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PII: S0048-9697(23)02166-6

DOI: https://doi.org/10.1016/j.scitotenv.2023.163547

Reference: STOTEN 163547

To appear in: *Science of the Total Environment*

Received date: 12 January 2023

Revised date: 27 March 2023

Accepted date: 13 April 2023

Please cite this article as: L. Flores, I. Josa, J. García, et al., Constructed wetlands for winery wastewater treatment: A review on the technical, environmental and socio-economic benefits, *Science of the Total Environment* (2023), https://doi.org/10.1016/j.scitotenv.2023.163547

Constructed wetlands for winery wastewater treatment: a review on the technical, environmental and socio-economic benefits

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Abstract

In wineries, wastewater production and solid waste generation can pose serious environmental threats. Winery wastewater production has a seasonal behavior and needs a treatment system that can adapt to these fluctuations while reducing costs, and environmental impacts and promoting other winery activities. The implementation of constructed wetlands (CWs) has been demonstrated to be a competitive solution for winery wastewater and sludge treatment. In this article, worldwide experiences over the last 25 years of CWs for winery wastewater treatment are reviewed. The review shows that the application of hybrid CWs coupled with anaerobic digestion can reduce more than 90% of the organic pollutants and solids from winery wastewater while avoiding clogging. These efficiencies and advantages can be also attained with French vertical systems. Not only CWs have a good technical performance, but they also reduce up to more than 90% the environmental impacts associated with winery wastewater treatment. It is due to low energy requirements, no chemicals consumption and avoidance of off-site management and transportation practices. In terms of costs, CWs can reduce up to 60 times the costs associated with winery wastewater treatment and management.

More efforts should be made in order to define the social benefits of this technology and the quality of the recovered resources (e.g. treated water, fertilizer) in order to promote the circular economy without compromising human and ecosystem health.

Keywords: Circular bioeconomy; life cycle assessment; wine industry; sustainability; nature-based solution.

1. Introduction

Every year, more than 100 million cubic meters of wastewater are generated worldwide from winemaking processes (Milani et al., 2020; Vlotman et al., 2022). This causes the wine production sector to have a particularly high water footprint (Saraiva et al., 2019). Winery wastewater (WWW) production and characteristics are highly variable depending on numerous factors such as winery location, scale, type of wine produced, winemaking processes involved, or disposal practices. Due to the uniqueness of each winery, the amount of WWW generated varies within a huge range. Indeed, between 0.5 and 14 L of wastewater per liter of wine are produced in wineries, with an average value of 4 L (Flores et al., 2019; Oliveira and Duarte, 2010).

The wine-producing sector is spread worldwide and is mainly present in Italy, France and Spain (which account for 48% of the total production), followed by the USA (9%), Argentina (5%), Australia (4.5%), Chile (4.5%), South Africa (4%) and Germany (3.5%) (OIV, 2020).

Wineries generate huge volumes of wastewater with high organic loads that are, in most of the cases, partially treated or discharged untreated into the environment or in the vineyards. These bad practices can cause environmental and health problems such as surface and groundwater contamination, eutrophication, soil microbial imbalance, soil degradation, damage to the vegetation and odor disturbances (Buelow et al., 2015; Kumar et al., 2019; Litaor et al., 2015; Mosse et al., 2012).

WWW comes from many winery operations such as grape crushing and pressing, rinsing of fermentation tanks, filtration, washing of surfaces, barrels and other equipment, aging and bottling (Ioannou et al., 2015; Musee et al., 2006). In some wineries, an additional discharge from domestic wastewater generated from tourism, restaurant and workers' activities is mixed with WWW (De La Varga et al., 2013; Milani et al., 2020; Rozema et al., 2016; Serrano et al., 2011; Valderrama et al., 2012).

In the last years, several technologies have been attempted to treat winery effluents, being conventional aerobic biological treatment (e.g. activated sludge) the most implemented one (Flores et al., 2019; UPC, 2018). Other treatments consist of physicochemical (e.g. photo-fenton) and anaerobic technologies (e.g. anaerobic fixed bed reactors) (Anastasiou et al., 2009; Ganesh et al., 2010; Ioannou et al., 2015; Litaor et al., 2015; Lofrano and Meric, 2016; Rodríguez-Chueca et al., 2017). Apart from treated effluents, these systems usually produce sludge that also needs to be treated. However, conventional technologies were reported to not fulfill effluent quality requirements during peak flows and loadings (Bolzonella et al., 2010; Brito et al., 2007; Petruccioli et al., 2002; Rodríguez-Chueca et al., 2017) and are difficult and expensive to operate and maintain (Mosse et al., 2011; Wu et al., 2015).

In this context, natural treatment solutions such as constructed wetlands (CWs) can be a suitable alternative to solve some of the challenges of this sector. CWs are designed and constructed to mimic and enhance natural wetland ecosystem processes. These systems are shallow basins that are filled with inert porous materials and planted with aquatic vegetation. Polluted water flows through the CWs and it is treated by chemical, physical and biological processes including sedimentation, filtration, retention, oxidation, reduction, precipitation, adsorption, transformation, degradation and volatilization (De La Varga et al., 2017; Kadlec and Wallace, 2009).

CWs can be classified into different types according to hydraulics characteristics. In vertical subsurface flow (VF) CWs and horizontal subsurface flow

(HSSF) CWs, the water table is below the substrate surface and the wastewater flows vertically and horizontally through the bed, respectively. In free water surface (FWS) CWs, there is no porous material and the water surface is exposed to the atmosphere. In hybrid systems, different combinations of HSSF, VF and FWS CWs can be used (Langergraber et al., 2020). In these systems, the advantages of each type of CW are combined to enhance the efficiency of treatment. Recently, French vertical flow wetlands have been gaining popularity due to their simplicity and treatment performance. Indeed, they receive raw wastewater and combine sludge and water treatment, avoiding the need for other treatment steps (e.g. primary treatment or sludge treatment units) (Dotro et al., 2017). These systems help to prevent clogging problems since the solids are retained and mineralised on the top of the beds.

CW technology can also be used for sludge treatment alone (i.e. sludge treatment wetlands - STWs, also known as sludge drying reed beds). In this system, sludge is dewatered and stabilised by means of natural processes, producing a final product that can be used as fertilizer for agricultural purposes (Brix, 2017). This technology can be a suitable on-site solution for the management of sludge from the primary treatment (e.g. septic tank) and/or from the secondary treatment of activated sludge systems, where the sludge is usually centrifugated, transported and treated by a third party (Flores et al., 2019, 2020).

Since the 1990s, there has been a growing interest in the application of CWs for WWW and sludge treatment (Masi et al., 2015; Vymazal, 2014; Wu et al., 2015). CWs have been proven to be efficient, easy to operate and maintain and are a low-cost solution compared to other technologies as well as they produce low environmental impact and can be integrated into the landscape (Flores et al., 2020; Holtman et al., 2018; Licata et al., 2017).

Until the present, several researchers have presented studies on the design and impacts of CWs for WWW. Given the need for expanding these systems in the near future to render the sector more sustainable, it is key to understand well the state-of-art of this technology.

In light of the above, this review aims to summarize the state of knowledge of CWs for WWW treatment focusing on full-scale on-site systems and highlighting technical, environmental and socio-economic benefits and drawbacks. While previous reviews considered only technical aspects (Masi et al., 2015), this paper gives a comprehensive overview of CWs for WWW treatment also in terms of environmental, economic and social aspects, resulting in a more holistic view of this sector than provided in earlier publications. Additionally, since 2015 several new CW systems for WWW treatment have been implemented. As such, this article provides a more updated insight into the topic.

2. Methodology

In this study, a methodology based on literature review was employed to evaluate the literature concerning the use of CWs for WWW treatment. The following combination of keywords was used to search publications in Scopus: “wine” AND “wastewater” AND “constructed wetland”, and the search was limited to documents in English.

The search yielded more than 30 documents that dealt with the topic under study. These documents were screened to check their eligibility for this review. Articles reporting case studies (i.e. full-scale systems) of CWs for WWW treatment were selected. Those studies that did not report the essential information (i.e., dimensions, CW type) and that were not implemented at full-scale in wineries were discarded.

In addition to journal articles retrieved from Scopus, surveys, documents and data obtained from the WETWINE project (http://wetwine.eu/) were also considered http://wetwine.eu/) (UPC, 2018). The WETWINE project aimed to promote environmentally friendly and innovative solutions to treat effluents produced by wine industries in the South-West of Europe (SUDOE Programme).

In the end, 28 case studies of full-scale CWs for WWW treatment were found to be eligible for this study. After reviewing all the publications, three main topics were considered to be central for the review as they are strongly related to sustainability. These topics are technical aspects, environmental aspects and socio-economic aspects.

From each system included in the review, general, technical, operational and socio-economic information was collected. As for general information, the data that was retrieved from each system was: location, type of wastewater treated, size of the winery and of the CW system, type of primary treatment and CWs, and macrophyte utilized. As for technical, operational and socio-economic details, the data collected was: hydraulic retention time (HRT), inflow, organic load rate (OLR), removal efficiency, effluent and sludge reuse, and costs per volume of treated water.

This article is structured following the three issues described above.

3. Results of the literature review

3.1. Technical aspects

Technical aspects are described in this section, including WWW and sludge characteristics, as well as the design of the reviewed CW system. Table 1, 2, 3 and 4 summarize the characteristics of the systems reviewed.

3.1.1. Winery wastewater characteristics

Several organic and inorganic complex compounds can be found in WWW. In Table 1, WWW characteristics from the different wineries reviewed are presented.

It can be observed that the organic fraction is mostly easily biodegradable. Nevertheless, recalcitrant compounds such as polyphenols, tannins, or lignins are also present (13.1 to 1450 mg/L). This could inhibit microbial activity during wastewater treatment (Bhat et al., 1998). The biodegradable contaminants contain highly soluble sugars (e.g. glucose and fructose), alcohols in a major quantity (e.g. ethanol and glycerol) and organic acids which are responsible for decreasing WWW pH (e.g. tartaric, acetic, lactic and malic) (Arienzo et al., 2009; Vymazal, 2014).

In the reviewed systems, the inorganic fraction contains sodium (1 to 1160 mg/L), potassium (12.4 to 8000 mg/L), calcium (1.8 to 2203 mg/L), magnesium (1.1 to 530 mg/L) and heavy metals coming mainly from cleaning and disinfection agents (e.g. sodium hydroxide and potassium hydroxide), residual pesticides and other processes carried out at the winery (Anastasiou et al., 2009; Arienzo et al., 2009; Chapman, 1995).

3.1.2. Sludge characteristics

According to Ruggieri et al. (2009), the sludge produced from WWW treatment can contribute around 12% of the total organic waste produced in a winery. Sludge can contain high pollutant concentrations which need to be characterized to provide safe reuse and guarantee environmental and human health. Sludge comes from the primary treatment (e.g. septic tank, anaerobic digester) and/or from the secondary treatment (e.g. in an activated sludge system). It is usually centrifugated, transported and treated by third parties. However, as mentioned above, it can be treated on-site with sludge treatment wetlands or even composted with other solid waste.

Table 2 shows sludge properties from different wineries. According to the collected data, sludge from wineries is rich in organic matter and contains nutrients whose concentration varies depending on each winery practices, WWW quality and treatment system (e.g. average of 9.51 g/kg of nitrogen and 5.54 g/kg of phosphorus). However, sludge contains concentrated heavy metals, pathogens and some residual organic compounds.

3.1.3. Constructed wetland design

The reported first application of CWs for WWW treatment was set up as a pilot scale in a winery in California (USA) in the 90s (Shepherd et al., 2001). Since then, CWs for WWW and sludge treatment have been applied in several countries around the world, including France, Italy, Germany, Spain, South Africa, and Canada.

A summary of the characteristics of the systems reviewed in this study can be found in Figure 1. Disaggregated data corresponding to the plots has been included in Tables 3 and 4, which contain, respectively, general information and technical aspects of the reviewed CWs.

Overall, different combinations of CWs and primary treatment have been reported up to date. A septic tank or an Imhoff tank with HSSF CWs is the most implemented solution in small wineries showing good performances (Table 3). The use of an anaerobic digester (i.e. upflow anaerobic sludge blanket (UASB), hydrolytic upflow sludge bed (HUSB)) with hybrid CW systems has been demonstrated to be an efficient solution in terms of reducing solids, organic matter and avoiding clogging risks (Flores et al., 2021; Serrano et al., 2011). In some cases, STWs have been implemented to treat and reuse the sludge from the primary treatment in the same winery (Flores et al., 2021). Among all the combinations, successful experiences have been reported by implementing French vertical flow systems which showed excellent performance, especially during the peak loads that characterize WWW treatment systems (Masi et al., 2018a; Rizzo et al., 2020).

As can be seen, there is a similar proportion of systems using winery wastewater and a combination of winery and domestic wastewater. Mixing WWW with domestic wastewater could benefit the performance of the CWs in terms of having a supplement of nutrients and reducing the possible phytotoxicity risk and plant death if treated water is reused in agriculture (Arienzo et al., 2009).

The inflow of the reviewed systems shows a very large range, thus, the reported dimensions of the CWs show high variations.

It can be seen that the most common macrophytes used in the systems analyzed are *Phragmites australis*, *Typha latifolia* and *Schoenoplectus tabernaemontani*. As WWW has low nutrient concentration, some authors recommend the addition of fertilizers to facilitate macrophyte growing during the growing season (Milani et al., 2020).

Regarding removal efficiency, most systems reviewed performed well. Horizontal and vertical CW systems can reach up to around 90% of organic components removal (Parde et al., 2021). Additionally, hybrid and French vertical flow systems can reach up to 96-99% organic matter removal efficiency (Ávila et al., 2016; Masi et al., 2018a). As an exception, the two systems built in Bordeaux did not perform efficiently (only between 50 to 70% BOD removal) as the design scheme of these systems was not capable of fulfilling discharging requirements even when recirculation was applied (Rochard et al., 2002).

Publications reporting CWs for WWW treatment have indicated various issues occurring during the treatment process, including short-circuiting problems due to solids overloading and fine particle presence (Grismer et al., 2003), clogging problems during the vintage season due to higher organic load (Masi et al., 2002; Masi et al., 2018a), and algal blooms in the FWS CWs (Masi et al., 2002). Most of these issues can be solved by improving the designs of the systems. While Grismer et al. (2003) did not describe a solution for the short-circuiting problems, other authors proposed using gravel as the preferred medium (Sundaravadivel and Vigneswaran, 2007; Williams et al., 1995). Regarding clogging, De la Varga et al. (2013) concluded that shallower HSSF had a higher risk of clogging and that the HUSB digester helps its prevention in CWs with a high suspended solids removal in comparison to other primary treatment systems (e.g., septic tanks and Imhoff tanks). Also, French vertical flow systems showed to be a suitable solution to avoid clogging (Rizzo et al., 2020). To deal with algal blooms in FWS CWs, Masi et al. (2002) inserted a gravel bed of small dimensions in the last stage of the FWS unit. This allowed for highly efficient water filtration before the last zone with deep water. Also, neutralization of pH in the inlet has been attempted to test if CWs performance increased but the results obtained in the WETWINE project were not enough to come up with a decision (WETWINE, 2019).

On the whole, CW systems performance strongly depends on the design. Indeed, well-designed CWs can reach appropriate removal efficiency, avoiding most of the aforementioned problems. In this sense, the analysis carried out in this review concluded that the optimal average design parameters are: i) OLR of 35 g COD m^{-2} day^{-1} and HRT of 6 days for the HSSF CWs; ii) OLR of 50 g COD m^{-2} day^{-1} for VF CWs and, iii) OLR of 65 g COD m^{-2} day^{-1} OLR for French vertical flow systems. It can be observed that the design OLRs are higher compared to CW systems that treat municipal wastewater (Dotro et al., 2017; García and Corzo, 2008). However, they correspond to average values since, as mentioned above, the organic load fluctuates during the year with peak values up to more than 200 g COD m^{-2} day^{-1}.

Finally, from a technical point of view, CWs are feasible technologies to treat both wastewater and sludge from wineries. In particular, the application of hybrid CWs with a compatible primary treatment (e.g. HUSB or UASB) and French vertical flow systems can reduce more than 90% of the organic pollutants and solids from WWW while avoiding clogging.

3.2. Environmental aspects

Even though wine production is perceived as an environmentally friendly sector, there exist several potential environmental threats linked to the different stages of its lifecycle. Wineries need a high amount of resources (inputs) such as tap water, energy, fertilizers, cleaning products, packaging, or other raw materials. Besides, they generate a huge amount of waste and pollutants (outputs) such as wastewater, solid waste, greenhouse gas emissions, emissions to water, or emissions to the soil (Arcese et al., 2012).

Hence, when designing and operating a WWW treatment system, the consideration of the environmental impacts is decisive to choose the best available technology. For this purpose, life cycle assessment (LCA) and other quantification and multicriteria analysis methodologies are helpful to provide a solid foundation during the decision-making process.

Many studies have approached the environmental impacts of wine production, but system boundaries seldom consider the wastewater treatment process despite it being a major output. To the best of the authors' knowledge only three studies have addressed the environmental impacts and carbon footprint of WWW treatment analyzing and comparing different treatment technologies (Flores et al., 2020, 2019; Masi et al., 2018a).

According to Flores et al. (2020), the implementation of CWs for WWW and sludge treatment can reduce the carbon footprint (CFP) up to 42 times (70-98%) compared to other practices and conventional technologies adopted (i.e. third-party management and activated sludge system). This is mainly due to the fact that CWs do not need chemicals nor excessive electricity consumption and can treat wastewater and sludge on-site, avoiding third-party transportation and management. Most of the CW systems reviewed have a passive operation where wastewater is fed by gravity.

Additionally, systems that require electricity are only for the use of small pumps and valves which only operate a few hours per day. The overall environmental impact of electricity in CWs could range between 0% to 30% depending on the impact category and season of the year (Flores et al., 2019). Usually, WWW systems are implemented on-site only to meet the requirements for discharge into the sewage system. Thus, WWW is further treated in a municipal wastewater treatment plant. To avoid this, it is important to ensure proper WWW treatment to promote its reuse for irrigation or other purposes on-site. This could reduce between 20 and 75% of the total impacts, as reusing treated water for irrigation could generate environmental benefits given that the use of clean water is avoided (Flores et al., 2019). Within the literature reviewed, around 40% of the CW systems reused the treated wastewater for irrigation.

Focusing on direct air emissions from a CWs system, the contribution to the CFP was reported at 30% during the vintage season and 5% during the rest of the year (Flores et al., 2020). The reason behind this huge difference was because CWs emitted greater greenhouse gas (GHG) emissions (i.e., N_2O and CH_4) during the vintage season as WWW had a higher organic load. GHGs mass emission per cubic meter of treated water could be up to 60 times higher during the vintage season (Flores et al., 2021). Despite the higher contribution of direct GHG emissions to the CFP in CWs in comparison with other conventional technologies, the indirect emissions caused by electricity and chemicals consumption are practically negligible, which therefore compensates for the overall environmental impacts. Overall, the CFP of CWs is up to 5 times lower compared to the conventional strategies for WWW treatment and management (i.e. third-party management, activated sludge system).

Around 10% of the total cases reviewed considered sludge treatment and reuse for land application in the same winery. Treating sludge on-site avoids severe environmental impacts coming mainly from fossil fuel requirements and direct GHG emissions produced during transportation and conventional treatment (e.g. incineration) and disposal (e.g. landfill). Moreover, sludge reuse can compensate for negative impacts and avoid the production of conventional fertilizers or soil conditioners (Flores et al., 2019; Ruggieri et al., 2009).

Masi et al. (2018a) estimated the energy consumption and CFP from different CWs to treat winery wastewater, including different WWW systems reviewed in this article (Masi et al., 2002; Rizzo et al., 2020; Serrano et al., 2011). The results obtained showed that the lowest CFP was achieved by the French vertical flow system coupled with HSSF and FWS CWs due to the lower energy consumption. In the second place, there was the anaerobic digestion (HUSB reactor) coupled with hybrid CWs (VF+HSSF). In last place, there was the combination of conventional treatment (sequencing batch reactor, SBR) with the sludge treatment through STW.

Finally, from an environmental point of view, CWs are decentralized technologies for winery wastewater treatment that help reducing up to more than 90% of environmental impacts associated with WWW treatment and management by avoiding wastewater and sludge transportation and reducing electricity and chemicals consumption compared to conventional solutions.

3.3. Socio-economic aspects

Even though past publications regarding the use of CWs for WWW and sludge treatment have focused more on technical aspects, some authors have also commented on the socio-economic benefits and disadvantages that such systems have. In the following sections, two main elements are reviewed, namely costs, and social considerations.

3.3.1. Costs

From an economic point of view, the most significant impacts are given by construction, operation, and maintenance. It needs to be noted that not all the reviewed publications report costs for the different lifecycle stages of the systems.

Regarding costs for the construction of the systems, their value can range between 0.23 to 2.30 € per cubic meter of treated water depending on the type of CW, the pretreatment, the total number of treatment stages and the inflow treated (Flores et al., 2020; Masi et al., 2002). Furthermore, building on already available infrastructure in wineries has the potential of reducing construction costs. This was the case of the Ornellaia winery, where an existing pond used for wastewater storage was converted into a combined FWS CWs and a polishing pond (Masi et al., 2002).

In comparison to construction costs, the operation and maintenance costs of CWs are low (around 0.04 € m^{-3}). According to Flores et al (2020), the use of CWs could allow reducing up to 60 times the operation and maintenance costs compared to conventional technologies or other external management options. Comparing the use of CWs alone or the combination of a conventional system (e.g. activated sludge systems) with sludge treatment through STW, the operational costs could be from 5 to 10 times higher in the latter (Masi et al., 2015). Indeed, on-site sludge treatment can avoid transportation and management costs (up to 92% of the costs). Besides, as claimed by (Ruggieri et al., 2009), co-composting sludge with solid organic waste (i.e. stalk) on-site can reduce 58% of the total waste management costs, which points to the economic feasibility of these systems.

Electricity costs can also be significantly reduced thanks to CWs operation. Gravity-feeding systems for CWs or passive HSSF and FWS CWs can work without electricity. Small solar panels could also work in compatible climate conditions as pumps and valves electricity requirements are low. Comparing different approaches from this review, the combination of a conventional SBR with sludge treatment through STWs resulted to be the most expensive solution. On the contrary, the use of French vertical flow wetlands was the cheapest option in terms of energy consumption (Masi et al., 2018a), demonstrating again that this last option is among the most competitive ones.

In light of the above, results from previous studies show that costs linked to the use of CWs for WWW are lower than those in which conventional systems (e.g. activated sludge) are used. If the treated water is reused, the economic cost of using clean water is also avoided. Moreover, if other resources (e.g. bioenergy from biogas, biofertilizer from sludge) are recovered, wineries can save part of the total costs from conventional resource consumption.

Finally, in terms of costs, CWs can reduce up to 60 times the costs associated with the treatment and management of WWW.

3.3.2. Social considerations

In CW systems, there is no need for specialized workers as the operation and maintenance of the systems are simpler than in conventional systems. Thus, the construction of these systems may provide job opportunities to local people. Additionally, CWs can very often be constructed with local materials, which can foster local development (Vymazal, 2021).

Besides, CWs provide multiple ecosystem services (Yang, 2008; Semeraro, 2015; Snyder, 2019). For example, in social terms, the implementation of these natural systems improves the landscape quality around the wineries transforming it into a rich ecosystem with an esthetic appearance, zero noise production and a huge added value as a recreative area for visitors or educational purposes.

Aside from employment and ecosystem services, there are other additional social factors that need to be examined in more detail, such as health issues. For instance, Hua (2003) mentions the potential of local health problems that might arise if the monitoring of CWs is not adequate.

Despite the importance of the above aspects, to the best of the authors' knowledge, no study has yet thoroughly assessed social issues concerning CWs for WWW.

4. Discussion: challenges and opportunities

One of the major challenges detected from the review is related to the fluctuations that characterize WWW treatment. WWW flows present instantaneous, hourly, daily and seasonal variabilities where the highest loads and almost 80% of the annual volume are concentrated during the vintage season (Chapman, 1995; De La Varga et al., 2017; Serrano et al., 2011). Especially during this season, WWW is characterized by high organic content, high levels of salinity, high acidity and low nutrient content (Bustamante et al., 2005; Flores et al., 2019; Sheridan et al., 2011).

For this reason, WWW treatment facilities must be adaptive to these seasonal changes and still have efficient removal rates to accomplish the legislation. Furthermore, WWW should be managed and treated in the same winery or community of wineries since it cannot be sent directly to a municipal wastewater treatment plant (Petruccioli et al., 2002; Ruggieri et al., 2009). It has been demonstrated that transporting and managing effluents outside of the winery can have huge environmental and economic impacts (Flores et al., 2020).

Another major challenge is the selection of the most appropriate CW system to ensure environmental, economic, and social benefits. The environmental impacts analyzed in the reviewed studies show that the implementation of nature-based approaches could allow for obtaining more environmental benefits. CWs can decrease the impact in terms of climate change with respect to conventional treatment (e.g. activated sludge) by 40 times (Flores et al., 2019). In terms of water eutrophication, the decrease in the potential impacts is of 4 times with respect to conventional treatment (Flores et al., 2019).

However, land availability is indispensable when only CWs are desired for the whole WWW and sludge treatment. Land requirements of CWs are 5–10 m^2/PE, 1–3 m^2/PE and 1–2.5 m^2/PE for HSSF, VF and French vertical flow systems, respectively (Dotro et al., 2017; Parde et al., 2021). For hybrid systems, it showed to be around 2 m^2/PE (Ávila et al., 2016). As mentioned above, French vertical flow systems do not require any primary treatment, which further reduces the area footprint. Thus, when sufficient land is not available, French vertical flow systems seem to be the most feasible option.

In the wineries that already have a conventional system (e.g. activated sludge), STW can be implemented to avoid sludge management outside of the wineries and reduce environmental and economic impacts (Flores et al., 2019).

As mentioned above, there is a wide range of CW types that can be optimal and sustainable to treat WWW. For instance, hybrid CWs for WWW and sludge treatment with anaerobic digestion as a primary treatment showed to be a suitable solution (Tables

1 and 2). Indeed, a UASB digester retains solids and reduces organic matter entering the CWs, which allows for avoiding the risk of clogging. Furthermore, this integral design promotes the circular bioeconomy by recovering resources such as treated water for irrigation purposes, stabilized sludge as a soil conditioner and biogas as an energy input in the same winery. Nonetheless, other systems can also be suitable depending on the context. For instance, French vertical flow systems have great potential especially when land availability is a concern. Moreover, these systems are simple to implement, maintain and operate. In fact, they treat sludge and wastewater in a single line avoiding the implementation of other units (e.g. for sludge treatment), reducing costs and easing their operation and maintenance (Masi et al. 2018a and b).

5. Conclusions

This review aimed to summarize the state of knowledge of constructed wetlands (CWs) for winery wastewater and sludge treatment focusing on full-scale on-site systems and highlighting technical, environmental and socio-economic benefits and drawbacks.

From a technical point of view, hybrid systems, coupled with anaerobic digestion, and French reed bed systems were shown to have the highest performance reaching high organic matter and solids removal efficiencies (>90%) while avoiding clogging. Only a few case studies considered, where needed, CWs for sludge treatment and reuse on-site, which allows for avoiding impacts given by sludge transportation and management. This solution can also be applied in wineries where a conventional system (e.g. activated sludge system) has been already implemented and sludge is transported and treated by a third party.

From an environmental perspective, CWs can minimize the environmental impacts (>90%) compared to conventional solutions by reducing the use of chemicals, energy and transportation due to the need for third-party management. Other environmental benefits of CWs include promoting the circular economy and avoiding the use of raw materials. In the studied systems, this was achieved with the reuse of treated water for irrigation as well as the reuse of treated sludge as a fertilizer or soil conditioner in the vineyards. However, proper monitoring of the treatment system should be assessed to ensure that water and sludge qualities comply with the legislation and no harmful effects are caused in the ecosystem.

From a socio-economic point of view, CWs can drastically reduce the costs (up to 60 times) associated with winery wastewater treatment and management compared to conventional treatment and management (e.g. activated sludge, third-party management). However, further studies should be carried out in order to systematically assess the social benefits of CWs in the wine sector.

Finally, future systems implemented should not only consider technical aspects but also environmental and socio-economic ones to promote sustainability in this sector and adopt a new waste-to-resource approach. In particular, more efforts should be made in order to define the social benefits of this technology and the quality of the recovered resources (e.g. treated water, fertilizer) in order to promote the circular bioeconomy without compromising human and ecosystem health.

Acknowledgments

This research was funded by the European Regional Development Fund (Interreg V-B SUDOE programme, WETWINE SOE1/P5/E0300) (http://wetwine.eu/). Laura Flores is grateful to the Ministry of Education and Culture (MECD) (Spain) for the FPU16/01491 scholarship. Joan García, Marianna Garfí and Laura Flores are grateful to the Government of Catalonia (Consolidated Research Group 2017 SGR 1029). Marianna Garfí is grateful to the Spanish Ministry of Economy and Competitiveness (RYC-2016-20059). The authors are grateful for the support provided by the WETWINE consortium and the wineries involved in this study.

List of abbreviations

CFP	Carbon footprint
COD	Chemical oxygen demand
CW	Constructed wetland
D	Depth
DM	Dry matter content
FVW	French vertical flow wetland
FWS	Free water surface
GHG	Greenhouse gas emissions
HRT	Hydraulic retention time
HSSF	Horizontal subsurface flow
HUSB	Hydrolytic upflow sludge bed
L	Length
LCA	Lifecycle assessment
O&M	Operation and maintenance
OC	Organic carbon
OLR	Organic loading rate

OM	Organic dry matter content
RY	Rest of the year
SBR	Sequencing batch reactor
STW	Sludge treatment wetland
TKN	Total kjeldahl nitrogen
TN	Total nitrogen
TP	Total phosphorous
TS	Total solids
UASB	Upflow anaerobic sludge blanket
VF	Vertical flow
VS	Vintage season
W	Width
WWW	Winery wastewater

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Table 1 Winery wastewater characteristics

Parameter	**Unit**	**Min**	**Max**	**References**
Physico-chemical characteristics and nutrients				
pH	-	2.8	12.9	Anastasiou et al., 2009; Arienzo et al., 2009; Bustamante et al., 2005; Chapman, 1995; Colin et al., 2005; De la Varga et al., 2013; Flores et al., 2019; Grismer and Shepherd, 2011; Johnson and Mehrvar, 2019; Kumar et al., 2006; Litaor et al., 2015; Masi et al., 2002; Rizzo et al., 2020; Rodríguez-Chueca et al., 2017; Serrano et al., 2011; Shepherd et al., 2001; Skornia et al., 2020; UPC, 2018; Valderrama et al., 2012; Vlyssides et al., 2005
EC	μS cm^{-1}	180	6,300	Anastasiou et al., 2009; Arienzo et al., 2009; Bustamante et al., 2005; Chapman, 1995; Johnson and Mehrvar, 2019; Kumar et al., 2006; Litaor et al., 2015; Rodríguez-Chueca et al., 2017; UPC, 2018; Valderrama et al., 2012
COD	mg L^{-1}	30	360,000	Anastasiou et al., 2009; Andreottola et al., 2007; Arienzo et al., 2009; Bustamante et al., 2005; Chapman, 1995; Colin et al., 2005; De la Varga et al., 2013; Flores et al., 2019; Grismer et al., 2003; Grismer and Shepherd, 2011; Johnson and Mehrvar, 2019; Litaor et al., 2015; Masi et al., 2002; Petruccioli et al., 2002; Rizzo et al., 2020; Rodríguez-Chueca et al., 2017; Rozema et al., 2016; Serrano et al., 2011; Shepherd et al., 2001; Skornia et al., 2020; UPC, 2018; Valderrama et al., 2012; Vlyssides et al., 2005
BOD$_5$	mg L^{-1}	15	130,000	Bustamante et al., 2005; Chapman, 1995; De la Varga et al., 2013; Flores et al., 2019; Johnson and Mehrvar, 2019; Kumar et al., 2006; Masi et al., 2002; Rozema et al., 2016; Serrano et al., 2011; UPC, 2018; Vlyssides et al., 2005
TOC	mg L^{-1}	143	2,674	Kumar et al., 2006; Lofrano and Meric, 2016; Rodríguez-Chueca et al., 2017; Serrano et al., 2011
TS	mg L^{-1}	748	188,000	Anastasiou et al., 2009; Bustamante et al., 2005; Chapman, 1995; Johnson and

				Mehrvar, 2019; Lofrano and Meric, 2016; UPC, 2018; Vlyssides et al., 2005
TSS	mg L^{-1}	0.7	84,400	Anastasiou et al., 2009; Andreottola et al., 2007; Arienzo et al., 2009; Bustamante et al., 2005; Chapman, 1995; Colin et al., 2005; De la Varga et al., 2013; Flores et al., 2019; Grismer et al., 2003; Grismer and Shepherd, 2011; Johnson and Mehrvar, 2019; Litaor et al., 2015; Masi et al., 2002; Petruccioli et al., 2002; Rodríguez-Chueca et al., 2017; Rozema et al., 2016; Serrano et al., 2011; Shepherd et al., 2001; UPC, 2018; Valderrama et al., 2012; Vlyssides et al., 2005
TN	mg L^{-1}	0	142.8	Bustamante et al., 2005; Flores et al., 2019; Litaor et al., 2015; Masi et al., 2002; Skornia et al., 2020; Valderrama et al., 2012
TKN	mg L^{-1}	0.51	14,300	Chapman, 1995; Grismer et al., 2003; Johnson and Mehrvar, 2019; Rozema et al., 2016; Serrano et al., 2011; UPC, 2018; Vlyssides et al., 2005
NO_3^--N	mg L^{-1}	0	362	Grismer et al., 2003; Petruccioli et al., 2002; Rizzo et al., 2020; Rozema et al., 2016; Shepherd et al., 2001; Skornia et al., 2020; UPC, 2018
NH_4^+-N	mg L^{-1}	0	118	Grismer et al., 2003; Masi et al., 2002; Rozema et al., 2016; Shepherd et al., 2001; UPC, 2018
NH_3-N	mg L^{-1}	0.001	170.6	Petruccioli et al., 2002; Serrano et al., 2011; Skornia et al., 2020
TP	mg L^{-1}	0.01	1,120	Bustamante et al., 2005; Chapman, 1995; Flores et al., 2019; Johnson and Mehrvar, 2019; Litaor et al., 2015; Masi et al., 2002; Petruccioli et al., 2002; Rizzo et al., 2020; Rozema et al., 2016; Skornia et al., 2020; UPC, 2018; Valderrama et al., 2012; Vlyssides et al., 2005
PO_4^{3-}-P	mg L^{-1}	0	35	Petruccioli et al., 2002; Serrano et al., 2011; UPC, 2018
Polyphenols	mg L^{-1}	13.1	1,450	Arienzo et al., 2009; Bustamante et al., 2005; Litaor et al., 2015; Petruccioli et al., 2002; Rodríguez-Chueca et al., 2017; Vlyssides et al., 2005
Macronutrients				
Na	mg L^{-1}	1	1,160	Bustamante et al., 2005; Chapman,

				1995; Johnson and Mehrvar, 2019; UPC, 2018
K	mg L^{-1}	12.4	8,000	Bustamante et al., 2005; Chapman, 1995; Johnson and Mehrvar, 2019; UPC, 2018
Ca	mg L^{-1}	1.8	2,203	Bustamante et al., 2005; Chapman, 1995; Johnson and Mehrvar, 2019
Mg	mg L^{-1}	1.1	530	Bustamante et al., 2005; Chapman, 1995; Johnson and Mehrvar, 2019
Heavy metals				
Al	mg L^{-1}	0.04	1,030	Johnson and Mehrvar, 2019
As	mg L^{-1}	0.001	0.02	Andreottola et al., 2007
Ba	mg L^{-1}	0.05	1.36	Andreottola et al., 2007
Cd	mg L^{-1}	<0.005	0.08	Anastasiou et al., 2009; Andreottola et al., 2007; Bustamante et al., 2005; Lofrano and Meric, 2016
Co	mg L^{-1}	0.11	0.3	Bustamante et al., 2005
Cr	mg L^{-1}	<0.005	0.72	Anastasiou et al., 2009; Andreottola et al., 2007; Bustamante et al., 2005; Lofrano and Meric, 2016
Cu	mg L^{-1}	<0.20	11.13	Anastasiou et al., 2009; Andreottola et al., 2007; Bustamante et al., 2005; Lofrano and Meric, 2016
Fe	mg L^{-1}	0.001	335	Bustamante et al., 2005; Chapman, 1995; Johnson and Mehrvar, 2019
Hg	mg L^{-1}	3.00E-04	2.20E-03	Andreottola et al., 2007
Mn	mg L^{-1}	0.06	1.74	Andreottola et al., 2007; Bustamante et al., 2005
Ni	mg L^{-1}	0.003	3	Anastasiou et al., 2009; Andreottola et al., 2007; Bustamante et al., 2005; Lofrano and Meric, 2016
Pb	mg L^{-1}	0.02	1.34	Andreottola et al., 2007; Bustamante et al., 2005
Zn	mg L^{-1}	0.012	46	Anastasiou et al., 2009; Andreottola et al., 2007; Bustamante et al., 2005; Lofrano and Meric, 2016

Table 2 Characteristics of sludge from winery wastewater systems

Type of winery wastewater treatment		Constructed wetland	Activated sludge system	Lagoon system	Constructed wetland	Activated sludge system
Type of sludge treatment		Sludge treatment wetland	Sludge evaporation system	-	Composting mixed with organic waste	-
Parameter	**Unit**					
pH	-	9.6	9.8	6	7.3	7.1
moisture	%	62.4	-	-	-	-
COD	g/kg	-	-	0.216	-	52.1
OC	%	6.55	18	-	-	-
TS	g/kg	-	-	15.2	-	44
TKN	g/kg	9.7		59	-	68
TN	g/kg	0.08	0.21	-	22	-
N_{org}	g/kg	9.51	-	-	-	-
TP	g/kg			7.71	1.4	7.51
P_2O_5	g/kg	5.35	<0.20	17.7	-	17.2
K+	g/kg			21.7	4.8	8.83
B	mg/kg			-	-	3.8
K_2O	g/kg	12.53	0.40	-	-	0.59
MgO	g/kg	3.88	0.10	-	-	0.17
CaO	g/kg	70.45	1.40	-	-	0.89
Na_2O	g/kg	8.08		-	-	0.19
Ca	g/kg			-	6.4	-
Mg	g/kg			-	1.3	-
OM	%	13.1	35	-	27.5	-
DM	%	30	35	-	30.8	-
Co	mg/kg	3.08		-	-	-
Cu	mg/kg	256	250	-	-	7.6
Fe	mg/kg	12.725		-	-	170
Mn	mg/kg	215.25		-	-	10.6
Mo	mg/kg	2.01		-	-	0.062
Zn	mg/kg	657.5	515	-	-	8.4
Cr	mg/kg	53.03	44	-	-	-
Ni	mg/kg	26.6	21	-	-	-
Cd	mg/kg	0.38	<0.42	-	-	-
Hg	mg/kg	0.21	0.15	-	-	-
Pb	mg/kg	29.3	21	-	-	-

Table 3. Review of constructed wetlands (CWs) for winery wastewater treatment. General winery information and treatment schemes.

	Location	Winery	Type of wastewater	Winery size (wine production, L year^{-1})	Starting operation date	Primary treatment	CW type	CWs (area, m^2)	CW size (L X W X D, m)	Macrophyte	Reference
1	Hopland (California, USA)	Fetzer Vineyards	Winery	Big (18,200,000)	Summer 1995	Upflow coarse-sand filter	Pilot HSSF	HSSF (14.9)	6.1 X 2.44 X 0.95	Typha domingensis, Scirpus acutus, Sagittaria latifolia	Shepherd et al. (2001)
2	Hopland (California, USA)	-	Winery	Big	1998	Solids removal + facultative pond	HSSF	HSSF (4,400)	50 X 88 X 1	Cattail and bulrush	Grismer et al. (2003)
3	Glen Ellen (California, USA)	-	Winery	Medium	-	Solids removal + rotary screen + facultative pond	HSSF	HSSF (304) + recirculation (during the study)	8 X 38 X 1	Cattail and bulrush	Grismer et al. (2003)
4	Bordeaux (France)	-	Winery + domestic	Small (50,000-60,000)	-	Straw screening	VF	2 VF series (35.6 total) + recirculation	-	18 different macrophytes	Rochard et al. (2002) in Masi et al. (2015)
5	Bordeaux (France)	-	Winery	Big (600,000)	-	Sand filter + aerated tank	VF	2 VF series (15.7 and 17.4) + recirculation	-	-	Rochard et al. (2002) in Masi et al. (2015)
6	Leghorn (Italy)	Ornellaia	Winery + domestic	-	2000 (upgraded in 2006)	Imhoff tank	Hybrid	2 VF parallel (90 each) + HSSF (102) + FWS (148) + pond (338) + recirculation	5 X 18 X 0.9 (VF); 17 X 6 X 0.7 (HSSF)	Different emergent and submerged macrophytes	Masi et al. (2002)
7	Siena (Italy)	La Croce	Winery	Small (<50,000)	2001	Imhoff tank + degreasers	HSSF	HSSF (215)	21.5 X 10 X 0.7	Phragmites australis	Masi et al. (2002)
8	Siena (Italy)	Luigi Cecchi & Sons	Bottling and aging (not wine making)	-	2001 (upgraded in 2009)	Imhoff tank	Hybrid	HSSF (480) + FWS (850)	30 X 16 X 0.7 (HSSF)	Phragmites australis (HSSF)	Masi et al. (2002)
9	Siena (Italy)	Luigi Cecchi & Sons	Bottling and aging (not wine making)	-	2009	-	Hybrid	3 FVW (400 each) + 4 HSSF parallel (960) + FWS (850) + optional sand filter (50) + emergency recirculation	D = 0.85 (FVW); 14 X 12 X 0.8 (3 new HSSF)	Phragmites australis (FVW and HSSF)	Rizzo et al. (2020)
10	Siena (Italy)	Luigi Cecchi & Sons	Bottling and aging (not wine making)	-	2009	-	Hybrid	3 FVW (400 each) + 4 HSSF parallel (960) + FWS (850) + optional sand filter (50) + emergency recirculation	-	Phragmites australis (FVW and HSSF)	Masi et al. (2018a)

11	Stellenbosch (South Africa)	Experimental winery ARC	Winery	-	2001	-	HSSF	HSSF (160)	40 X 4 X 1	Phragmites australis	Sheridan et al. (2014)
12	Western Cape (South Africa)	-	Winery + distillery	Small	2002	Facultative pond	HSSF	HSSF (180)	45 X 4 X 1.2	Phragmites australis, Typha sp. and Scirpus sp.	Mulidzi (2007)
13	Vercia (France)	-	Domestic + winery (during VS)	-	2004	Biological aerobic trickling filter	VF	2 partially saturated VF series (600 each) with sludge accumulation layer (1st stage)	D = 0.8	-	Kim et al. (2014)
14	Piedmont (Italy)	Podere Ruggeri Corsini	Winery	-	June 2007	Septic tank + grid + Imhoff tank	HSSF	HSSF (24)	-	Phragmites australis	Rochard et al. (2010) in Masi et al. (2015)
15	Galicia (Spain)	-	Winery + domestic	Big (315,000)	April 2008	Storage tank + HUSB	Hybrid	VF (50) + 3 HSSF parallel (100 each)	D = 1.2 (VF); D = 0.3-0.6 (HSSF)	Phragmites australis (VF), Juncus effusus (HSSF)	Serrano et al. (2011)
16	Ontario (Canada)	-	Winery + domestic	-	2008	Septic tank + pretreatment cell + storage tank	VF	4 VF series (101 each)	11.75 X 8.6 X 1.2	Typha latifolia L, Schoenoplectus tabernaemontani (C.C.Gmel.) Palla	Rozema et al. (2016)
17	California (USA)	-	Winery	Medium (aprox 126,000)	-	Septic tank	HSSF	2 HSSF parallel (58 each) (one unplanted)	-	Typha domingensis, Scirpus acutus, Sagittaria latifolia	Grismer and Shepherd (2011)
18	California (USA)	-	Winery	Medium (aprox 126,000)	-	Septic tank	HSSF	2 HSSF parallel (72 and 49) (one unplanted)	D = 0.91	Typha domingensis, Scirpus acutus, Sagittaria latifolia	Grismer and Shepherd (2011)
19	Gardegan (France)	Bardet's	Winery	Big (600,000)	-	Storage tank	VF	2 VF series (39.6 and 33.1)	6 X 3.5 X 1 (VF1a); 6 X 3.1 X 1 (VF1b); 5.8 X 2.7 X 1 (VF2a); 5.8 X 3 X 1 (VF2b)	Common reed	Aina et al. (2012)
20	Sicily (Italy)	Marabino	Winery + domestic	Medium (150,000)	October 2013	Screening + Imhoff tank + septic tank	Hybrid	VF (230) + HSSF (60) + FWS (30)	D = 0.6 (HSSF); D = 0.7 (FWS)	Phragmites australis (VF), Cyperus papyrus and Canna indica L. (HSSF)	Milani et al. (2020)
21	Tanzania (Eastern Africa)	-	Banana wine	-	2014	Screening + septic tank + primary clarifier + UASB reactor (biogas collection)	Hybrid	2 HSSF series (225 each) + SDRB	30 X 7.5 X 1 (HSSF)	Papyrus	Paschal et al. (2017)

22	Galicia (Spain)	-	Winery + domestic	Big (368,000)	July 2017	Storage tank + HUSB	Hybrid	2 VF parallel (15 each) + HSSF (30) + 4 STW (5 each)	5 X 3 X 1 (VF); 6 X 5 X 0.6 (HSSF); 1.5 X 3.3 X 1.2 (STW)	Phragmites australis and some Iris pseudacorus (STW)	Flores et al. (2021, 2020, 2019); UPC, 2018
23	Ontario (Canada)	-	Winery + domestic	Big	-	Septic tank (domestic); septic tank + ASFF reactor (winery)	VF	3 VF series (54.8 each)	7.4 X 7.4 X 1.2	Typha latifolia L, Schoenoplectus tabernaemontani (C.C.Gmel.) Palla	Johnson and Mehrvar (2019)
24	Ontario (Canada)	-	Winery + domestic	Big	-	Septic tank (domestic); ASFF reactor (winery)	VF	3 VF series (25 each)	5 X 5 X 1.2	Typha latifolia L, Schoenoplectus tabernaemontani (C.C.Gmel.) Palla	Johnson and Mehrvar (2019)
25	Ontario (Canada)	-	Winery + domestic	Big	-	Septic tank (domestic); septic tank + ASFF reactor (winery)	VF	3 VF series (30.6 each)	7.23 X 4.23 X 1.2	Typha latifolia L, Schoenoplectus tabernaemontani (C.C.Gmel.) Palla	Johnson and Mehrvar (2019)
26	Ontario (Canada)	-	Winery + domestic	Big	-	Septic tank + ASFF reactor	VF	4 VF series (68.3 each)	6.5 X 10.5 X 1.2	Typha latifolia L, Schoenoplectus tabernaemontani (C.C.Gmel.) Palla	Johnson and Mehrvar (2019)
27	Ontario (Canada)	-	Winery + domestic	Big	-	Septic tanks (domestic and winery); ASFF reactor (winery)	VF	3 VF series (29.2 each)	5.4 X 5.4 X 1.2	Typha latifolia L, Schoenoplectus tabernaemontani (C.C.Gmel.) Palla	Johnson and Mehrvar (2019)
28	Ontario (Canada)	-	Winery + domestic	Big	-	Septic tank (domestic and winery) + recirculation	VF	4 VF series (86.2 cell1 and 37.9 the other) + recirculation	14.6 X 5.2 X 1.2 (cell1); 7.3 X 5.2 X 1.2 (the other)	Typha latifolia L, Schoenoplectus tabernaemontani (C.C.Gmel.) Palla	Johnson and Mehrvar (2019)

Note: VF: vertical flow CW; HSS: horizontal subsurface flow CW; FWS: free water surface flow CW; STW: sludge treatment wetland; FVW: French vertical wetland; HUSB: hydrolytic upflow sludge blanket reactor; L: length; W: width; D: depth: - Not reported

Table 4. Review of constructed wetlands (CWs) for winery wastewater treatment. Technical and operational and economic details.

	Location	HRT (days)	Inflow (m^3 day^{-1})	OLR (g COD m^{-2} day^{-1})	Removal efficiency (%)											Effluent reuse	Sludge reuse	Costs (€ m^{-3} treated water)	Reference
					COD	BOD_5	TSS	NO_2-N	NO_3-N	NH_4-N	NH_3-N	TKN	TN	PO_4^{3-}	TP				
1	Hopland (California, USA)	10	106-172 (VS) 46-100 (RY)	34.5-164	98	-	97	-	-	-	-	78.2	-	63.3	-	Irrigation	-	-	Shepherd et al. (2001)
2	Hopland (California, USA)	10 (1hour during VS if short-circuiting)	137	120	49 (VS) 79 (RY)	-	30 (VS) 85 (RY)	-	17 (VS) 73 (RY)	29 (VS) 62 (RY)	-	25 (VS) 66 (RY)	-	-	-	-	-	-	Grismer et al. (2003)
3	Glen Ellen (California, USA)	5	21	-	98.5	-	98	-	-	-	-	-	-	-	-	-	-	-	Grismer et al. (2003)
4	Bordeaux (France)	-	-	50-150	50-70	-	-	-	-	-	-	-	-	-	-	-	-	-	Rochard et al. (2002) in Masi et al. (2015)
5	Bordeaux (France)	-	-	50-150	50-70	-	-	-	-	-	-	-	-	-	-	-	-	-	Rochard et al. (2002) in Masi et al. (2015)
6	Leghorn (Italy)	6-10	10	23.6 (average) 56 (VS) 2-6 (RY)	92.2 (VS)	93.3 (VS)	75.4 (VS)	-	-	-	-	-	90 (VS)	-	93.8 (VS)	Reuse for irrigation	-	1.06 (capital)	Masi et al. (2002)
7	Siena (Italy)	6	8	35.2 (peak value)	87.5	91.6	-	-	-	-	-	-	54	-	-	Discharge in a water body	-	0.4 (capital)	Masi et al. (2002)
8	Siena (Italy)	3.5 (HSSF) 12 (FWS)	35	32.9	97.8	98.4	89.1	-	-	-	-	-	82.2	-	73.5	Reuse for irrigation	-	0.23 (capital)	Masi et al. (2002)
9	Siena (Italy)	5-6	90-100	8-145; 230 (peak value)	97.5	-	-	84.7	39.9	-	-	-	-	-	45.5	Discharge in a water body	-	-	Rizzo et al. (2020)

10	Siena (Italy)	-	90	Up to 200	96-99	-	-	-	-	-	-	-	-	-	-	-	Soil conditioner	0.01 (only energy)	Masi et al. (2018a)
11	Stellenbosch (South Africa)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	Sheridan et al. (2014)
12	Western Cape (South Africa)	14	4	-	82	-	-	-	-	-	-	-	-	-	-	Crop irrigation	-	-	Mulidzi (2007)
13	Vercia (France)	-	77 (VS) 70 (RY)	122 (VS) 56 (RY)	94.4	97.9	98.8	-	-	-	-	97.2	70.9	-	59.6	-	-	-	Kim et al. (2014)
14	Piedmont (Italy)	5-10	-	53 (average) 136 (peak value)	99	-	-	-	-	-	-	-	-	-	-	-	-	-	Rochard et al. (2010) in Masi et al. (2015)
15	Galicia (Spain)	3	6.83 (average) 15.10 (peak value)	30.4 (average) 466 (peak value)	73.3 (average) 50 (VS)	74.2	86.8	-	-	-	55.4	52.4	-	17.4	-	Municipal WWTP	Soil conditioner	-	Serrano et al. (2011)
16	Ontario (Canada)	-	6.97 (VS) 11 (RY) (4.3 max WWW)	34	98.9	99.9	98	-	-	85	-	94	-	-	83	Subsurface leaching bed discharge	-	-	Rozema et al. (2016)
17	California (USA)	6	-	-	96.8 (planted) 93.5 (unplanted)	-	76.1 (planted) 52.8 (unplanted)	-	-	-	-	-	-	-	-	-	-	-	Grismer and Shepherd (2011)
18	California (USA)	17.5 (planted) 24 (unplanted)	-	92	99.3 (planted) 97.9 (unplanted)	-	91.1 (planted) 85.5 (unplanted)	-	-	-	-	-	-	-	-	-	-	-	Grismer and Shepherd (2011)
19	Gardegan (France)	-	-	250-280	-	-	86.5	-	-	-	-	61.8	-	-	62.9	Discharge into a ditch	-	-	Aina et al. (2012)
20	Sicily (Italy)	5.6 (HSSF) 3.8 (FWS)	3 (only part of the total generated WWW)	15.74	78	81	69	-	-	57	-	-	56	38	-	Reuse for irrigation	-	-	Milani et al. (2020)

21	Tanzania (Eastern Africa)	-	62.4 (during study) 200 (design)	-	99	98.6	96	-	88.7	4.29	-	-	-	50.8	-	Reuse for irrigation	Land application	-	Paschal et al. (2017)
22	Galicia (Spain)	6.5 (HSSF)	1 (VS) 2 (RY) (2.5 peak value)	138 (VF, VS) 27 (VF, RY) 51 (HSSF, VS) 15 (HSSF, RY)	77 (average) 94 (VS) 88 (RY)	-	93 (VS) 66 (RY)	97	36	52	-	-	59 (VS) 66 (RY)	-	32 (VS) 33 (RY)	-	Fertilizer or soil conditioner	2.30 (capital) 0.04 (O&M)	Flores et al. (2021, 2020, 2019); UPC, 2018
23	Ontario (Canada)	-	22.5	-	-	-	-	-	-	-	-	-	-	-	-	Reuse for toilet flushing + subsurface leaching bed discharge	-	-	Johnson and Mehrvar (2019)
24	Ontario (Canada)	-	12	-	-	-	-	-	-	-	-	-	-	-	-	Subsurface leaching bed discharge	-	-	Johnson and Mehrvar (2019)
25	Ontario (Canada)	-	11.16	-	-	-	-	-	-	-	-	-	-	-	-	Subsurface discharge (shallow buried trench system)	-	-	Johnson and Mehrvar (2019)
26	Ontario (Canada)	-	10.6	-	-	-	-	-	-	-	-	-	-	-	-	Subsurface discharge (shallow buried trench system)	-	-	Johnson and Mehrvar (2019)
27	Ontario (Canada)	-	10.4	-	-	-	-	-	-	-	-	-	-	-	-	Subsurface discharge (shallow buried trench system)	-	-	Johnson and Mehrvar (2019)

28	Ontario (Canada)	-	10	-	-	-	-	-	-	-	-	-	-	-	-	Subsurface disposal	-	-	Johnson and Mehrvar (2019)

Note: HRT: hydraulic retention time; OLR: organic loading rate; VF: vertical flow CW; HSSF: horizontal subsurface flow CW; FWS: free water surface flow CW; VS: vintage season; RY: rest of the year; WWTP: wastewater treatment plant; O&M: operation and maintenance; - Not reported.

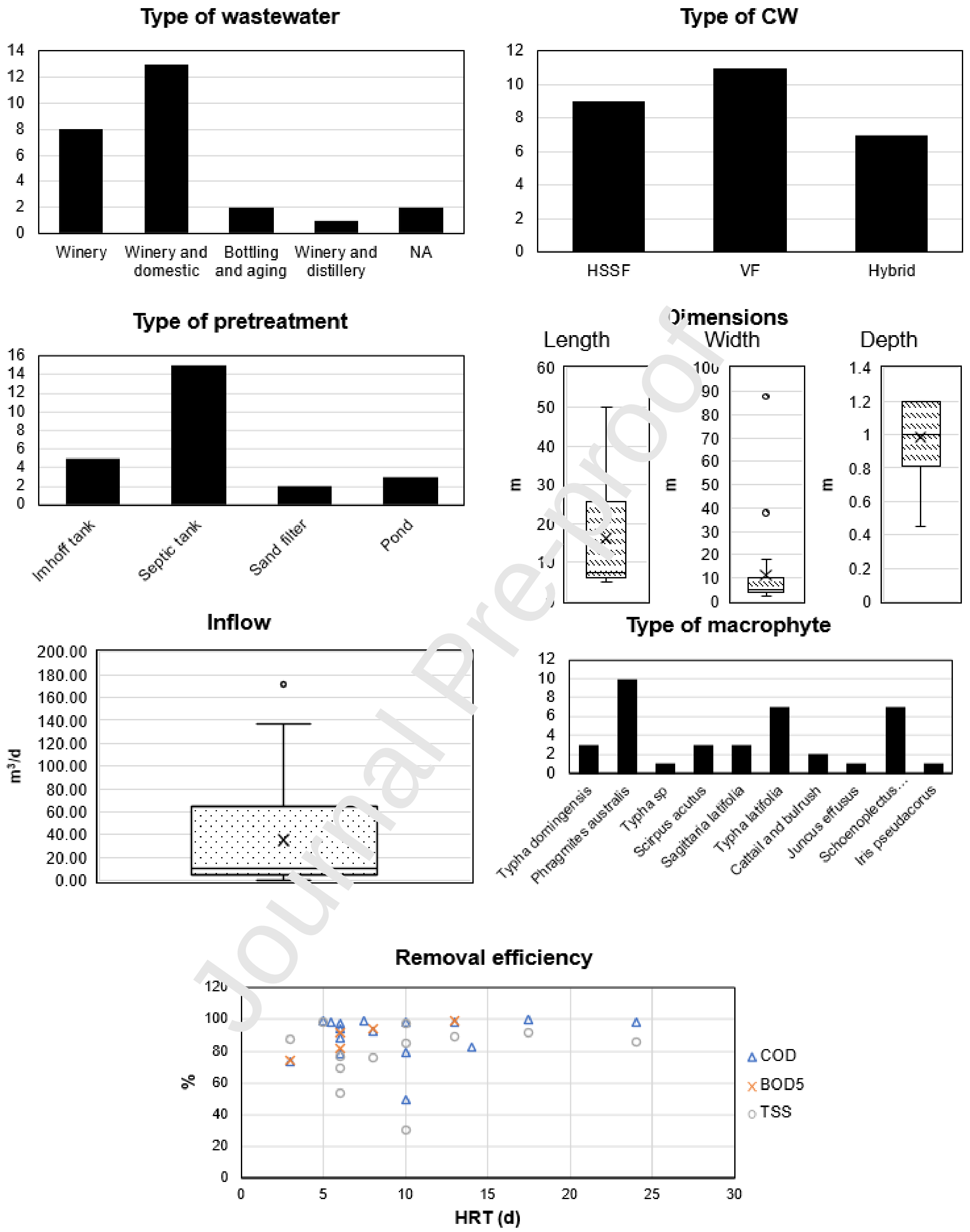

Figure 1 Summary of main characteristics of the constructed wetlands reviewed

CRediT authors' statement

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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

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Graphical abstract

Highlights

- CWs showed to be suitable solution for winery wastewater treatment
- CWs reduce > 90% of the organic pollutants and solids in winery wastewater
- CWs reduce up to 90% environmental impact associated with winery wastewater
- CWs reduce up to 60 times costs associated with winery wastewater
- Social benefits of CWs in the wine industry should be better assessed and explored