Wineries wastewater treatment by constructed wetlands: a review

F. Masi, J. Rochereau, S. Troesch, I. Ruiz and M. Soto

ABSTRACT

The application of wetland systems for the treatment of wineries wastewater started in the early 1990s in the USA followed a few years later by France, Italy, Germany and Spain. Various studies demonstrated the efficiency of constructed wetlands (CWs) as a low cost, low maintenance and energy-saving technology for the treatment of wineries wastewater. Several of these experiences have also shown lessons to be learnt, such as some limits in the tolerance of the horizontal subsurface flow and vertical subsurface flow classic CWs to the strength of the wineries wastewater, especially in the first stage for the multistage systems. This paper is presenting an overview of all the reported experiences at worldwide level during the last 15 years, giving particular attention and provision of details to those systems that have proven to get reliable and constant performances in the long-term period and that have been designed and realized as optimized solutions for the application of CW technology to this particular kind of wastewater. The organic loading rates (OLRs) applied to the examined 13 CW systems ranged from about 30 up to about 5,000 gCOD/m^2 d (COD: chemical oxygen demand), with the 80th percentile of the reported values being below 297 gCOD/m^2 d and the median at 164 gCOD/m^2 d; the highest OLR values have in all cases been measured during the peak season (vintage) and often have been linked to lower surface removal rates (SRRs) in comparison to the other periods of the year. With such OLRs the SRRs have ranged from a minimum of 15 up to 4,700 gCOD/m^2 d, with the 80th percentile of the reported values being below 308 gCOD/m^2 d and the median at 112 gCOD/m^2 d.

Key words | constructed wetlands, high organic load, hybrid systems, multistage treatment wetlands, treatment wetlands, wineries wastewater

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INTRODUCTION

World wine production is estimated nowadays to be around 250 millions of hectolitres per year, with about 62% of this total amount created in Europe, and is generating relevant fluxes of wastewater produced during the grape processing (vintage and racking) period and the following months when bottling and cleaning of containers are almost continuous operations. These fluxes of winery wastewater are often a concerning environmental problem in wine-producing countries (Serrano *et al.* 2011). This particularly complex wastewater is characterized by fluctuations in terms of quality and quantity during the whole year, which are caused by different factors such as the adopted industrial process chain and its seasonality and the kind of produced wine; on average for 1 L of wine about 1.6–2.0 L of wastewater are generated and the ratio between the organic load and the produced wine is 5–10 kgCOD/m^3 (COD: chemical oxygen demand) (Fernández *et al.* 2007; Anastasiou *et al.* 2009). Table 1 shows the characterization for wineries wastewater based on the available literature to date.

The organic content of winery wastewater consists of highly soluble sugars, 25 different alcohols, acids and recalcitrant high molecular weight compounds (e.g. polyphenols), 26 tannins, and lignins. Detailed studies of the composition of winery wastewater have revealed that ethanol and, to a smaller extent and on a temporary basis, sugars (fructose and glucose) represent more than 90% of the organic load. Organic acids, alcohols, and phenols have variable degradation rates.

Biodegradable contaminants (e.g. sugars and alcohols) tend to degrade first, leaving behind wastewater containing less easily degraded compounds, i.e. phenols and tannins (Arienzo *et al.* 2009). The phenolic composition of wines depends on the variety of grapes and on the vinification

doi: 10.2166/wst.2015.061

Table 1 | Winery wastewater characteristics in the literature (adapted from Shepherd et al. (2001) and Conradie et al. (2014))

Parameter	Min	Max	Mean	Common treatment targets
COD mg/L	340	49,103	14,570	120–160
BOD_5 mg/L	181	22,418	7,071	20–40
TSS mg/L	190	18,000	1,695	35–80
pH	3.5	7.9	4.9	6–8
N mg/L ($NH_4^+ + NO_3^-$)	2.88	364	26	15–35

COD: chemical oxygen demand; BOD_5: 5-day biochemical oxygen demand; TSS: total suspended solids.

conditions. Phenolic compounds, which are plant secondary metabolites and the main antioxidant compounds in grapes and grape products, can be divided into two groups: phenolic acids and related compounds and flavonoids. The major phenolic compounds in grape wastes are anthocyanins, catechins, glycosides of flavonols and phenolic acids (Lafka et al. 2007).

Past experiences showed that the winery wastewaters, at certain concentrations, can have phytotoxicity effects on various wetland plants species. Understanding the phytotoxicity of winery wastewater is fundamental to the design and implementation of constructed wetlands (CWs) for its treatment. The ideal plant should tolerate high-organic loads and be capable of removing significant amounts of contaminants and purifying the effluent in a relatively short time period (Arienzo et al. 2009).

Several treatment approaches have been adopted for the wineries wastewater treatment. Often it is stored and partially treated in aerated or facultative ponds and disposed of via post-harvest vineyard irrigation (Storm 1997). An exhaustive and comprehensive overview of the treatment methods has been produced by Andreottola et al. (2009); the biological treatments are subdivided into five main categories:

1. aerobic/anoxic processes using suspended biomass: activated sludge, membrane bioreactors, sequencing batch reactors (SBRs);
2. aerobic biofilm systems: rotating biological contactors, fixed bed biofilm reactors, moving bed biofilm reactors;
3. anaerobic processes using suspended biomass: anaerobic digesters (ADs), anaerobic SBRs;
4. anaerobic biofilm systems using granules (upflow anaerobic sludge blanket (UASB)) or fixed supports (anaerobic filters) or mobile supports (fluidized bed reactors);
5. CWs.

Other treatment methods can be chemical oxidation (by Fenton reaction), photocatalysis and fertirrigation (Agustina et al. 2008).

The main problems in processing this particular wastewater can be listed as:

- variable pH, usually ranging from 4 to 8 in the different periods of the year (Shepherd et al. 2001);
- low nutrient content and consequent unfavorable C/N ratio for the microbial growth;
- high content of biodegradable compounds that often leads to difficulties in operating biological systems, for instance poor sludge settleability, floc disintegration and increased presence of solids in the treated effluent (Silva et al. 2011);
- seasonality and load fluctuations;
- clogging in filtering reactors;
- phytotoxicity and microbial inhibition by toxic organic and inorganic compounds, i.e. sulfur, phenols, tannins (Arienzo et al. 2009).

The application of wetland systems for the treatment of wineries wastewater started in the early 1990s in the USA followed a few years later by France, Italy, Germany and Spain. Various studies (Shepherd et al. 2001; Masi et al. 2002; Müller et al. 2002; Rochard et al. 2002; Grismer et al. 2003; Mulidzi 2007; Vymazal 2009; Serrano et al. 2011; de la Varga et al. 2013a, b) demonstrated the efficiency of CWs as a low cost, low maintenance and energy-saving technology for the treatment of wineries wastewater. Several of these experiences have also shown lessons to be learnt, such as some limits in the tolerance of the horizontal flow (HF) and vertical flow (VF) classic CWs to the strength of the wineries wastewater, especially in the first stage for the multistage systems or in the single stage ones.

In general terms the treatment train can be related to the size of the winery, which is usually expressed in terms of quantity of produced wine per year (hL/year) and the specific treatment targets and final fate of the effluents. The lower the amount of wastewater to be treated, the simpler usually is the chosen scheme. Nowadays, there are for instance about 100 CW systems operating in Northern and Central Italy for wineries wastewater, and very often, when the productivity is lower than 2,000 hL of wine per year, the treatment scheme consists of a pretreatment by septic or Imhoff tanks, with also an equalization role, followed by a single-stage CW, horizontal subsurface flow beds in most cases or also vertical subsurface flow beds. For bigger size wineries instead the more adopted solutions are combinations of wetland systems (called multistage treatment wetlands) or combinations of CWs with other technologies, like anaerobic digestion systems (UASB, hydrolytic upflow sludge blanket (HUSB)) or aerobic biological treatments (SBR, AS).

SUMMARY OF RESULTS FROM DIFFERENT EXPERIENCES

For a synoptic view, all the different schemes adopted until now for the treatment by CW systems of wineries wastewater are summarized in Figure 1.

To enable comparison, the main characteristics and average results of the systems shown in Figure 1 and described and discussed in the paper are displayed in Table 2.

The description and critical review of all the analyzed treatment plants is structured in the following paragraphs by the typology of CWs used in the treatment scheme, followed by more detailed analysis of long-term performances for multistage and combined systems, and general discussion and conclusions.

HF CWs

Shepherd *et al.* (2001) described a pilot work for the wastewater treatment in the medium-size winery Fetzer Vineyards, Hopland, California, producing about 182,000 hL of wine per year. The system was a simple HF CW with a surface area of 14.9 m^2 (length/width = 2.5) filled with pea gravel ($D_{60}/D_{10} = 2.2$; hydraulic conductivity 2 mm/s), receiving the effluent from an upflow coarse-sand filter (0.378 m^3 by 0.25 m of height) used as pretreatment, and treating it in a single stage with a long hydraulic retention time (HRT) of about 10 days. The CW was planted with *Typha dominicus*, *Scirpus acutus* and some *Sagittaria latifolia* in October of 1995. In this experience the wastewater has been diluted with increasing final COD concentrations for performing four experiments. The diluted wastewater was applied at the beginning to the CW system at 500 L/d and 993 mgCOD/L (organic loading rate (OLR): 34.5 gCOD/m^2 d); then the COD concentration was increased up to 5,000 mg/L (OLR: 164 gCOD/m^2 d). With the exception of some reduced plant growth at the front end of the CW, the system did not exhibit any negative responses to high OLRs. Furthermore, the CW system appeared capable of withstanding fluctuating water quality without sacrificing good performances, obtaining on average 98 and 97% COD and total suspended solids (TSS) removal efficiencies. The same paper provides interesting results of a monitoring campaign for the characterization of the wastewater produced by the winery throughout the year. The measured quantity of produced wastewater was about 106–172 m^3/d during the peak season and 46–100 m^3/d for the rest of the year; the ratio between wastewater and produced wine was 2.2 L/L. The pH varied between 4 and 8. The COD fluctuations were quite considerable, from 500 to 45,000 mg/L in peak season and from 600 to 13,000 mg/L in off season. Grismer *et al.* (2001) published a study performed on the same pilot plants where the planted bed, in operation for 3 years, was compared with an unplanted reactor measuring the residence time distribution (RTD) of tracers. The study demonstrated that while tank outflow tracer RTDs could not be described using either plug-flow reactor or simple continuously mixed-system models, 20–35 tanks-in-series models adequately replicated the measured outflow RTDs. No preferential flows were observed in the CW tanks because outflow RTDs were nearly symmetric and very similar.

A single stage CW is operating in Italy, at La Croce winery (<500 hL wine/year), near Siena, and consists of an Imhoff tank and a single gravel-based HF bed (215 m^2); the measured HLR was 37 L/m^2 d and the OLR 35.2 g/m^2 d with these peak values reported during the vintage and racking season (Masi *et al.* 2002). The observed removal efficiencies were 87.5% for COD and 91.6% for 5-day biochemical oxygen demand (BOD_5). Owing to the small amount of wastewater generated by the winery (<8 m^3/d) and following the European Community directives, the local authority has authorized for this facility the assimilation of the winery effluents to domestic wastewater without fixed limits. After 14 years of operation the system is still working properly, at least apparently because the owners of the system are requested to make only a single analysis of the effluents each year and so the monitoring cannot be considered as very representative. The size of this winery is anyway the most relevant in terms of occurrence in the Italian territory, as well as in France, Spain and Greece: there are hundreds of similar facilities spread in the countryside, so this treatment approach, simple and reliable if the pretreatment (Imhoff or three-chamber septic tanks) is properly managed (in terms of periodical sludge exhaustion from the tanks), can be considered as a valid option also for the related cheap realization and management costs.

Grismer *et al.* (2003) presented an evaluation of two full-scale HF CWs servicing a moderate-production winery near Hopland and a smaller production winery near Glen Ellen, both in California. The smaller HF (304 m^2, $Q = 21$ m^3/d, HRT 5 days, OLR 553 gCOD/m^2 d) was filled with washed

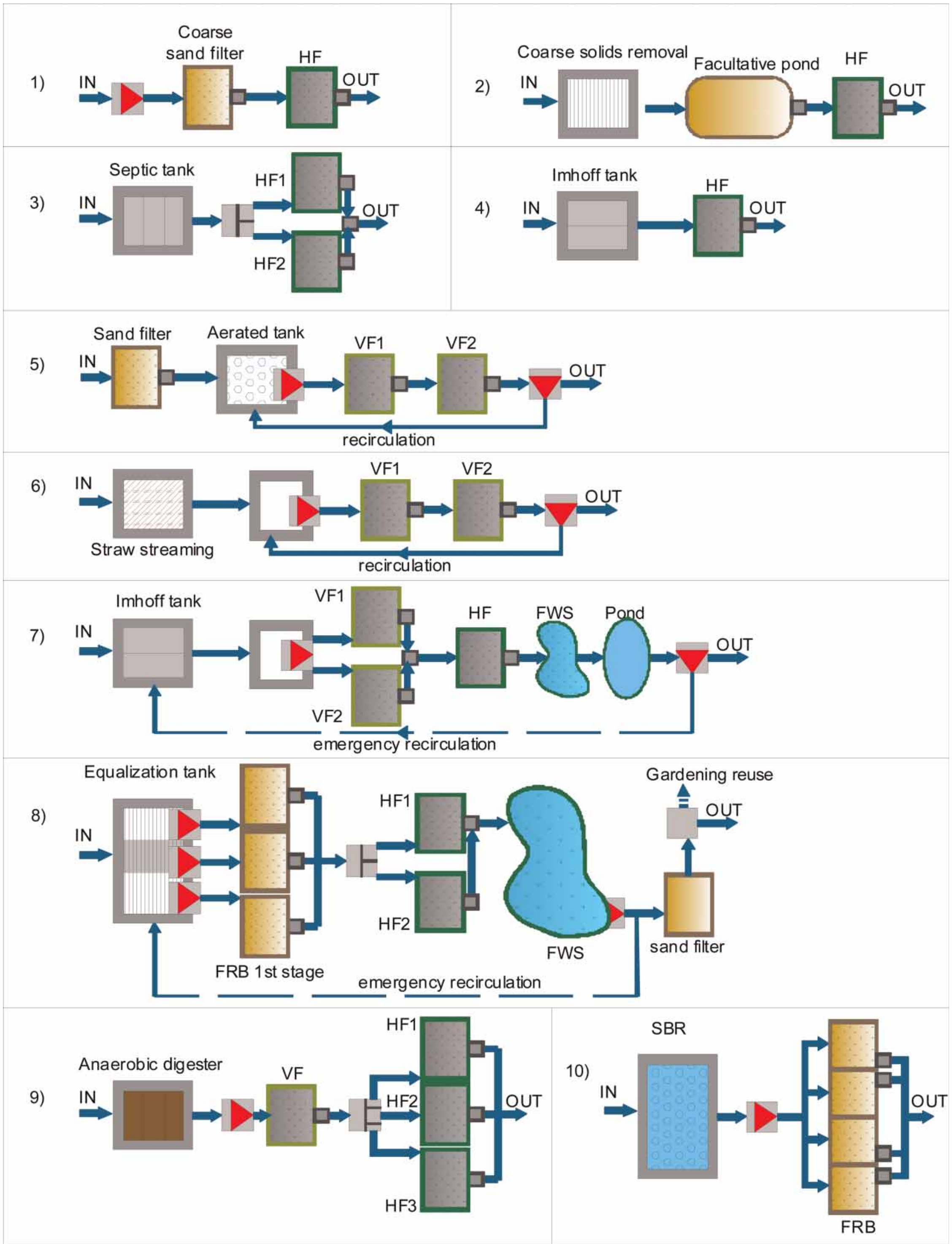

Figure 1 | Adopted treatment approaches for wineries CWs (the numbers in each box correspond to the IDs in Table 2).

pea gravel (about 4 mm) while the bigger in Hopland (4,400 m^2, $Q = 137\ m^3/d$, HRT 10 days, OLR 120–270 $gCOD/m^2\,d$) with crushed and not washed rocks (10–30 mm diameter); this material created some sandy areas in the bed, and tracer studies confirmed that the water was flowing around them, effectively reducing the expected

Table 2 | Treatment schemes and operational parameters of the analyzed treatment plants

ID	Pretreatment	CWs (area)	HRT (d)	OLR range (g COD/ m^2 d)	Average COD removal (%)	Reference
1)	Coarse sand filter	(pilot-scale) HF (14.9 m^2)	10	34.5–164	98	Shepherd *et al.* (2001)
2)	Coarse solids removal + facultative pond	HF (304 m^2)	5	553	approx. 100	Grismer *et al.* (2003)
2)	Coarse solids removal + facultative pond	HF (4,400 m^2)	10	120–270	79 (off season) 49 (peak season)	Grismer *et al.* (2003)
4)	Facultative pond	HF (180 m^2)	14	315	82	Mulidzi (2007)
4)	Facultative pond	HF (180 m^2)	7	630	60	Mulidzi (2010)
4)	Grid + Imhoff tank	HF (24 m^2)	5–10	53 (average) 136 (peak season)	99	Rochard *et al.* (2010)
3)	Septic tank	2 HF parallel (58 m^2 each)	10	3,775	93.5 (unplanted) 96.8 (planted)	Grismer & Shepherd (2011)
3)	Septic tank	2 HF parallel (72 m^2) (49 m^2)	10	92	97.9 (unplanted) 99.3 (planted)	Grismer & Shepherd (2011)
4)	Imhoff tank	HF (215 m^2)	6	35.2 (peak season)	87.5	Masi *et al.* (2002)
5)	Sand filter + aerated tank	VF CW (15.7 m^2) + VF CW (17.4 m^2) (with recirculation)	–	50–150	50–70	Rochard *et al.* (2002)
6)	Straw screening	2 VF CW (35.6 m^2 total) (with recirculation)	–	50–150	50–70	Rochard *et al.* (2002)
7)	Imhoff tank	2 VF in parallel (180 m^2)+ HF (86 m^2) + FWS (140 m^2) + final pond (440 m^3) (with emergency recirculation)	6–10	2–6 (off season) 56 (peak season)	92.2 (peak season)	Masi *et al.* (2002)
8)	Equalization	FRB (1,200 m^2) +4 HF parallel (960 m^2) + FWS (850 m^2) + sand filter (50 m^2) (with emergency recirculation)	5–6	232	96–99	Masi *et al.* (2002)
9)	AD (6 m^3)	VF (50 m^2) +3 HF parallel (100 m^2 each)	3	30.4 (average) 593 (peak season)	73.3 (average) 50 (peak season)	Serrano *et al.* (2011)
10)	SBR (50 m^3)	4 sludge drying reed beds in parallel (14 m^2 each)	–	–	99	Rochereau and Troesch (this paper)

HRT by about 50%. Both beds were 1.2 m deep, with 1 m of water. Both systems included a pretreatment by facultative lagoons and some screening for TSS. The Hopland CW system showed COD and tannin removal rates ranging from 49% to 79% and 46% to 78%, respectively, with greater removal taking place in the spring non-crush period; even with HRT = 1 h, COD removal was about 50%. The Glen Ellen CW system achieved an almost complete COD removal (from ~8,000 to ~5 mg/L) through use of the recirculation system. The monitoring period was limited to the first 3 years of operation.

A small HF CW (160 m^2–1 m deep) was built at the experimental winery ARC, Stellenbosch, South Africa, in 2001. It was filled with dolomite gravel ($CaMg(CO_3)_2$) with a mean diameter of 20 mm and a porosity of approximately 40% and planted with *Phragmites australis*. Some attempts to model the removal of organics have been made and described by Sheridan *et al.* (2006, 2011) together with a characterization of the wastewater, in which COD concentrations ranged between 500 and 7,000 mg/L. Interesting findings have been described by Sheridan *et al.* (2014) about the COD components' biodegradation, observing that ethanol, contributing to more than 90% of the COD, was completely biodegraded, while acetic acid did not appear to change concentration along the CW longitudinal transect, indicating probably a dynamic equilibrium between its consumption and its generation in the system, most probably for anaerobic processes involving polysaccharides and ethanol, with an average final concentration in the outlet of about 75 mg/L, corresponding to the outlet COD. The concentrations of ethanol and COD decrease approximately in an exponential way from the inlet to the outlet zones of the CW bed.

Still in South Africa, Mulidzi (2007) described an HF CW (180 m^2, HLR 22.5 L/m^2 d, HRT 14 days, OLR 315 gCOD/m^2 d) servicing a small winery at Goudini. The system is gravel-based and planted with *Phragmites australis*, *Typha* sp. and *Scirpus* sp. About 4 m^3/d of winery wastewater with an inlet COD concentration of about 14,000 mg/L have been treated, reaching a final outlet COD concentration of about 500 mg/L, with a removal efficiency over 80%. With the aim of reducing the treatment footprint the same author presented the results of an experiment conducted on the same HF CW loading it with a double quantity of wastewater and so reducing the HRT to 7 days (Mulidzi 2010). The outlet COD concentrations obtained in this experiment were about 5,000 mg/L, indicating a removal efficiency of about 60%. These outlet concentrations are accepted in South Africa for the reuse of the treated winery wastewater for soil irrigation. In the 2007 study Mulidzi also demonstrated that the treated effluent was appropriate for cabbage cultivation and producing positive effects on soil composition.

A further single stage HF CW (24 m^2, HLR 40–80 L/m^2 d, HRT 5–10 days, OLR 56–136 gCOD/m^2 d) was realized at the Podere Ruggieri Corsini in Piedmont, Italy, during June 2007. The bed was filled with a chemically active material, zeolitite, a porous rock containing 20–90% of zeolites, and also the planted *Phragmites australis* was mycorrhizated. The system proved to be able to process on average 53 gCOD/m^2 d even during the peak events with an OLR of 136 gCOD/m^2 d. Two weeks after the startup the system reached and maintained quite constant performances with 99% of COD removal efficiency and a final effluent concentration below 20 mg/L. The authors observed that the usage of porous and active media together with the mycorrhizated macrophytes can produce a reduction in the needed surface area of up to 0.24 m^2 per population equivalent (Rochard *et al.* 2010).

Always reporting on single stage HF systems with a classic pretreatment, Grismer & Shepherd (2011) analyzed the performances for two wineries in California; the 'Winery A' system was composed of two HF beds in parallel, each one treating half of the produced fluxes with a surface area of 58 m^2; the 'Winery B' instead had two HF beds still in parallel but differently sized and treating proportional amounts of wastewater with surface area (As) of 72 m^2 and 49 m^2, respectively, and 0.91 m depth. At both wineries one of the two beds was planted (*Typha domingensis*, *Scirpus acutus* and *Sagittaria latifolia*) while the other was kept unplanted for a performance comparison; the primary treatment was a septic tank with a 2 days HRT for both systems. Even though the systems were designed for the same theoretical HRT of 10 days, the real operational conditions have demonstrated a constant overloading of system A and underloading of system B.

At Winery A the operational conditions were as follows: Q = 6 m^3/d; HLR = 52 L/m^2 d; OLR = 3,775 gCOD/m^2 d; R% COD = 96.8 planted, 93.5 unplanted; percentage removal (R%) TSS = 76.1 planted, 52.8 unplanted. At Winery B instead: Q = 2.2 m^3/d; HLR = 18 L/m^2 d; OLR = 92 gCOD/m^2 d; R% COD = 99.3 planted, 97.9 unplanted; R% TSS = 91.1 planted 85.5 unplanted. It must be noted that this monitoring program was performed when both systems were only 1 year old, so eventual clogging problems created by the overloading in the system A could have been not yet evident. While TSS concentrations at the inlets were similar at both wineries (about 300 mg/L), much greater HRTs at winery B resulted in greater COD removal efficiencies. At both wineries, the planted wetlands outperformed unplanted wetlands; both systems showed a good pH stabilization, and also in this case the planted systems performed better than the unplanted. It has to be mentioned that such high values of OLR were related to a very short monitoring period of 14 days during vintage and in two systems that started operating a few months before, so those values cannot be considered as maximum allowed loads, at least not until the long-term performances of those systems becomes available.

VF CWs

A system of two VF CWs in series (15.7 + 17.4 m^2) was applied in France (Rochard *et al.* 2002), in the Bordeaux region, at a 6,000 hL wine/year facility with a pretreatment by sand filters and intensive aeration in a first equalization basin (600 m^3). The same author also described another small system (winery size: 500–600 hL/year), where the winery wastewater together with domestic wastewater after a pretreatment by straw screening was treated by two VF CWs in series for 35.6 m^2 in total, planted with 18 different macrophytes. The VF CWs have been designed following the French guidelines, making use of pea gravel in the first stage and sand in the following one. The average removal efficiencies for both the systems during the test trials have been about 50–70% for COD, testing three

OLRs – 150, 80 and 50 gCOD/m^2 d – and making use of pre-aeration and recirculation. The conclusions were that this kind of treatment scheme and sizing procedure were not fulfilling the discharge requirements (300 mg/L for COD).

Multistage CWs

The Ornellaia winery system, in Bolgheri (Leghorn province), is a multistage treatment wetland (MTW) system using two parallel VF CWs as a first stage (area = 90 m^2 each) followed by an HF bed (area = 86 m^2) and then by a free water surface (FWS) system (As = 148 m^2) and a final pond (As = 338 m^2) with recirculation to the first stage or reuse for irrigation. The flow rate during the winemaking period is about 10 m^3/d, with an OLR of 56 gCOD/m^2 d and HLR of 55 L/m^2 d; both the VF beds present light clogging problems after the vintage season but the black sludge layer on top of the beds has been periodically digested during the period January–August every year, in which a very low quantity of water is loaded in the treatment system (HLR 5–10 L/m^2 d, OLR 2–6 gCOD/m^2 d). The good development of the reeds community has moreover shown an increase in the vertical beds' permeability and the superficial sludge decomposition. The performances monitored in the observed peak period were 74.7% for TSS, 92.2% for COD and 93.3% for BOD_5 (Masi *et al.* 2002). The Ornellaia winery wastewater shows an appropriate content of nutrients in the inlet (about 50 mg/L as ammonium) due to the mixing of the domestic wastewater, mainly black water, produced by the employees). For this treatment scheme it must be noted that the last tertiary treatment by the FWS with a high HRT (up to 13 days) had a relevant role in the organic matter removal and offered an important buffer effect during the peak season. The monitoring phase started about 2 months after the beginning of the winemaking period (September 2001). The average removal efficiencies observed in the three stages were VF 21%, HF 15%, FWS 65% for BOD, and VF 31%, HF 38%, FWS 82% for COD. The system has been upgraded in 2006 for treating 42 m^3/d after an expansion of the production; the primary treatment by septic tanks has been rebuilt and two new stages have been added in the MTW. Nowadays the system has the following configuration: septic tank + HF (two beds in parallel) + VF + VF + VF + FWS + ponds. The total surface area is 1,316 m^2.

The winery wastewater produced by the Casa Vinicola Luigi Cecchi & Sons (Castellina in Chianti – Siena) has been treated with an MTW system since 2001. The system consisted of an Imhoff tank, followed by a single stage HF (As = 480 m^2) and then by an FWS (As = 850 m^2). The system was designed to treat 35 m^3/d, and starting from the year 2006 the production at the winery greatly improved and consequently flows to the CW increased up to 70 m^3/d. A prolonged overload, for about 2–3 years, resulted in a severe clogging of the HF bed. In 2009, the treatment system was upgraded in the following configuration: a French system for raw wastewater (French reed bed (FRB)) followed by four parallel HF beds (the old and refurbished bed plus three new ones), by the existing FWS and finally by an optional sand filter before discharge into fresh water (Gena River). The MTW system is treating nowadays flows up to 100 m^3/d with an average organic content of about 3,800 mgCOD/L. This particular winery wastewater is characterized by a quite constantly high organic matter content, low level of nutrients, light acidity and large variations during the usual daily operations which are producing effluents. This winery, in fact, is producing wine elsewhere or buying it from local producers, and the industrial complex where the MTW is located is only bottling and aging the wine in cellars. So, the effluents are created by the washing procedures for bottles, tanks, silos, ground floors, pipes, etc., operations that are planned with an industrial approach and well distributed in the production cycle throughout the year. The choice of a French system for raw wastewater as first stage of an MTW system enhances the sustainability of the treatment plant, by the reduction of primary sludge production and sludge cycle management costs and is also providing more robustness to the treatment train, minimizing a big part of the problems observed in the above cited experiences at the same site with the older 'Imhoff + HF + FWS' configuration. The FRB system consists of a batch-fed filtering bed, mostly comparable to unsaturated vertical flow CWs. The main characteristic of this system is that it accepts raw wastewater directly without a primary settlement stage. The settled materials remain on the surface of the basins as a sludge layer, which is kept in a highly aerated condition by the presence of a reed community growing in it. The installation of the first stage FRB has resulted in removal of the old Imhoff tank, which was creating some problems in the HF CW for frequent events of exceptionally high flows and linked wash-out events from the Imhoff tank itself, when unmeasured amounts of primary sludge reached the inlet section of the HF, surely contributing to its clogging. Masi *et al.* (2014) described the results obtained in the first 3 years of operation of the upgraded CW treatment system, comparing them with the historical data of the last 10 years. Results indicate that a COD reduction of up to 96% has been achieved even at peak loads and along the whole observed period of time. The average OLR to the FRBs ranged in 2012 from 56 to 205 gCOD/m^2 d, while

COD average removal efficiency was 75%. For the following HF unit, the average OLR ranged from 2 to 107 $gCOD/m^2$ d, while COD average removal was 87%. Surface removal efficiencies upto 232 $gCOD/m^2$ d were reached by the overall (FRB + HF + FWS) system. Overall system removals ranged from 96 to 99% of COD. The results from this study have shown that the French system (FRB) applied as first stage has obtained good performances in the treatment of raw winery wastewater, reaching a removal efficiency up to 75% and eliminating the clogging problems of the second stage HF CWs.

Anaerobic digestion + CWs

A first mention of a combined system, where anerobic digestion has been coupled with CWs for winery wastewater treatment, was the system in Eschbach, Germany, described by Müller *et al.* (2002). The authors only mentioned the existence of a full-scale system consisting of a two-stage AD followed by a VF CW (As = 120 m^2) and unfortunately did not provide further details on the operational conditions and performances.

Serrano *et al.* (2011) studied, for about 2.2 years, the performance of a full-scale plant located in Galiza (northwest Spain), designed to treat winery wastewaters coming from a winery with a production capacity of 3,150 hL of white wine per year, and additionally discharges from tourist and restaurant activities that take place at the same establishment. The treatment plant consisted of an HUSB AD (6 m^3), combined with a CW system: a VF CW (50 m^2) made of 3–6 mm granitic gravel and three parallel subsurface HF CWs (100 m^2 each) filled with 6–12 mm washed gravel up to a depth of 0.35 m (HF1) or 0.65 m (HF2 and HF3). CWs were planted with *Phragmites australis* (VF) and *Juncus effusus* (HF) and started up on April 2008. Raw wastewater entered a 20 m^3 storage tank and was pumped to the bottom of the HUSB digester at an average flow rate of 6.8 m^3/d and an HRT of about 0.8 d. Average characteristics of the winery raw wastewater during the overall operation period were 520 mgTSS/L, 2,107 mgCOD/L and 1,199 $mgBOD_5$/L, but in the periods of vintage and first winemaking operations there were higher flow and concentration peaks. The AD removed on average 76.4% TSS, 26.3% COD and 21.3% BOD_5, so the average values of the influent concentration to the CWs system for selected periods ranged from 72 to 172 mgTSS/L, 422 to 2,178 mgCOD/L and 216 to 1,379 $mgBOD_5$/L. The average surface loading rates (SLRs) applied to the CWs were 2.5 $gTSS/m^2$ d, 30.4 $gCOD/m^2$ d and 18.4 $gBOD_5/m^2$ d, and the overall CWs system reached average removal efficiencies of 86.8% of TSS, 73.3% of COD and 74.2% of BOD_5, reaching concentrations generally below 400 mgCOD/L and 200 $mgBOD_5$/L. During the vintage periods OLRs reached maximum weekly averages of 593 $gCOD/m^2$ d and 322 $gBOD_5/m^2$ d for the VF unit and 46 $gCOD/m^2$ d and 32 $gBOD_5/m^2$ d for the HF unit, and as a result of these high OLRs, the overall removal efficiency decreased to near 50% during vintage periods. The system also removed 52.4% of total Kjeldahl nitrogen, 55.4% of NH_3-N and 17.4% of phosphates.

In the same treatment plant, a comparative study of the three subsurface HF CWs was carried out (de la Varga *et al.* 2013a). The water depth for HF1 was 0.3 m, while the depth for HF2 and HF3 was 0.6 m. HLR ranged from 7 to 93 L/m^2 d, while SLRs were 4 to 85 $gCOD/m^2$ d, 2 to 49 $gBOD_5/m^2$ d and 0.5 to 6 $gTSS/m^2$ d. TSS were efficiently removed in all HF units, which reached TSS effluent concentrations below 44 mg/L and TSS removal efficiencies of 74%. COD and BOD removals were generally between 60 and 80% but clearly decreased when the influent concentration or the SLR applied increased. In comparison to the deeper HFs, the shallower HF showed a lower performance at the higher influent concentrations. More oxygenated effluents were provided by the HF1 unit but only for the lower SLR. Solids accumulation was significantly higher in HF1, although high hydraulic conductivities were found in all cases after 2.8 years of operation.

The AD performance and its effects on the overall CW operation in this winery treatment plant was presented by de la Varga *et al.* (2013b), focusing on suspended solids (SS) removal and accumulation. This paper presented also the results in a municipal wastewater treatment plant. AD showed a high SS removal efficiency in both plants and helped CWs to operate at high rates without clogging. The AD treating winery wastewater reduced the TSS loading rate to the CW system by 76%, lowering the high influent TSS concentration to below 200 mg/L. No clogging was observed after 2 years of operation at SLR of 18 $gBOD_5/m^2$ d for the overall CW system. After 2.2 years of operation solids accumulation into the HF CWs reached 4.6 $kgTSS/m^2$, while hydraulic conductivity resulted in 134 m/d. Methane emissions from the HF units ranged from 143 to 1,899 mg CH_4/m^2 d, depending on the season and operating conditions.

SBR + CWs

At this moment around 20 wine producers in France and seven in Spain and Portugal, with a production ranging from 1,800 hL to 14,000 hL wine/year, are equipped with combined systems composed of an SBR followed by a CW. In France, the winery wastewater treatment is mainly approached by activated sludge plants, SBRs or extensive aerated ponds, these last for the cases with lower hydraulic and pollutants loads, that are designed in order that the whole pollutant load reaches the legal discharge limits, often adding a tertiary treatment by CWs that play a polishing and sludge treatment role.

An SBR + CW plant for winery effluent treatment (Cantemerle winery, Gironde, France) has been monitored during a period of one and a half years after its commissioning (2005–2006). Thus, it was possible to test the treatment plant during a whole process of wine making including vintage.

The Cantemerle winery has a production of 2,700 hL wine/year and the plant was designed to treat 6.5 m^3/d (58.5 kgBOD_5/d and 117 kgCOD/d). The plants consist of: (i) a buffer tank of 10 m^3 (HRT = 1.5 to 2 days); (ii) screening unit (1 mm sieve); (iii) an SBR of 50 m^3 (designed with a volumetric loading of 1.2 kg BOD_5/m^3 d); and (iv) four sludge drying reed bed filters (SDRB) of 14 m^2 each with a sludge storage aimed free board of 0.6 m, in parallel.

The reed bed filters are designed with a loading rate of 25 kg SS/m^2 year, which allows a sufficient sludge dewatering (dry matter content >20%) and mineralization without any clogging problem (2 months of operation followed by a 10 months rest period).

The reed bed filter is filled with the following layers from top to bottom:

– 10 cm of sand
– 50 to 60 cm of coarse gravel (2 to 6 mm)
– 20 cm of drainage layer (particle diameter 15–25 mm to 30–60 mm).

COMPARISON OF DIFFERENT TREATMENT CONFIGURATIONS

In this section some unpublished and updated data on the performances of three monitored hybrid CW systems for winery wastewater, already described in the former section, are presented and compared, in order to elaborate suggestions for the design of new systems and to understand the possible causes of the different observed values. All these three systems are conceived in a way to minimize the clogging processes linked to the typical high loads of this kind of effluents by the use of a first stage aimed at strongly reducing the inlet solids and organic content, using FRB, SBR or AD.

The Cecchi system (Masi et al. 2002, 2014) has shown in both the old and the upgraded configuration, adopted along the 13 years of operation, a constant fulfillment of the treatment goals; Figure 2 shows the behavior of COD in the effluent for the whole observed period and also, when available, the concentrations in the different stages of the system. Although the constant overloading that took place 4 years from the startup, due to an expansion of the production, brought a severe clogging of the first stage HF, the insertion of the FRB as first stage is instead providing more stable performances and no clogging signals can be noticed up to now after 5 years of operation from the upgrading. The OLR that clogged the former HF bed has been estimated at about 500 gCOD/m^2 d, loaded to the reed bed 5 days per week for a period of about 1 year.

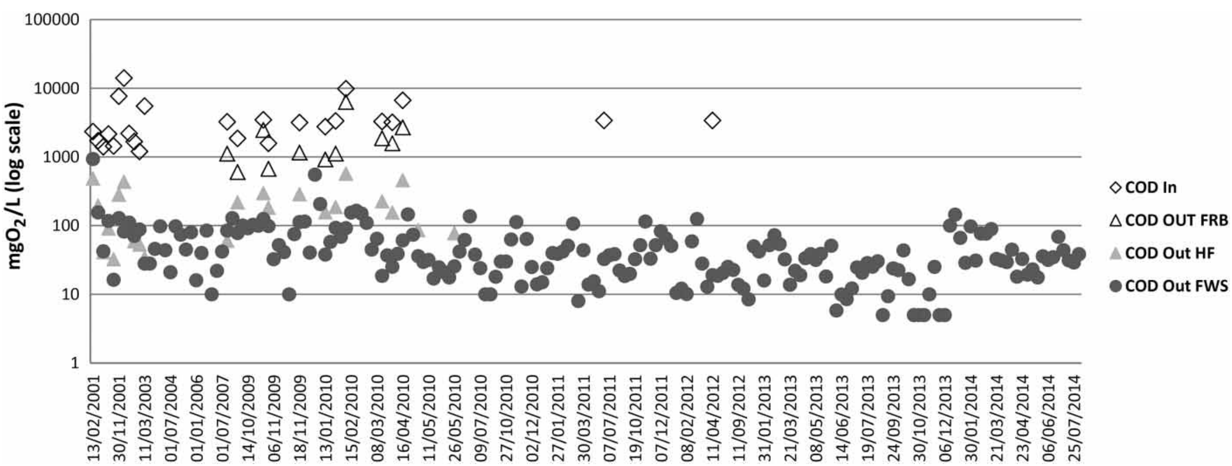

Figure 2 | COD concentration evolution (Cecchi – Castellina in Chianti).

Figure 3 shows the data obtained for COD concentrations observed at every step of the treatment through the year 2012, by monthly sampling events and the related surface removal rates (SRRs): the observed trends are showing a relevant influence of the load on the FRB's removal efficiencies; as first stage, the action of the FRB is to buffer the inlet concentrations for all the following stages, which are therefore less affected by the raw wastewater quality and quantity. In this present configuration the multistage CW system does not present any inhibition by COD inlet concentrations higher than 600 mg/L as was reported by de la Varga in 2013. These better performances could be related to the positive effect of the first stage FRBs, that are retaining a relevant amount of the organic load and therefore probably reducing the inhibitory compounds. Anyway also in the second stage HF beds the higher values of SRR are linked to the highest concentrations, i.e. with about 1,000 mg/L of COD in the inlet the SRR is about 75 $gCOD/m^2$ d, surely higher performances if compared to the Spanish ones reported by de la Varga in 2013 where the maximum SRR has been about 15–22 $gCOD/m^2$ d.

An ever stronger approach for managing the high loads is represented by the French SBR + SDRB combination described before for the Cantemerle winery: Figure 4 presents the concentrations of COD in the inflow of the plant, in the inflow of the reed beds and the outflow of the plant, between November 2005 and March 2007. The performance of this plant has been very good, with the exception of the wine harvesting period in 2006 where a period of acclimatizing had been necessary in order to treat the applied load, otherwise the plant always met the legal discharge limits (300/100/100 mg/L for COD/BOD_5/SS, respectively). The activated sludge plant treats a great part of the COD load and the reed beds complete the treatment. This complementary effect of the reed beds varies with the type of effluent, and thus with the season. In November 2005 for instance, the major part of the COD was treated by the reed beds, while in March 2006 the activated sludge plant was the more active stage.

As with the COD evolution, the outlet SS concentration always meets discharge limits (<100 mgSS/L), with the exception of the first weeks of the harvesting period in September/October 2006. While the two steps of the treatment system contribute to the TSS removal, it can be noticed that the reed beds are the more efficient in solids reduction. The activated sludge tank reduces SS by an average of 38%, while the reed beds allow for an overall elimination of 89%. These observations can lead to the conclusion that the integration of a CW into a classical biological treatment stage is providing some mitigations to the numerous problems listed in the introduction and related to winery wastewater treatment by biological methods. This configuration is anyway linked to operational costs that are at least five to ten times higher in comparison with the FRB + CWs and AD + CWs schemes, but also lower investment costs and footprint.

Also, the Spanish experiences focused on an optimization of the treatment scheme for several aspects:

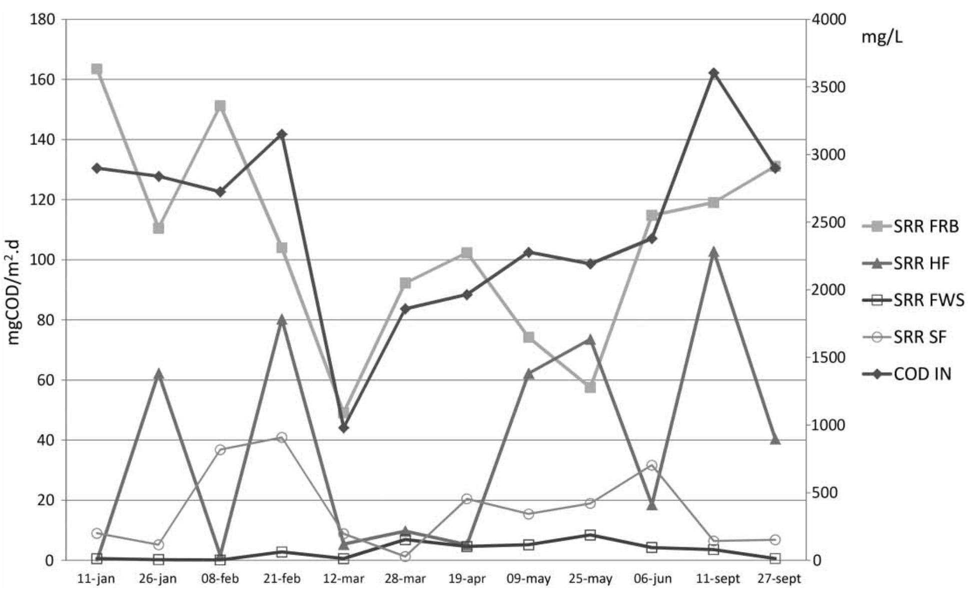

Figure 3 | SRR for the different stages of the Cecchi winery MTW versus COD inlet concentration (Masi et al. 2014).

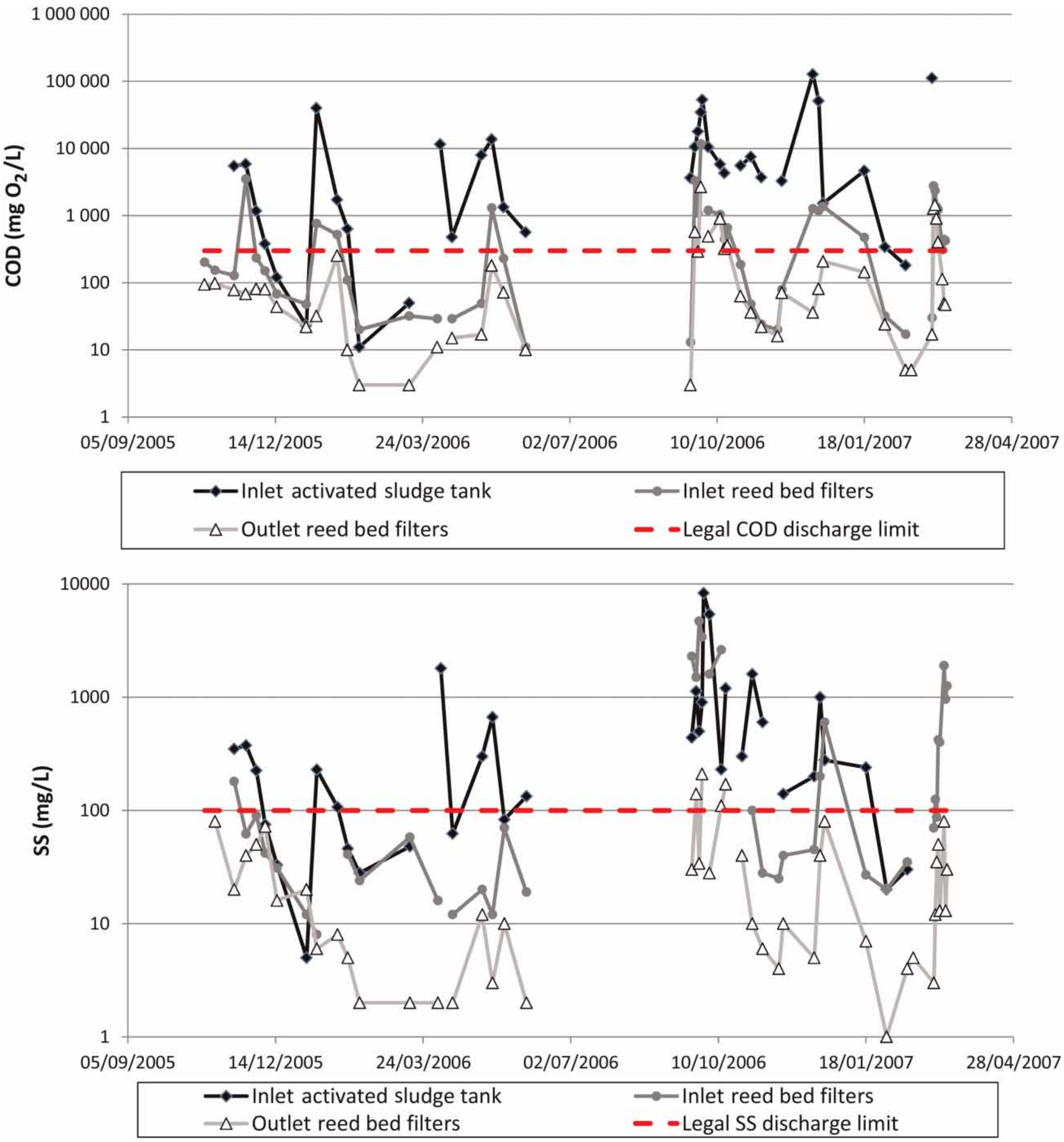

Figure 4 | COD and TSS concentration evolution (Cantemerle Castle).

1. mitigation of the CW clogging by the use of AD as first stage;
2. for avoiding or limiting uncontrolled anaerobic processes, a VF CW unit was placed as the first CW unit after the AD because of its higher oxygenation potential in comparison to an HF CW;
3. the HF CWs units were designed shallower (0.6 and 0.3 m) than the usual depth of about 0.7–1.2 m reported by other authors (Shepherd *et al.* 2001; Masi *et al.* 2002; Grismer *et al.* 2003; Mulidzi 2007), based on the consideration that the treatment capacity of an HF CW could mainly be due to oxygen-transfer through the water–air interface, so shallower beds could present more oxygenated medium and higher treatment capacity, while higher methane emissions would be expected from deeper HF CWs due to the predominance of anaerobic processes.

As expected, the results indicated that AD was very effective in preventing clogging (de la Varga *et al.* 2013b), and the VF wetland showed higher removal efficiency than HF wetlands (Serrano *et al.* 2011); however, the shallow HF CW (0.3 m) showed a worse performance than the other units (0.6 m), appearing to be more affected by high influent concentrations (de la Varga *et al.* 2013a).

As shown in Figure 5, SS concentration in the effluent of the VF unit was generally below 90 mg/L (with an overall average value of 65 ± 38 mgTSS/L), and showed a further decrease in the final effluent, after the HF unit (17 ± 15 mgTSS/L). COD and BOD_5 concentrations entering the CWs system decreased in the effluent of both units. The VF effluent presented overall average values of 711 ± 769 mgCOD/L and 418 ± 482 $mgBOD_5$/L. The final effluent presented overall average values of 448 ± 541 mgCOD/L and 279 ± 430 $mgBOD_5$/L, reaching concentrations generally below 400 mgCOD/L and 200 $mgBOD_5$/L, except for the vintage periods in 2008 and 2009.

Good correlations of SRR with SLR for the overall (VF + HF) system were obtained for all parameters except for phosphate. The overall system showed increasing TSS and COD SRRs during the observed period, while instead BOD_5 SRR reached a plateau, indicating that the system reached its maximum biological removal efficiency at those operating conditions. Considering that the HRT of this configuration is about 3 days and that the OLRs are instead lower than for the FRB + CWs scheme, the performances can most probably be increased by enlarging the size of the HF beds in order to reach HRT values higher than 5 days.

DISCUSSION AND CONCLUSIONS

All the abovementioned international experiences of CW systems applied for winery wastewater treatment have shown interesting results, even if the available literature is still missing to provide further useful observations for completing the analysis of this particular application.

It is already evident that for very small wineries, with a yearly production of wine lower than 1,000 hL, whenever

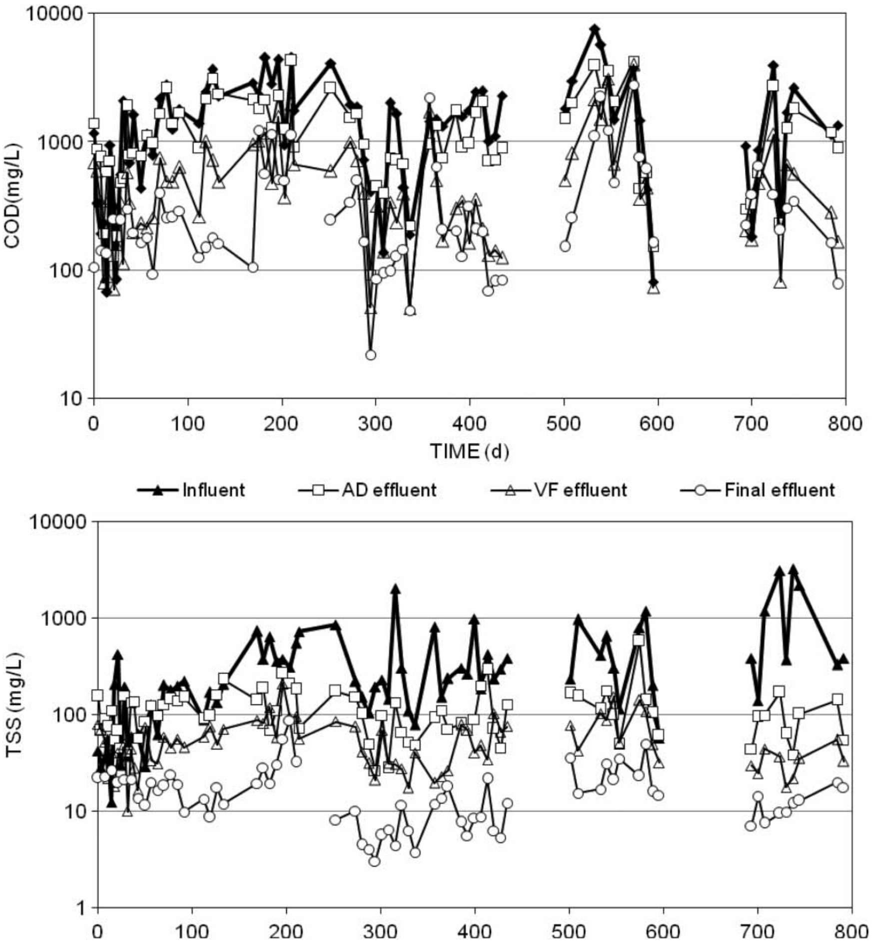

Figure 5 | COD and TSS concentration evolution (Pazo de Señoráns, Galiza).

the local regulations are permitting, a simple configuration like a septic tank (or equivalent) and an HF CW with an HRT of more than 5 days, calculated on the vintage season peak flow, can ensure a proper treatment for discharging in fresh water or even better for reusing the effluents for irrigation. All the reported single stage HF systems with an OLR below 50 $gCOD/m^2$ d demonstrated average removal efficiencies for COD of about 90%, while an OLR increase showed worst performances, as in the case of the South African experience. This is not fitting the results described for California, and the only reasonable explanation for this and for the exceptionally high OLRs and removal efficiencies is the very partial and limited monitoring of those systems when the papers were published. In particular a description of the historical behavior for these HF CWs is not available and so it is not possible to verify if the expected clogging of the beds took place after few months or years since the startup. Other useful information that can be deducted from the South African results is that whenever the OLR is raised up to more than 600 $gCOD/m^2$ d, the removal efficiency still can reach 60%.

The OLRs applied to the CW systems ranged from about 30 up to about 5,000 $gCOD/m^2$ d, with the 80th percentile of the reported values being below 297 $gCOD/m^2$ d and the median at 164 $gCOD/m^2$ d; the highest OLR values have in all cases been measured during the peak season (vintage) and often linked to lower SRR in comparison to the other periods of the year. The 80th percentile and median values can be used for a conservative approach in designing similar systems.

With such OLRs the SRRs have ranged from a minimum of 15 up to 4,700 $gCOD/m^2$ d, with the 80th percentile of the reported values being below 308 $gCOD/m^2$ d and the median at 112 $gCOD/m^2$ d.

The lesson learnt is that a quite efficient first stage of treatment is necessary to avoid a short life period of the CWs due to tending to get clogged; the important loads of organic matter and solids contained in the raw winery wastewater have to be controlled and reduced before feeding to the CWs; the still very high content of soluble carbon, mainly composed of ethanol and acetic acid, can instead be easily removed by the wetlands without sludge formation and accumulation. Phytotoxic or even microbial inhibitory effects have not been evidently observed, except for some unclearly linked occasions during the overload periods in the peak season. The key function of the first stage is to retain and degrade particulate organic matter; another important role is to retain and degrade the phytotoxic components of the organic matter (polyphenols etc.), and this action can be better exploited with the presence in the first stage of an organic matrix able to bind for adsorption mechanisms the targeted molecules. The desired COD and TSS reduction by the first stage should be, for medium and big size wineries, about 40–50% of the original loads. For the small size ones, as formerly defined, the usual 20–30% of reduction that can be obtained by settling reactors (septic, Imhoff, ponds, etc.) can be enough if the treatment plant will be operated at its nominal capacity only during the vintage period, having then almost 10 months every year as a sort of resting and regeneration period.

As a general trend when HF CWs have been included in the treatment, the deeper beds have shown slightly better performances, with similar HLRs and OLRs, in comparison to the shallower ones.

Sheridan *et al.* (2014) have proposed some explanations about the organic content degradation pathways in HF CWs for winery wastewater treatment, mainly focusing on the ethanol transformations. The measured almost constant concentration throughout the bed of acetic acid, which is the first product from the ethanol oxidation, was interpreted as a signal of a fast aerobic degradation of the alcohol directly by the bacteria cell respiration, going directly to CO_2, or otherwise of an equal rate of formation and consumption of the acetic acid; the preferential transformation pathway for the acetic acid in anaerobic conditions is methanogenesis and so this could be a reasonable cause of the better performances for the deeper beds.

A cause of some of the different performances observed could also be the content in nutrients as a limiting factor for the bacterial activity; some of the considered systems are mixing the black water from restrooms and from a few domestic households, restaurant effluents, and so on, so there are small differences in the inlet wastewater composition that could produce evident changes in the results. The low nutrients content may suggest anaerobic conversion plays an important role in organic matter degradation. Anaerobic bacteria require much less nutrients than aerobes. The processes in the HF CW are mainly anaerobic and in the VF CW are aerobic, but even in this case, being extensive systems, the growth and accumulation of biomass is low, so the need of nutrients is also low.

The acidity of the wastewater in particular during vintage can also be considered as another factor influencing the performances, even though in all the examined experiences there was not the need of a chemical neutralization and the final pH in the CW outlets tended to rise up to 6–6.5 or even close to neutralization.

In all the systems reported by the analysed literature, the outlet concentrations for N, P, surfactants, salinity and several other minor parameters, have never been a concern in term of treatment goals, mainly because of the already very low inlet values; therefore the specific discharge limits have always been respected.

The open questions for future research activities are listed as following:

1. what are the pathways for the more active processes for organic matter and solids removal in the CW systems during the various operational conditions (i.e. measuring the gas exchanges, methane and carbon dioxide production from the beds, etc.)?
2. can additive nutrients improve the treatment especially in the peak season?
3. even though problems linked to low pH were not considered of importance in the almost 15 years of experiences reflected in this paper, could a light neutralization increase the performances during the overload periods as suggested by Serrano *et al.* (2009)?
4. as a good strategy for minimizing the treatment footprint and to avoid clogging of the CW beds, such as through the adoption of AD, FRB or SBR as first stage, would it be a good alternative to aerate the inlet section of the eventual HF CWs at least during the overload periods?

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First received 13 September 2014; accepted in revised form 27 January 2015. Available online 26 February 2015