Biological treatment of winery wastewater: an overview

G. Andreottola, P. Foladori and G. Ziglio

ABSTRACT

The treatment of winery wastewater can realised using several biological processes based both on aerobic or anaerobic systems using suspended biomass or biofilms. Several systems are currently offered by technology providers and current research envisages the availability of new promising technologies for winery wastewater treatment. The present paper intends to present a brief state of the art of the existing status and advances in biological treatment of winery wastewater in the last decade, considering both lab, pilot and full-scale studies. Advantages, drawbacks, applied organic loads, removal efficiency and emerging aspects of the main biological treatments were considered and compared. Nevertheless in most treatments the COD removal efficiency was around 90–95% (remaining COD is due to the un-biodegradable soluble fraction), the applied organic loads are very different depending on the applied technology, varying for an order of magnitude. Applied organic loads are higher in biofilm systems than in suspended biomass while anaerobic biofilm processes have the smaller footprint but in general a higher level of complexity.

Key words | biodegradability, biofilm systems, biological treatment, winery wastewater

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INTRODUCTION

The production of wastewater from a winery ranges from 0.7 (our data) to 1.2 times the production of wine (Vlyssides *et al.* 2005). Winery wastewater is produced by processing operations and cleaning practices in wineries, such as washing operations during crushing and pressing of grapes, rinsing of fermentation tanks, barrel washing, bottling, etc… (Musee *et al.* 2006). The rapid expansion of wineries in rural areas during the last decades and the more stringent effluent criteria have resulted in an increased interest in winery wastewater treatment.

The treatment of winery wastewater can become difficult as a consequence of some peculiar aspects: (1) large seasonal fluctuations in volume and composition, (2) high variability of organic loads, which typically assume concentrations of 1,000–20,000 mgCOD/L, depending on the harvest load and processing activities (Andreottola *et al.* 2005). The high concentration of ethanol and, on a temporary basis, sugars (fructose, glucose) in winery wastewater justifies often the choice of a biological treatment. But the distinctive wine processing style of each winery generates wastewater with unique properties, causing the impossibility to meet a general agreement on the most suitable cost-effective alternative for the biological treatment of this wastewater. Several solutions are currently offered by technology providers while current research envisages the availability of new promising technologies for winery wastewater treatment. Criteria to be considered when selecting the adequate treatments are: (i) maximization of removal efficiency; (ii) flexibility in order to handle variable concentrations and loads; (iii) moderate capital cost; (iv) easy to operate and maintain; (v) small footprint; (vi) ability to meet discharge requirements for winery effluents (*inter alia* Aybar *et al.* 2007). Small producers with relatively modest financial capacity are interested in simple treatment systems with low maintenance and low manpower requirement.

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The present paper intends to present a brief state of the art of the existing status and the advances in biological treatment of winery wastewater in the last decade, considering either lab, pilot and full-scale studies. Advantages, drawbacks and emerging aspects in this field were considered.

HOW MUCH IS WINERY WASTEWATER BIODEGRADABLE?

The fractionation of total COD in raw winery wastewater has been evaluated by Andreottola *et al.* (2005) and Beck *et al.* (2005), on the basis of the subdivision proposed in the Activated Sludge Model No. 1 (ASM1) and further versions. Results of COD fractionation for some winery wastewaters are indicated in Table 1, referred to grape harvesting period. Readily Biodegradable COD (S_S) is the most part of total COD, being 71.4 and 85% for Andreottola *et al.* (2005) and Beck *et al.* (2005) respectively. The high percentage of this fraction is due to the prevalent presence of ethanol and, to a smaller extent, sugars and organic acids; in fact ethanol is the largest part of the soluble COD (80%) as referred to by many authors (*inter alia* Bories *et al.* 2005).

The concentration of slowly biodegradable COD (X_S) is low, ranging from 2.9% to 9.4% of total COD. Un-biodegradable soluble fraction of COD (S_I) resulted quite different in the two cited experiences, being probably affected by the different approaches used for the quantification of COD fractionation by the Authors. However this fraction plays a very important role, because it is discharged in the effluent without any change, being also not settleable.

Therefore further efforts are required in the future for the quantification of the S_I fraction in more sources of winery wastewater in order to predict S_I concentration in the effluent and the capability to respect discharge limits for COD concentration.

Table 1 | Fractionation of total COD in winery wastewater during grape harvesting period

	Grape harvesting period	
Fraction of total COD	**Andreottola *et al.* (2005)**	**Beck *et al.* (2005)**
Readily biodegradable COD (S_S)	71.4%	85%
Inert soluble COD (S_I)	12.4%	1.2%
Slowly biodegradable COD (X_S)	2.9%	9.4%
Inert particulate COD (X_I)	13.3%	5%

Moreover, COD fractionation plays an important role in modelling of treatment processes (especially readily biodegradable, readily hydrolysable, slowly hydrolysable fractions) as observed by Stricker & Racault (2005) during the application of ASM1 to the activated sludge treatment of winery wastewater.

HOW IS BIOLOGICAL TREATMENT ACHIEVED?

A common alternative chosen by many wineries is the co-treatment of municipal and winery wastewater in conventional activated sludge processes; that is generally a feasible solution for the treatment of these streams at relatively low costs (Brucculeri *et al.* 2005; Bolzonella *et al.* 2007). Sometimes this practice is associated with occasional bulking phenomena, decrease of sludge settleability and increase in SST concentration in the treated effluent, especially during the grape harvest period (lasting few weeks), due to the rapid increase of applied organic loads and a temporary plant overloading. In the full-scale experience referred to by Brucculeri *et al.* (2005) the pre-denitrification configuration was modified during the harvesting period, using the pre-denitrification reactor as a high loaded oxidation unit in order to maintain a high efficiency in COD removal. The addition of winery wastewaters to enhance the nutrient removal process in activated sludge of municipal WWTPs or SBRs was studied by Rodríguez *et al.* (2007): a denitrification rate similar to the one of domestic wastewater was found, with a COD/N ratio of 7.7. The improvement in N removal at low cost and the advantage of reducing the amount of winery wastewater to be treated in-situ, make interesting its use as carbon source in conventional WWTPs (Rodríguez *et al.* 2007).

Among the alternatives for treating winery wastewater in a dedicated plant, several biological systems have been proposed, including:

(i) aerobic/anoxic processes using suspended biomass: activated sludge, membrane bioreactors (MBR), sequencing batch reactors (SBR);

(ii) aerobic biofilm systems, such as conventional rotating biological contactors (RBC) or innovative fixed bed biofilm reactors (FBBR) or moving bed biofilm reactors (MBBR, SBBR);
(iii) anaerobic processes using suspended biomass, such as conventional anaerobic digesters or anaerobic sequencing batch reactors (ASBR);
(iv) anaerobic biofilm systems using granules (Upflow Anaerobic Sludge Blanket, UASB) or fixed supports (anaerobic filters) or mobile supports (fluidised bed reactors). Some technologies include two strategies, such as hybrid USBF reactors, which is a digester with a sludge bed at the bottom and an anaerobic filter at the top (Andreottola *et al.* 1998; Moletta 2005);
(v) constructed wetlands.

In Table 2 the main aspects of the technologies applied for winery wastewater treatment are briefly highlighted.

A widely applied solution for treating effluents originated from small wineries–less than 10–15,000 hL of wine per year (Torrijos & Moletta 1997)–is the activated sludge SBR systems, in which filling + reaction + settling + discharge are sequenced in time in a single reactor adopting simplified automation. Recently, with the objective to overcome frequent periodic bulking problems typical of activated sludge processes and to improve effluent quality, MBR systems demonstrated an increased interest and nowadays this technology counts several full-scale applications (Bolzonella *et al.* in press; Guglielmi *et al.* 2009).

With regards to biofilm systems proposed for winery wastewater, rotating biological contactors could be an effective primary treatment system to lower the COD to more acceptable levels for a subsequent treatment by constructed wetlands or other biological processes (Malandra *et al.* 2003). Recently, a lot of interest has been devoted to more effective high-rate biofilm systems (FBBR, MBBR, SBBR, UASB), instead of using freely suspended microorganisms.

At high organic loading rates, anaerobic treatment is the most attractive primary treatment due to the over 80% BOD removal, combined with energy recovery in the form of biogas. In this case, biomethanation is the primary treatment step, often followed by an aerobic post-treatment before discharge. Effluent COD concentrations below 300 mg/L or in accordance with discharge regulations can be obtained (Moletta 2005). The digesters are generally heated to reach the mesophilic range using the produced biogas. Alternatives for achieving anaerobic digestion are well reviewed by Moletta (2005).

Anaerobic systems have various potential benefits, including low excess sludge production and avoiding odour problems. Furthermore, high rate anaerobic digesters based on granules or biofilm supports also have a high treatment capacity and hence low site area requirements. On the other hand, anaerobic ponds have been progressively replaced, because large area requirement and odour problems restrict its applications. However, this latter aspect has been recently overcome using nitrate as electron acceptor for the curative treatment of odours in evaporation ponds (Bories *et al.* 2005, 2007). Moreover, anaerobic treatment typically requires at least 15 days of start-up period after a shut down (Moletta 2005).

HOW IS THE PERFORMANCE OF BIOLOGICAL TREATMENT?

In Table 3 various biological processes are compared, considering applied loads (volumetric, specific and per surface unit in the case of biofilm systems), hydraulic retention time (HRT) and COD removal efficiency. The range of volumetric organic loads applied to the various systems are graphically compared in Figure 1, while the ranges of COD removal efficiency are compared in Figure 2. Nevertheless the COD removal efficiency can reach in most case 80–90%, the applied organic loads are very different depending on the applied technology, varying for an order of magnitude. The systems having the small footprint (higher applied load) have a higher level of complexity.

WHAT ABOUT MANAGEMENT?

Temporary buffer storage

A temporary buffer storage unit installed at the start of the flow-line is generally an imperative requirement in

Table 2 | Advantages and drawbacks of the main technologies for winery wastewater treatment (ww = wastewater)

Biological treatment	Advantages	Drawbacks
Aerobic/anoxic Suspended biomass		
Activated sludge (co-treatment with municipal ww)	Low cost	Temporary plant overloading during harvest period
	Winery ww useful as carbon source in pre-denitrification	Occasional bulking phenomena
		Occasional decrease of sludge settleability
Activated sludge	Significant reduction in COD	Energy intensive process
	Easy management	Periodic occurrence of bulking
		Supplementation with N and P for microbial growth
Jet-loop activated sludge	High mixing and turbulence without mechanical devices for aeration (Petruccioli *et al.* 2002)	Limited literature and applications
	Reduced Energy Consumption	
MBR	Great improvement in treated water quality	
	Effluent free of SST and bacteria with UF membrane	Additional costs for membrane modules
	Possibility of direct reuse on-site	Increase energy consumption compared with activated sludge
	Lower sludge production	Decrease in filterability caused by membrane fouling
	Rapid start up	
	Low footprint area	
	Absence of voluminous secondary settler	
	Operations not affected by settling properties of sludge	
SBR	Widespread solution for small wineries	Need of a daily storage aimed to reduce the shock loading
	Optimal configuration is a SBR fed once a day (20 h reaction + 3 h settling + discharge + filling) (Torrijos & Moletta 1997)	
	Simplified automation	
	Low capital cost	
	Moderate operating costs	
Aerobic biofilm systems		
FBBR	High empty space of plastic media	
	Backwashing not required	
	Simple management	
	No bulking problems	
MBBR	High empty space of plastic media	Additional cost of plastic media compared with activated sludge
	Backwashing not required	
	Simple management	

Table 2 | (continued)

Biological treatment	Advantages	Drawbacks
	No bulking problems	
SBBR	High empty space of plastic media	Additional cost of plastic media compared with activated sludge
	Backwashing not required	
	Simple management	
	No bulking problems	
Anaerobic processes		
Anaerobic digestion with suspended biomass	Enhanced methane production in the case of co-digestion with waste activated sludge	
	Low cost	
ASBR	Biogas production and energy recovery	On-line monitoring and modelling needed for optimisation
	Optimisation of cycle length by automation	
	Low excess sludge production	
UASB	High activity of granular sludge	Occasionally accumulation of floating scum
	Good settleability Low sludge production	Pre-treatment requiring aerobic post-treatment for effluent COD concentration of 100 mg/L (Kalyuzhnyi *et al.* 2001)
Anaerobic filters	Long solids retention time High removal rate per unit of reactor volume and at low HRT Low sludge production	Problems of clogging or channelling (shortcircuiting, plugging or flow by-pass), especially with high specific surface media No (or very low) solid concentration required
Hybrid USBF	Combination of main advantages of the anaerobic filter and UASB reactors	
	No clogging problems	
	Low sludge production	
Fluidised bed reactors	High removal rate per unit of reactor volume	Small fluidised particles
	Low sludge production	High fluid velocities
Wetland		
Constructed wetlands	Attractive for moderately sized wineries	Locations related to climate conditions
	Good performance using a pre-treatment for suspended solids removal and aeration	Requirement of wide areas due to large footprint of the plants, often located on valuable vine land
		Overloads in the case of high solid concentration

Table 3 | Comparison of applied COD loads, HRT and COD reduction for biological treatments

	Applied COD load					
Biological treatment	**Volumetric** $kg\,COD\,m^{-3}\,d^{-1}$	**Specific** $kg\,COD\,kg\,TSS^{-1}\,d^{-1}$	**Superficial** $g\,COD\,m^{-2}\,d^{-1}$	**HRT**	**Total COD reduction (%)**	**References**
Aerobic/anoxic suspended biomass						
Activated sludge (co-treatment with municipal ww)	0.81	0.09	–		90	Brucculeri *et al.* (2005)
Activated sludge	0.4–3.2	0.1–0.8	–		88–98	Fernández *et al.* (2007)
Jet-loop activated sludge	0.4–5.9			2.1–4.4 d	94–98%	Petruccioli *et al.* (2002)
MBR	0.5–2.2		–	1.8 d	>97%	Artiga *et al.* (2005, 2007)
SBR	0.8–1.3	0.25	–	24 h	>90%	Torrijos & Moletta (1997)
Biofilm						
FBBR	0.4–5.5	–	3–38	–	91%	Andreottola *et al.* (2005)
MBBR	0.3–9.0	–	0.8–30	–	78–97%	Unpublished data
SBBR	4.6–9.0	–	15–30	10 h	86–99%	Andreottola *et al.* (2002)
Anaerobic processes						
An. digestion (suspended biomass)	1–5			48 h	65–95%	Daffonchio *et al.* (1998) and Moletta (2005)
ASBR	8.6	0.96 $kg\,COD\,kg\,VSS^{-1}\,d^{-1}$	–	2.2 d	>98% (referred to soluble COD)	Ruíz *et al.* (2002)
UASB				24 h	90%	Keyser *et al.* (2003)
	5–15				80–98%	Moletta (2005)
	2–15			43–48 h	93–96%	Andreottola *et al.* (1998)
	4.7 (1 reactor at 10°C)	–	–	~1 d	60%	Kalyuzhnyi *et al.* (2001)
	2.2 (2 reactors at 10°C)	–	–	~2 d	>70%	Kalyuzhnyi *et al.* (2001)
Anaerobic filters	5–20			20–38 h	88–98%	Moletta (2005)
Hybrid USBF	5–13	–	–	>20 h	85–98%	Molina *et al.* (2007)
Fluidised bed reactors	15–30				80–98%	Moletta (2005)
Constructed wetlands				14 d	77–88%	Mulidzi (2007)

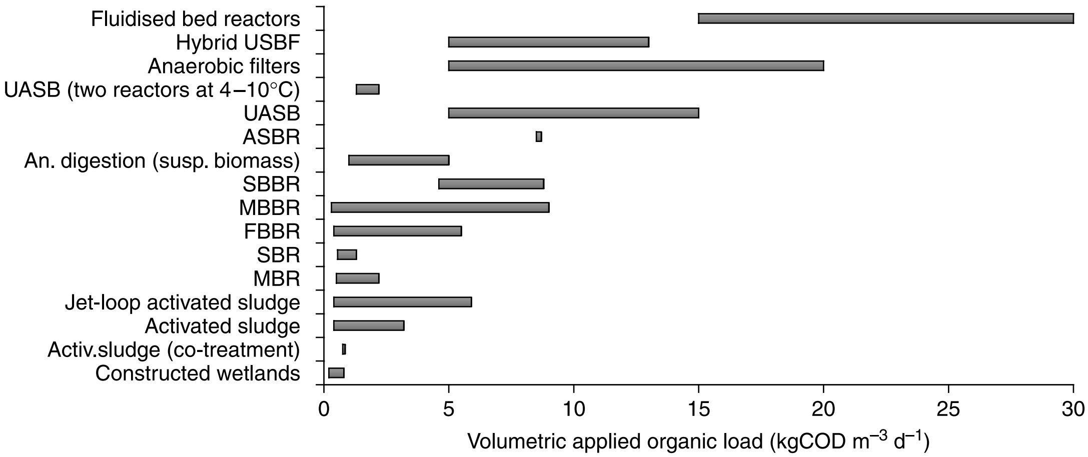

Figure 1 | Comparison among volumetric applied organic loads for some biological processes used for winery wastewater treatment.

biological treatments in order: (1) to reduce the effects of shock loading, (2) to facilitate the control of the inlet flow rate, maintaining a quite constant value into the reactor, (3) to accumulate the wastewater during the period after harvesting, when the discharge by the winery is very irregular and the flow rate is very low and therefore to allow the eventual shutdown of the biological treatment during this period. Due to the seasonal activity of wineries, the raw wastewater discharged occasionally into the storage tank during low load periods, can be stored (generally after good sieving) and treated within several months. In the storage tank of the waste wastewater occurs an acidic fermentation, if the residence time is long enough (Moletta 2005). In the case of mixing or aeration are provided in the storage unit the following aspects can be achieved, if necessary: (a) pH neutralisation, (b) addition of N or P for microbial synthesis requirement.

pH control

Control of the pH of the inlet wastewater is generally needed: a dosage of caustic soda or acid to the wastewater flow is needed to maintain a pH of the raw wastewater in an optimal range.

Nutrients

Nutrients are generally required for the aerobic biological treatment of winery wastewater due to the fact that

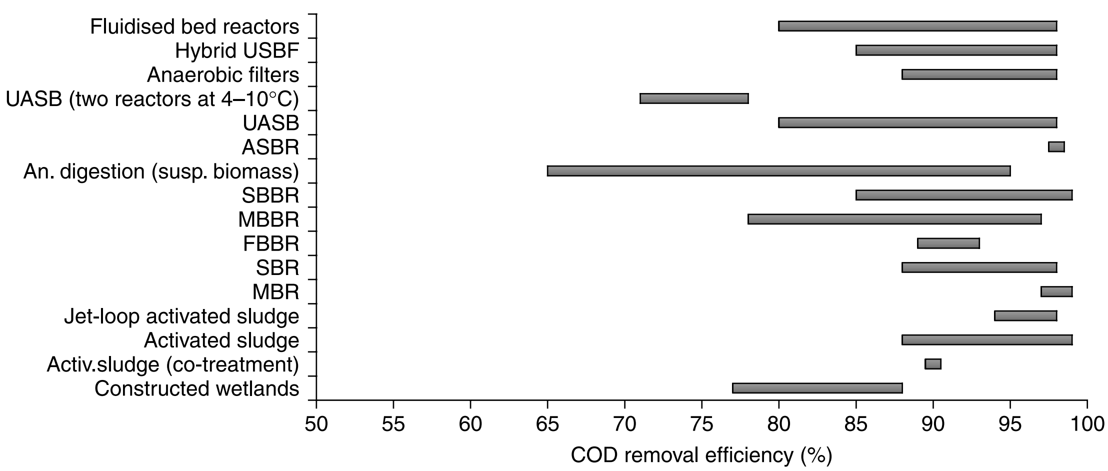

Figure 2 | Comparison among COD removal efficiency for some biological processes used for winery wastewater treatment.

COD/N/P ratio is unbalanced. N and P are usually provided by the addition of ammonia, urea and phosphoric acid. The flow rate of these chemicals into the wastewater stream may be directly proportional to the influent wastewater flow. In the case of anaerobic digestion the COD/N/P ratio is generally in the order of 800/5/1 (Moletta 2005) and thus the N and P requirement could be not necessary.

CONCLUSIONS

Based on this overview of biological processes for winery wastewater treatment, the following conclusions can be drawn:

(1) the high biodegradability (due to the high concentration of ethanol or sugars) in winery wastewater justifies often the choice of a biological treatment;
(2) in most treatments the removal efficiency of total COD was around 90–95%; the remaining COD concentration is due to the un-biodegradable soluble fraction of COD (ranging approximately around 5–10% of total COD), that cannot be removed by biological process or settling;
(3) nevertheless the COD removal efficiency can reach in most case 80–90%, the applied organic loads are very different depending on the applied technology, varying for an order of magnitude.
(4) the applied organic loads are higher in biofilm systems than in suspended biomass while anaerobic biofilm processes have the smaller footprint.
(5) the systems having the small footprint (higher applied load) have in general a higher level of complexity.

Because environmental issues are really a critical factor in industry competitiveness, the following possible actions will become more and more relevant towards an eco-efficient strategy in the winery industries: (i) choice of technologies with adequate extent of experience at different scale levels and especially at full-scale and at long-term; (ii) optimization of wastewater treatment processes in order to reduce impacts, save energy and reduce excess sludge production, (ii) reuse of treated effluents.

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