Application of a membrane bioreactor for winery wastewater treatment
D. Bolzonella, F. Fatone, P. Pavan and F. Cecchi

ABSTRACT

Winery wastewaters are variable in nature and are hard to treat by means of the conventional activated sludge process because of the high organic loading associated with their production, especially during vintage. To face this situation, recently, membrane bioreactors have been widely applied to treat winery wastewaters. In this study, a full-scale membrane bioreactor treated some 110 m$^3$/d of wastewater and organic loadings up to 1,600 kg COD per day. The average removal efficiency was 95% while the corresponding sludge yield was only 0.1 kg MLVSS per kg COD removed, as usual for these wastewaters. A detailed analysis of energy consumption showed specific energy demands of 2.0–3.6 kWh/m$^3$ of treated wastewater or 1 kWh per kg of COD removed.

Key words | energy requirements, membrane bioreactor (MBR), winery wastewater

INTRODUCTION

Wine-making produces large amounts of polluted wastewater: typical specific production is reported in the range 1–4 m$^3$ per m$^3$ of wine produced, 60–70% during the vintage period (Vlyssides et al. 2005; Andreottola et al. 2009). Moreover, these streams show high COD concentrations, up to 10 kg per m$^3$ and relatively low presence of solids and nutrients (Bolzonella & Rosso 2009).

In Europe, where 50% of the wine is produced worldwide, these wastewaters are typically discharged in sewers and co-treated with municipal wastewaters in centralized wastewater treatment plants (WWTPs) as reported by Beck et al. (2005) and Bolzonella et al. (2007a). On the other hand, especially in large wineries, these wastewaters are pre-treated by small wastewater treatment plants adopting the activated sludge process and are then released in the sewerage system; Torrijos et al. (2006) showed that up to 70% of the produced wastewaters are treated by means of the activated sludge process in large wineries. However, the intrinsic variability in flow and characteristics, the imbalance of nutrients (COD:N ratio in the range 50–100), and the necessity to face high organic loading for relatively short periods during harvesting and vintage generally determine problems for the operation of the activated sludge process because of the effluent COD or the dispersion and escape of suspended solids from the secondary clarifier. In order to overcome these problems, in recent years the use of membrane bioreactors (MBRs) have been introduced (Artiga et al. 2007; Shah et al. 2008; Guglielmi et al. 2009). In fact, membrane bioreactors allow for the maximum flexibility of the biology according to the influent loadings as the process is no longer dependent on the sedimentation characteristics of the activated sludge.

In this study we considered the start up and steady state performances of a full scale membrane bioreactor treating the effluent of a wine-making and bottling facility based in north-east Italy and producing sparkling white wines.
MATERIALS AND METHODS

The treatment plant

The full scale MBR is dedicated to the treatment of the effluents of a wine-making facility where both wine production and wine/spirits bottling are carried out.

Wastewaters are basically produced by washing activities and are then treated in an internal wastewater treatment plant equipped with submerged microfiltration membranes. Wastewaters are screened by a drum type siever with 1 mm holes (installed power 0.55 kW). This was necessary in order to prevent the accumulation of grapes seeds and tartaric acid salts. This step has been shown as crucial by previous works related to the treatment of both municipal and industrial wastewaters in MBRs (Frechen et al. 2007; Fatone et al. 2008). Screened wastewaters are then stored in a 80 m³ tank where they are homogenized by a mixer with a power of 1.1 kW. This volume, which is very reduced, guarantees a continuous hydraulic feeding and smoothing of the COD loadings. This is a typical unit operation for bioreactors for carbon removal (Fatone et al. 2008). Homogenized wastewaters are pumped by two pumps (1.1 kW each) to the bioreactor. This is a 325 m³ tank designed on the basis of a 0.06 kg BOD₅/kg MLSS per day food to biomass ratio, considering a concentration of the activated sludge of some 12 kg MLSS/m³, a typical value for plate and frame membranes. This design value involves a compact (reduced volume) configuration on one hand but also an α factor < 0.5, thus high energy consumptions (Germain et al. 2007), on the other hand. However, the necessity for small volumes and footprints is a must for wineries, where most of the space is dedicated to the wine-making activities. The design organic loading rate was set at 0.77 kg BOD₅/m³ per day. The aeration of the tank is guaranteed by a 22 kW blower able to supply from 500 m³/h up to 1,220 m³/h of air with a 400 mbar prevalence. The air supply is obtained by membrane disks (diameter 280 mm, holes 60 μm) with a minimal air flow rate of 2 – 6 Nm³/h. The filtration unit, by Kubota (UK), is due to two trains of 200 modules with a surface of 138 m² per train. The modules are plate and frame microfiltration membranes (0.4 μm) with a 10 mm space between two adjacent panels. The operational flux is in the range 15 – 20 LMH. The membrane scouring is obtained by course bubbles and an air flow rate of 360 m³/h for a specific aeration density (SADm) of some 1 m³/m²h, a value double the typical SADm reported for the treatment of municipal wastewater (Judd 2006). The installed power of the aeration pump is 7.5 kW.

The membrane modules are periodically washed with a NaClO solution. Waste activated sludge is periodically discharged by a 1.1 kW pump with a flow rate of 14 m³/h and thickened up to a solid content of 3% in a separate tank. The same pump provides the activated sludge recycling. Because of the high solid retention time (SRT) applied the sludge is already bio-stable and is not treated further. Table 1 resumes the design data of the MBR plant.

Experimental plan and analysis

The treatment plant was started up in September 2006 and then monitored for the period 2007 – 2008. COD, total solids, nitrogen and phosphorus were determined according to the Standard Methods on grab samples of the raw wastewater and the effluent (permeate) as well as waste activated sludge to perform mass balances. Wastewater was also monitored to better define its characteristics in terms of biodegradability by analyzing the different COD fractions by means of respirometric methods while the contents of ethanol and sugars were determined by enzymatic analysis.

RESULTS AND DISCUSSION

Wastewater characterization

An important part of the research was dedicated to the definition of the wastewater characteristics: during

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Value</th>
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<tbody>
<tr>
<td>Flow rate</td>
<td>m³/d</td>
<td>100</td>
</tr>
<tr>
<td>Max flow rate</td>
<td>m³/h</td>
<td>20</td>
</tr>
<tr>
<td>pH</td>
<td></td>
<td>6.5 – 8.5</td>
</tr>
<tr>
<td>COD load</td>
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</tr>
<tr>
<td>BOD load</td>
<td>kg/d</td>
<td>250</td>
</tr>
<tr>
<td>N-NH₄ total</td>
<td>kg/d</td>
<td>8.5</td>
</tr>
<tr>
<td>P total</td>
<td>kg/d</td>
<td>0.32</td>
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summer-autumn 2007, in particular, the wastewater was analyzed in detail to define the presence of COD and its fractions, as well as the presence of easily biodegradable organic compounds. Table 2 reports the main findings of that survey and compares the COD fractions with literature data. The different compounds found are typical of winery wastewaters but their concentrations (see ethanol and sugars) were clearly lower than characteristics reported in literature (e.g. Colin et al. 2005; Bolzonella & Rosso 2009).

**Membrane bioreactor performances**

The MBR started its operation in autumn 2006: it was inoculated with sludge taken from a conventional activated sludge process for the treatment of winery wastewater and after a start up of some 3 months the bioreactor reached stable steady state conditions and its performances were monitored for two years. Figure 1 shows the influent and effluent COD (kg/d) for the period 2006–2008: average influent COD was determined in some 500 kg/d but it evidently showed picks up to 1,600 kg/d during vintage (September–November) and in spring (April–May) when the bottling activity starts. The effluent COD was determined in some 30 kg/d and its behavior followed the influent COD: picks up to 150 kg/d can be observed in correspondence with the higher influent loads. However, an average removal efficiency of 94% was observed on a month basis during the period 2007–2008.

During this period the activated sludge concentration, expressed as MLSS, passed from some 2 g/L to 10–12 g/L during the start phase (2006) and then ranged between 12 and 30 g/L in the two following years depending on the influent organic loading.

The produced excess sludge was some 100 kg per day as MLSS, 70–80% was volatile fraction (MLVSS). The observed yield can be calculated in some 0.13 kg MLVSS per kg COD removed. This value was associated to an operative temperature of some 30°C due to the heat developed by the fermentative process, demonstrating the potential energy uncoping linked to high F/M applied to activated sludge processes (Liu et al. 1998).

Therefore, the organic substrates were basically removed through respiration which determined some 60% of the overall COD removal, rather than biomass growth.

The average concentration for nitrogen and phosphorus in excess sludge were some 5 and 1% on a dry matter basis. These results are in perfect agreement with results observed in conventional activated sludge processes treating both winery and municipal wastewaters (Brucculeri et al. 2005).

A detailed analysis of the MBR performances was carried out during summer-autumn 2007. During this period some 110 m³/d of wastewater was treated, on average (Figure 2).

With specific reference to the organic pollution, measured as COD, the influent concentration was extremely variable, ranging from some 3,000 mg/L in summer up to some 9,500 mg/L in October. The soluble fraction, SCOD, was some 80% of the total COD. Moreover,
respirometry tests showed that this soluble fraction was basically readily biodegradable, in full accordance with previous findings of the authors and other researchers (Beck et al. 2005; Bruculeri et al. 2005; Andreottola et al. 2005, 2007; Guglielmi et al. 2009). Despite the quick and high variations (up to 500%) in the influent characteristics, the system showed its elasticity and reliability and the effluent concentration never exceeded some 300 mg/L (97% soluble) confirming that the association of the activated sludge process with the membrane system can be a very promising technique for the treatment of wastewaters from the food processing industry (Bolzonella et al. 2007).

In perfect accordance with the global data for the period 2007–2008 discussed above, the average influent COD during this period was some 500 kg COD/d. Therefore, this period can considered representative of the routine situation of the plant.

The total suspended solids in the influent stream showed relatively low concentrations ranging between 100 and 400 mg/L. The permeate was virtually solids free as expected.

The biomass concentration ranged between 9 and 12 g/L and the corresponding F/M some 0.15 kg COD/kg MLVSS per day. The production of waste activated sludge was some 50–60 kg/d (observed yield of some 0.11 kg MLVSS/kg COD removed) and the calculated solid retention time (SRT) was some 60 days. This high value together with the high temperature developed in the process (up to 40–45°C) can justify the low yield observed.

In this period the activated sludge appeared well structured and compact and the sludge volume index (SVI) was typically in the range 50–80 cc/g.

As for nitrogen (see Figure 3), this was some 30–50 and more times lower in concentration compared to COD and the average influent concentration for total nitrogen was some 70 mg/L; generally 50 to 80% of influent total nitrogen (TN) was due to nitrates and the rest to ammonia while organic nitrogen was virtually absent. Effluent nitrogen was some 10 mg N/L, mainly nitrates. According to the data reported for excess sludge (some 50–60 kg/d and 5% for nitrogen concentration), it turns out clear, on a mass balance basis, how biomass growth determined some 50% of the nitrogen removal. As a consequence, denitrification processes occurred despite the extended aerobic conditions: probably, the high biomass concentration in the reactor together with high availability of readily biodegradable COD, determined the presence of micro- anoxic zones in sludge cores were nitrates were reduced to nitrogen gas.

As for phosphorus, this showed influent concentrations ranging between 15 and 60 mg P/L (35 mg P/L on average), while the effluent concentrations were some 20 mg P/L on average. Some 60 up to 90% of this was soluble phosphate, both in the influent and the effluent. Considering the production of excess sludge observed in that period and the typical TP concentration on a dry matter basis equal to some 1.5%, it turns out evident that the mass balances cannot be closed. In particular, the excess sludge stream can justify some 50% of the removed phosphorus. This problem was probably due to the high variability of this parameter in the influent and the sampling frequency.

However, in this case, the P concentration in the waste activated sludge is typical of conventional processes,
therefore anaerobic cores and luxury uptake phenomena can be excluded (Figure 4).

According to reported and discussed data, the MBR was able to face dramatic hydraulic and organic loading also during the vintage period and its performances were reliable.

Energy consumptions

The list of machines and installed power present in the wastewater treatment plant are reported in the materials and methods section above. The energy consumptions for the MBR were determined according to the number of hours effectively worked per month by a given machine, the efficiency and the installed power. The efficiency of the different machines was set equal to 0.85 except for the aeration blower system for the oxygen supply of the bioreactor whose frequency was automatically modulated. In this case the effective consumption for this machine was calculated considering the typical specific consumption of some 3 kWh per kg of O₂ supplied to the system and the process oxygen requirements.

The distribution of the energy consumptions is illustrated in Figure 5: clearly, the oxygen supply played a major role in the calculation and the bioreactor aeration represented 58% of the energy requirements. Then, the aeration of the membranes was responsible for a further 32%.

This distribution is typical of MBRs applications (Fatone et al. 2007).

It is interesting to note how the energy consumption determined on a monthly basis ranged between 2.0 and 3.6 kWh per m³ of wastewater treated and was equal to 2.8 kWh per m³, on average. This value is in perfect agreement with results reported in literature for the treatment of wastewaters from the food processing industry by means of membrane bioreactors, which is generally in the range 2.15–3.75 (Judd 2006). Moreover, this consumption was clearly related to the COD load treated in that period as shown clearly in Figure 6. The specific energy demand per kg of COD removed was in the range 0.4–2.2 kWh per kg CODₐm with an average value of some 1 kWh per kg CODₐm.

CONCLUSIONS

In conclusion, the following remarks can be reported.

- The membrane bioreactor was able to face the highest hydraulic and organic loadings observed during the harvest period, producing a permeate of good quality and a relatively small amount of wasted sludge. The COD...
removal efficiency was typically around 95%, also for organic loading rate up to 2 kg COD per m³ of bioreactor per day.

- Specific energy consumptions were in the range 2.0–3.6 kWh/m³ of treated wastewater or 1 kWh per kg of COD removed and were mainly related to the energy necessary for air supply to the activated sludge bioreactor and the membrane system (90% globally).

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**REFERENCES**


