also require energy-intensive aeration, which is a drawback when compared to their anaerobic counterpart, which can additionally produce biogas as a by-product.
Advanced oxidation is novel relatively to the other technologies. These methods are very promising as a post-treatment step after biological processes because of the possibility to remove or inactivate persistent microcontaminants such as pharmaceuticals, endocrine disrupting compounds, caffeine or antibiotic-resistant bacteria (Davididou and Frontistis, 2021). However, the relatively high electricity demands and cost of chemical reagents did not allow for a full-scale implementation yet (Davididou and Frontistis, 2021).
Reverse osmosis as the most pronounced membrane process applicable for WWW treatment provide similar advantages to advanced oxidation, with the ability to reduce toxicity, remove persistent compounds and yield excellent effluent quality. However, significant pretreatment is necessary to remove suspended solids and other contaminants that would lead to rapid membrane fouling.
One unit operation is generally not sufficient to improve the WWW quality for its discharge into environment, or to reuse it in the facility. For this reason, combined processes are considered a promising prospect. However, such process can consist of an arbitrary number and sequence of the abovementioned unit operations/methods and the high variety in published literature shows that there is no “silver bullet” to this challenge. This is discussed in the following chapter.

4. Discussion

This chapter provides insights on winery wastewater (WWW) treatment challenges and future perspective. It also highlights some insights that the available literature implies, but they have not been given enough attention.

4.1 Challenges

Many wineries do not face the question “what technology”, but whether or not they should build a dedicated treatment plant on site. Up-to-date information about the number wineries equipped with such technologies is not available, however, a 2004 survey from Italy shows that the majority of WWW was discharged into sewerage and treated in the municipal wastewater treatment plants, around one quarter of WWW was transported to a treatment plant by trucks, and merely 5 % was treated directly in the winery, with a rather alarming fraction of 10 % spread on land (Airoldi et al., 2004).
If a winery uses an external subject to treat their wastewater, the motivation to invest into a treatment technology is stronger with a favorable (short) payback period thanks to savings on WWW disposal fees and/or transport. This motivation can magnify a) during the vintage season when municipal wastewater treatment plants cannot process the high organic loads, b) for wineries without access to a sewerage system, c) with strict limits and/or high fees related to the discharge. However, specific cost (including capital and operating expenditures) tend to be significantly higher for small wineries common in Europe, e.g., approximately 5 times higher for a winery processing <1,000 t/y when compared to the capacity >50,000 t/y (Kyzas et al., 2016). This is in agreement with the general opinion that conventional biological processes are less cost-effective for small capacities. They also tend to have a large spatial footprint, which makes their employment in areas with high cost and low availability of land difficult.
Another challenge is the overall removal capability of the treatment technology. For, not uncommon, peak values of COD >10,000 mg/L, even 99 % removal efficiency does not yield a sub-100 mg/L effluent COD typically necessary for discharge into the environment. Additionally, some persistent inorganics (for instance Na and K from cleaning agents) are not removed by biological action (Mader et al., 2022), therefore a polishing step might be necessary, especially with respect to water reuse.

4.2 Volatile compounds, the overlooked suspects?

A very interesting pattern can be found across the different processes: any pre-treatment removing volatile compounds significantly improves the overall efficiency of the technology. Note that the highest efficiencies achieved in advanced oxidation processes (see Table 1) follow after evaporation and air stripping, both of which drive more volatile components of the wastewater (Davididou and Frontistis, 2021). Interestingly, Ioannou et al.

report the highest efficiency for a combined process of long-term aerated storage followed by Fenton's reagent oxidation, with the first step clearly removing the volatile components (Ioannou et al., 2015).
This finding is supported by a number of authors mentioning that relatively volatile ethanol is a major contributor to the COD of WWW, with reported COD fractions of 90 % (Masi et al., 2015), 85–90 % (Sheridan et al., 2011) and 75–99 % (Colin et al., 2005). The research efforts to specifically target ethanol, however, have been limited. Nevertheless, a study from 2005 (Colin et al., 2005) shows that stripping combined with evapo-concentration eliminates over 99 % COD and that stripping alone removes 78–85 % of COD.

4.3 Circular economy and water reuse

There are multiple directions heading toward circular economy in the area of WWW treatment. Zacharof (2017) suggests the biorefinery concept applied to winery waste, on the other hand WWW specifically has not been widely used as biotechnological conversion feedstock. In broader terms, anaerobic processes generating biogas fall under this concept, with reported specific methane production of around 0.3 m^3 $CH_4 \cdot kg^{-1}$ COD (Bolzonella et al., 2019) and methane concentration of up to 82 % (Ioannou et al., 2015). While this fuel production is not significant, it can partly offset energy consumption of a winery.
Winery wastewater contains not only undesirable compounds, but also some components with added value. Kyzas et al. (2016) suggest an innovative prospect of molecular imprinting to recover some commercially demanded compounds present in winery wastewater, particularly resveratrol and other polyphenols. However, current results in this area are limited to the laboratory scale.
A straightforward idea supporting a circular economy within a winery is water reuse. The simplest approach is characterized by the use of relatively clean wastewater for operations where lower water quality suffices (Kyzas et al., 2016). The approach to label, sort and match wastewater quality could be further improved and done in a more systematic manner, applying the proven pinch method, which can be extrapolated outside its origin (heat integration) as demonstrated in the case study of plastic flow minimization (Varbanov et al., 2021).

5. Conclusions and future predictions

In 2022, the challenging selection of the right technology for winery wastewater treatment dramatically changed its dynamic. The current sharp increase in energy and material prices related to the Ukraine crisis influences both the operating and capital cost of a technology. While the share of small- and medium-sized wineries already called for more cost-effective technological solutions than the conventional biological wastewater treatment processes, this will be truer than ever in the upcoming decade.
There are three promising directions that can improve the economy for smaller wineries: a) yielding wastewater of such quality that would make it eligible for water reuse, ideally food grade quality required for equipment rinsing, b) intensive treatment in compact equipment to minimize spatial footprint, material used for construction and the associated capital cost, c) anaerobic treatment to produce methane, which can make the treatment partially energy self-sufficient.
Two out of three directions are combined in the concept of Zero Liquid Discharge (ZLD), an idea of eliminating wastewater discharge while maximizing water reuse. The most efficient methods expected to rise in popularity in the close future and comply with this concept are evaporation (over 99 % COD removal when coupled with stripping), membrane bioreactor (up to 97 % COD removal) and reverse osmosis (97 % COD removal). Using a sequence of these methods could allow for: I) effective pre-treatment focused on volatile compound removal, II) bulk contaminant removal targeting biodegradable pollutants, III) final polishing to remove persistent contaminants and potentially approach food grade quality.
The future research will address ZLD, as there is an apparent research gap, which can be demonstrated by no results returned from a Scopus search using keywords "zero liquid discharge" and "winery" or "wine". The pioneering idea to approach WWW treatment with ZLD ideas reflects the current pressure on water reuse and nutrient recovery and can potentially offer additional economic and environmental benefits.

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