Feasibility study to upgrade a textile wastewater treatment plant by a hollow fibre membrane bioreactor for effluent reuse

F. Malpei, L. Bonomo and A. Rozzi†

Hydraulic, Environmental & Survey Engineering Dept., Environmental Section, Politecnico di Milano, Piazza Leonardo da Vinci 32, 20133 Milan, Italy (E-mail: *francesca.malpei@polimi.it*)

Abstract A pilot plant membrane bioreactor has been tested in parallel with a full-scale activated sludge wastewater treatment plant fed on the wastewater from a textile factory. The possibility to upgrade the final effluent for internal reuse was investigated. The pilot and full-scale plants are located in a textile factory (Boselli & C., Olgiate Comasco, North Italy) which manufactures and finishes polyester fabric. The activated sludge wastewater treatment plant (WWTP) is an extended aeration system. The MBR pilot plant is a ZW-10 bench hollow fibre module (membrane surface area: 0.93 m^2) submerged in a 200 L tank. Performance and operation of the membrane bioreactor (MBR) were evaluated in terms of permeate characteristics and variability (COD, colour, total N and P, microbiological counts), of membrane specific flux (l m^{-2} h^{-1} bar^{-1}) and other operational parameters (sludge growth and yield).

Keywords Hollow fibre; membrane bioreactor; reuse; textile wastewater

Introduction

Much of the waste generated by the textile dyeing industry derives from wet finishing processes (scouring, dyeing, printing, etc.) which generate large volumes of wastewater containing a wide range of contaminants, that must be treated prior to disposal. Wastewater reuse, combined with the recovery of process chemicals, whenever possible, should be applied to reach a more sustainable management of textile mills.

A pilot scale membrane bioreactor (MBR) and a full-scale activated sludge wastewater treatment plant (WWTP) were operated in parallel on the effluent of a polyester textile finishing factory. The preliminary results related to the comparison of their performance are presented in this paper. The comparison between the two systems was based on removal efficiency, on the characteristics of the activated sludge and the quality and constancy of the effluent, in view of a possible recycle within the factory.

Materials and methods

The wastewater

The wastewater used during the tests is discharged by a textile factory which processes polyester fabric (desizing/scouring, debaka, dyeing and finishing) woven elsewhere. Scouring is performed with hot water (60–80°C) and surfactants to remove the soluble polyester-based size used in weaving and the oils used in spinning. Debaka is a process typically applied to polyester fabrics, consisting of a superficial attack and solubilisation of the polyester fibre by NaOH, to obtain a better (smoother) texture. Dyeing is carried out with disperse dyes, and finishing involves several different processes (thermal fixing of the fibre plus antistatic, softening, waterproofing treatments, etc). The water supplied to the factory is pumped from a private well. More than 95% of it (120,000 m^3 $year^{-1}$) is softened and used as process water. The COD concentration of the wastewater during the period of the tests (May–November 2001) ranged from 1.5 to 3.4 kgCOD m^{-3}.

The biological treatment plants

The wastewater (average $Q = 390\ m^3d^{-1}$) is treated in a biological activated sludge (AS) extended aeration (WWTP located at the factory and discharged to a public sewer prior to further treatment. The treatment steps are: neutralisation/equalisation ($V = 2{,}400\ m^3$), extended aeration ($V = 1{,}500\ m^3$) and secondary settling with aerobic digestion of the wasted sludge.

The membrane bioreactor pilot plant used during the tests is a ZeeWeed® ZW-10 bench rig (Zenon Env. Inc., Oakville, CDN). The membrane module is a vertical bundle of hollow fibres (nominal cut-off = 0.2 µm; external diameter $d = 3$ mm; inner volume of fibres = 0.13 L, total surface $S = 0.93\ m^2$) which are potted into two PVC heads. The module is submerged into a reactor tank ($V = 200$ L). Air is provided by a blower at the base of the module. The fibres are aerated to maintain an adequate turbulence and control fouling.

The permeate is extracted by suction from the hollow fibres or is pumped back (during backwashing), to clean the membrane surface by a volumetric (two heads) pump. An additional air diffuser (pore disc) was placed on the bottom of the tank to fulfil the oxygen requirements of the biomass. Dissolved oxygen (DO) concentration in the mixed liquor was always maintained in the range 1.5–4 mg L^{-1}.

The ZW-10 was filled with 100 L of mixed liquor drawn from the full-scale plant and 100 L of tap water. The initial total suspended solids (TSS) concentration in the bioreactor was 8 g L^{-1}. The feed was provided continuously by a peristaltic pump (model 315, Watson Marlow Bredel, Falmouth, UK). During the first period (60 days), the pump sucked up the feed directly from the neutralisation/equalisation tank of the WWTP, located at some distance (over 70 m) from the pilot. Suspended solids settling in the long tube clogged the line, and the variable pressure losses made it impossible to maintain a constant flow and therefore a constant influent COD load. During the second part of the research, batches of neutralised/equalised wastewater were loaded into a tank ($V = 200$ L), located near the pilot plant, to make a constant feed (COD variations less than 5%) lasting several days.

Analytical methods

The following parameters were analysed on the influent, effluent and mixed liquor, according to IRSA methods (IRSA, 1994), very similar to the *Standard Methods* (1995). Total and/or filtered (0.45 µm) COD, TSS, volatile suspended solids (VSS), non-ionic surfactants were evaluated according to the Tetrakis salt method (UNI10511-1). Colour was determined as absorbance on a Shimatzu UV1204 Spectrophotometer (Japan) with an optical path equal to 0.01 m at wavelengths of 426, 558 and 660 nm. These wavelengths were selected because they were used by the operators of the WWTP and in previous research related to textile water reuse in the Lake Como area as the most representative in local textile effluents (Rozzi *et al.*, 1999; Bergna *et al.*, 1999). Total coliform, faecal coliforms and *E. coli* counts were evaluated according to IRSA methods (IRSA, 1994).

Results and discussion

In Figure 1 the influent COD load, the removal efficiency and the mixed liquor suspended solids (MLSS) concentration in the existing WWTP are plotted versus time. The plant operates at a MLSS concentration which is very high and uncommon for a conventional activated sludge treatment (range 8 to over 14 gMLSS L^{-1}). This feature is mainly due to the fact that the surplus sludge is not wasted by the plant operator on a scheduled basis and consequently the food: biomass ratio (F/M) is very low and typically < 0.08 kgCOD $kgMLSS^{-1}\ d^{-1}$, as indicated in Figure 2.

This management of the biological treatment is very simple and reduces the mass of sludge to be wasted, and at the same time it makes it possible to obtain good removal efficiencies. However, it has significant drawbacks such as frequent foaming and/or bulking problems of the aerated sludge, which frequently cause high TSS and turbidity in the effluent and, in some cases, overflow of the foam from the aerated tank. A microbiological analysis of the sludge, according to the Jenkins method (Jenkins *et al*., 1993), evidenced a very abundant presence of *Microtrix parvicella*. This bacterial species is normally associated with very low F/M ratios and low DO concentrations. In the Boselli plant, DO is usually lower then 1 mg L^{-1}.

The average COD removal efficiency of the existing WWTP during the experimental period was ≈90% (standard deviation: 4.7%), with an average influent concentration of 2,240 mg L^{-1} and average effluent concentration of 228 mg L^{-1} as total COD. However, high oscillations were observed in the effluent COD daily values (range: 90–490 mg COD L^{-1}), partly because of the very high TSS contents in some periods. Most values were in the range 40–60 mgTSS L^{-1}, but in some samples values as high as 200 mgTSS L^{-1} were reached.

In Table 1 the range of the main operating parameters of the ZW-10 plant during the six months of continuous operation are reported. The MLSS for this pilot unit, according to the manufacturer's instructions, should be maintained below 10 gTSS L^{-1}, to avoid possible fouling and reduction of the permeate flow. However, during the investigation, higher TSS concentrations than the above value were tested for limited periods and no detrimental effects were observed in terms of permeate flows, at least up to a concentration of the order of 15–16 gTSS L^{-1}, as discussed below.

The ZW-10 provided an excellent and quite constant COD removal efficiency, as shown in Figure 3. Average COD removal during the whole experimental period was close to 94%

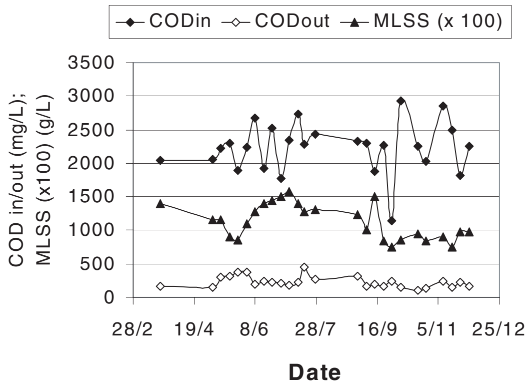

Figure 1 Main operating parameters of the Boselli factory wastewater treatment plant

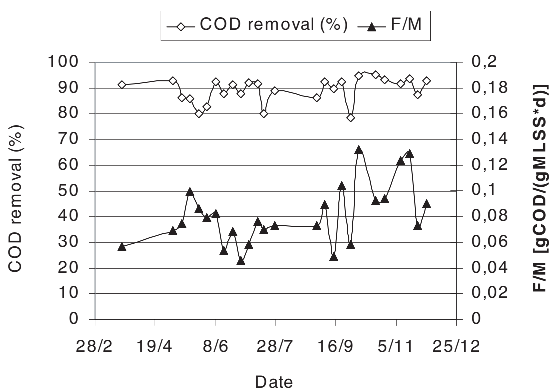

Figure 2 F/M ratio and COD removal efficiency of the Boselli factory wastewater treatment plant

Table 1 Main operating parameters of the ZW-10 MBR pilot plant

	Units	Average value	Range
Influent and permeate flow rate	L h^{-1}	3.1	1.4–10
Temperature	°C	18	6–25
HRT	hours	80	20–143
Influent COD	G m^{-3}	2.62	1.12–10
MLSS	gTSS L^{-1}	10.7	4.4–23.5
MLVSS/MLTSS	%	88.8	84–90
F/M ratio	GCOD $gTSS^{-1}$ d^{-1}	0.097	0.017–0.36

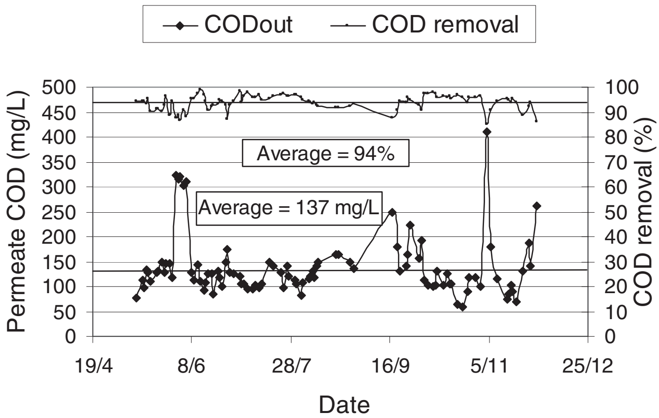

Figure 3 Permeate COD and COD removal of the pilot ZW-10

(93.8%), with a standard deviation of 2.3%. Average COD values in the permeate were 137 mg L^{-1}, with a standard deviation of 39 mg L^{-1}. As one can observe in Figure 3, the permeate COD concentration was below 150 mg L^{-1} during most of the test period and occasionally even lower then 100 mg L^{-1}.

The few peaks of the permeate COD concentration in Figure 3 apparently are not caused by variations in operating conditions (i.e. influent COD load or DO concentration). The MBR responded very well to unexpected and occasional peaks in the influent concentration, as it happened during the first period of operation, maintaining permeate COD values below 100 mg L^{-1} with influent concentrations of 4,000–5,000 mg L^{-1} and F/M ratio of 0.2–0.25 kgCOD $kgTSS^{-1}$ d^{-1}. As a general observation, neither the COD removal efficiency nor the effluent COD appreciably depend on the COD load, on the F/M ratio or on other parameters, such as temperature, DO concentration or MLSS. For example, the average values of COD removal and concentration related to the 30 coldest days, when the temperature of the bioreactor was lower then 10°C, are 92.9% and 149 mg L^{-1} respectively, slightly worse then the average values referred to throughout all the experimental period.

The COD concentration of the filtered mixed liquor was always appreciably higher then the COD concentration of the permeate. The difference between the two values was not constant. The average 0.45 μm filtered COD during the whole experimental period was 194 mg L^{-1}, therefore approximately 1.4 times the average permeate COD. The same filtered effluent concentration was appreciably lower (0.85) compared to the average WWTP effluent COD. Note however that the latter comprises the COD due to the effluent TSS (40–60 mgTSS L^{-1} as already indicated). Suspended solids in the permeate were analysed occasionally in the permeate as a control, and their concentration was always found to be < 1 mg L^{-1}.

Colour was removed very efficiently by the MBR, as shown in Figure 4. The average abatement of absorbance was 96.5% at 426 nm and 98.7% at 660 nm. Lower, but still

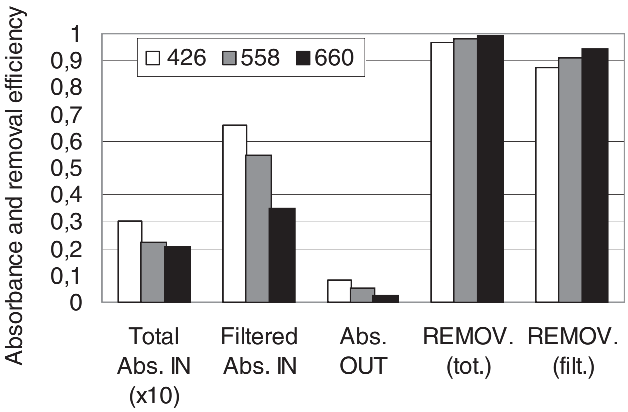

Figure 4 Average absorbance and efficiency in the pilot ZW-10 influent and permeate

significant abatement, were measured with reference to the absorbance measured on the filtered influent. The average absorbance at 426 nm measured in the permeate was 0.08 (range: 0.016–0.142). Most values (75% of the total number of measurements), however, were lower then 0.1. These values are comparable with the ones obtained by Rozzi *et al*. (2000a) in the permeate of a ZeeWeed® microfiltration module fed with the mixed liquor of a centralised WWTP treating prevailingly textile influent. Grab measurements on the WWTP effluent samples indicated values of absorbance up to three times the values of the ZW-10 permeate.

Non-ionic detergents, the only surfactants used at the factory, were found in the raw wastewater at concentrations ranging from 75–95 mgTAS L^{-1}. In the permeate, their concentration dropped to 1.5–5 mgTAS L^{-1}, with removal rates in the range 95–98%.

The presence of microorganisms indicators of pathogenicity is a very important issue for water reuse, not only in the case of irrigation. The draft of the Italian law on water reuse now in discussion for instance, requires a maximum of 2 CFU/100 mL for *E. coli* for any kind of reuse. For this reason, the evaluation of the removal efficiency of the ZW-10 on three of the most common indicators: total coliforms, faecal coliforms and *E. coli* was considered to be very important. Five analyses, each in three replicates, were made during the experimental period on the influent and the permeate. Results are reported in Table 2. The total and faecal coliforms were not completed removed, even though a very high log abatement (almost four orders of magnitude) was achieved. On the contrary, in three out of the five samples, *E. coli* were completely removed from the influent, possibly because their concentration was much lower, and the abatement was "only" close to three orders of magnitude.

Growth of MLSS and apparent yield

Growth and apparent yield of the MLSS in the MBR have been calculated on the basis of the cumulative curves of sludge increase (sum of daily increase/decrease of the MLSS plus

Table 2 Average values and ranges of total and faecal coliforms and *E. coli* in the influent and permeate of the ZW-10 module

Microorganisms	Influent (CFU/100 ml)		Permeate (CFU/100 ml)		Removal (log units)	
	Average	Range	Average	Range	Average	Range
Total coliforms	134,000	9,000–290,000	70	2–183	3.8	2–4.1
Faecal coliforms	120,237	7,050–288,000	18	1–89	3.8	1.6–4.4
E.coli	1,590	350–5,000	0.75	0–3	2.9	2.5–3.3

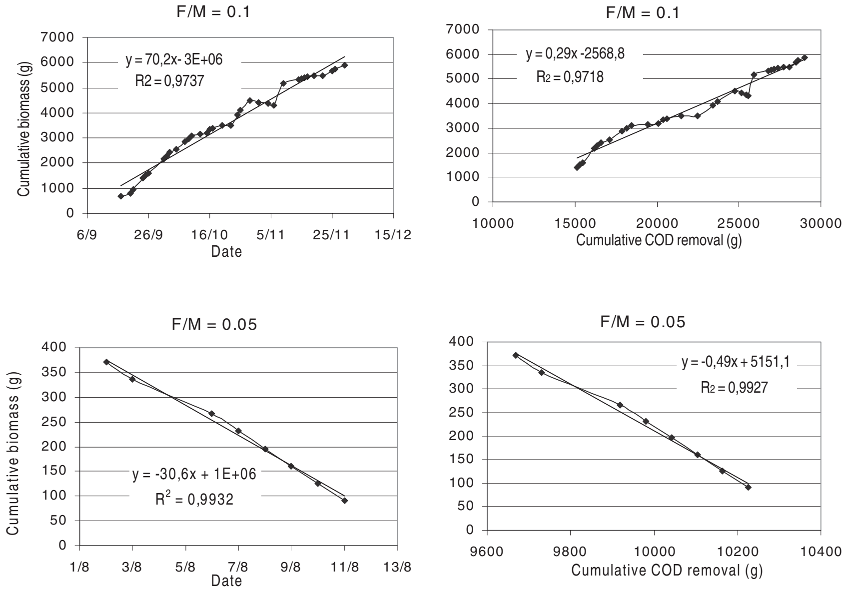

Figure 5 Total suspended solids curve versus time (left) and versus cumulative COD removed (right), during the two periods at average F/M = 0.05 and 0.1 kgCOD kgTSS d^{-1}

the sludge wasted (three times) during the whole experimental period (21 June, 6 and 22 November) and COD removal. The trend and correlation of both parameters with respect to the F/M ratio were not always consistent, i.e. different periods at the same F/M ratio did not always result in comparable values of growth and yield, and in some cases at higher F/M values lower values of growth and yield were observed. Two possible reasons for these inconsistencies may be the loss of MLSS that occasionally occurred due to foam overflow from the tank and the uncontrolled presence in the influent of appreciable concentrations of VSS (0.6 to 1.8 gVSS L^{-1}), probably polyester fibre fragments, that were not completely hydrolized and biodegraded during the treatment and caused an increment of volatile solids (inert, non biomass). Figure 5 summarises the most consistent results obtained during two periods at F/M ratio of 0.1 and 0.05 gCOD $gTSS^{-1}$ d^{-1}.

Specific flux

The permeation flux was in the range 2–13 L m^{-2} h^{-1} and the average was equal to 4 L m^{-2} h^{-1}. This value is indeed low, but was determined by the low reactor volume to membrane surface of the pilot. In other words the influent flow rate (and therefore the flux) could not be increased to higher values because of the limitation on the organic load by the limited total mass which could be maintained into the reaction vessel. The actual performance is better when the specific permeate flux (per unit transmembrane pressure) is considered: values higher than 200 L m^{-2} h^{-1} bar^{-1} were obtained at quite low suction negative pressures (<0.05 bar) provided that the MLSS concentration was maintained below 15 g L^{-1}. Above this value, the suction pressure increased appreciably to reach a maximum close to 0.27 bar for MLSS = 23 gTSS L^{-1}.

Conclusions

On the basis of the experimental data obtained on the hollow fibre ZW-10 membrane bioreactor, the application of this process for the production of purified water to be reused in a dyeing textile factory is feasible. In fact, taking into account a preliminary investigation carried out at the Boselli factory (Malpei *et al.*, 2000), the residual SST, COD and absorbance of the permeate make it suitable for reuse in some operations of the dyeing cycle such as the first washing. Compared to the existing extended aeration WWTP, the ZW-10 pilot MBR makes it possible to obtain higher COD removal and colour abatement, besides a much higher removal efficiency for suspended solids and microorganisms.

Taking into account experimental results previously obtained with a ZeeWeed hollow fibres module used as simple microfiltration unit of the secondary effluents of a WWTP fed on prevailingly textile effluents (Rozzi *et al*., 2000a). The permeate of the ZW-10 pilot plant could be directly fed to a nanofiltration or RO module to produce a water suitable for any textile process.

The apparent yield (i.e. cumulative increase of mixed liquor TSS with respect to the cumulative COD removed) in the ZW-10 at a F/M ratio of 0.1 gCOD $gTSS^{-1}$ d^{-1} was very high (0.29 gTSS $gCODremoved^{-1}$), if compared to the values of net yield usually observed in activated sludge plants (both conventional and membrane bioreactors) operating at the same F/M range (Tchobanoglous and Burton, 1991; Rozzi *et al*., 2000b). This aspect needs further investigation, but the most probable reason seems to be the presence in the influent of significant concentration of VSS that are not completely solubilised and biodegraded.

Acknowledgements

This research has been partly funded by MIUR (cofin99 9908165245 "Advanced wastewater treatment and options for reuse"). The most valuable cooperation of the textile company Boselli is gratefully acknowledged.

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