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Halophilic biological treatment of tannery soak liquor in a sequencing batch reactor

O. Lefebvre[a,b,*], N. Vasudevan[b], M. Torrijos[a], K. Thanasekaran[b], R. Moletta[a]

[a]*Laboratory of Environmental Biotechnology, Institut National de la Recherche Agronomique (INRA), Avenue des Etangs, 11 100 Narbonne, France*

[b]*Centre for Environmental Studies, Anna University, Guindy, Chennai 600 025, India*

Received 7 October 2004; received in revised form 30 November 2004; accepted 2 December 2004

Abstract

Hypersaline wastewater (i.e. wastewater containing more than $35\,g\,l^{-1}$ total dissolved solids (TDS)) is generated by various industrial activities. This wastewater, rich in both organic matter and TDS, is difficult to treat using conventional biological wastewater treatment processes. Among the industries generating hypersaline effluents, tanneries are prominent in India. In this study, tannery wastewater from soak pit was treated in a lab-scale SBR for the removal of organic matter. The characterisation of the soak liquor showed that this effluent is biodegradable, though not easily, and highly variable, depending on the origin and the nature of the hides. TDS was in the range of $21–57\,g\,l^{-1}$ and COD was in the range of $1.5–3.6\,g\,l^{-1}$. This soak liquor was biologically treated in an aerobic sequencing batch reactor seeded with halophilic bacteria, and the performance of the system was evaluated under different operating conditions with changes in hydraulic retention time, organic loading rate and salt concentration. The changes in salinity appeared to affect the removal of organic matter more than the changes in hydraulic retention time or organic loading rate. Despite the variations in the characteristics of the soak liquor, the reactor achieved proper removal of organic matter, once the acclimation of the microorganisms was achieved. Optimum removal efficiencies of 95%, 93%, 96% and 92% on COD, PO_4^{3-}, TKN and SS, respectively, could be reached with 5 days hydraulic retention time (HRT), an organic loading rate (OLR) of $0.6\,kg\,COD\,m^{-3}\,d^{-1}$ and $34\,g\,NaCl\,l^{-1}$. The organisms responsible for nitrogen removal appeared to be the most sensitive to the modifications of these parameters.

Keywords: Hypersaline effluent; Tannery effluent; Sequencing batch reactor (SBR); Wastewater treatment

Abbreviations: ALR, ammonia loading rate; BOD_5, biochemical oxygen demand (5 days); COD, chemical oxygen demand; HRT, hydraulic retention time; MLVSS, mixed liquor volatile suspended solids; OLR, organic loading rate; SBR, sequencing batch reactor; SEPs, solar evaporation pans; SS, suspended solids; SVI, sludge volume index; TDS, total dissolved solids; TKN, total Kjeldahl nitrogen.

*Corresponding author. Laboratory of Environmental Biotechnology, Institut National de la Recherche Agronomique (INRA), Avenue des Etangs, 11 100 Narbonne, France. Tel.: +33 468425151; fax: +33 468415260.

E-mail address: olivier2703@yahoo.com (O. Lefebvre).

0043-1354/$ - see front matter
doi:10.1016/j.watres.2004.12.038

1. Introduction

Hypersaline effluents are generated by various industrial activities. This wastewater, rich in both organic matter and total dissolved solids (TDS), is difficult to treat using conventional biological wastewater treatment processes (Ludzack and Noran, 1965). Use of halophilic bacteria is required (Larsen, 1962). The interest in treating that kind of wastewater is growing at a fast rate.

Among the industries generating hypersaline effluents, tanneries are prominent in India. Tanning is one of the oldest professions in India, with 2000 units spread mostly across Tamil Nadu, West Bengal, Uttar Pradesh, Andhra Pradesh, Karnataka, Rajasthan and Punjab. Leather tanning is almost wholly a wet process from which a large volume of liquid waste is continuously generated. Due to the variety of chemicals added at different stages of processing of hides and skins, the wastewater has complex characteristics. The tanning process and the effluents generated have already been reported in the literature (Wiegant et al., 1999; Sreeram and Ramasami, 2003; Stoop, 2003) and an overview is presented in Fig. 1.

In this study, tannery wastewater was collected after the soaking of hides and skins. Salt (sodium chloride (NaCl)) is used to preserve the fresh skins from decomposition immediately after they are stripped in the slaughterhouse, and the excess of salt has to be removed in the tannery before further processing. This is done by soaking, using a lot of water, which generates the first source of effluent. This soak liquor is characterised by high organic load, high suspended solids (sand, lime, hair, flesh, dung, etc.) and high salinity. Because of that high salt content, this wastewater is generally segregated and sent to solar evaporation pans (SEPs), as indicated in Fig. 1. The presence of high concentrations of dissolved organic matter and suspended solids (SS) retards the rate of evaporation in SEPs. Thus, tanneries require large areas to dispose the soak liquor and the salt obtained cannot be reused because of its high organic content. This salt is then discharged on open land and contributes to soil and water pollution. Treatment of this soak liquor, before sending it to SEPs, in order to remove the excess of organic matter, would accelerate the rate of evaporation, reduce the odour of the effluent and improve the purity of the salt obtained. This salt could then be reused in the tannery itself, during the pickling stage (treatment of the skins with an aqueous solution of acids and salt, which allows the skins to

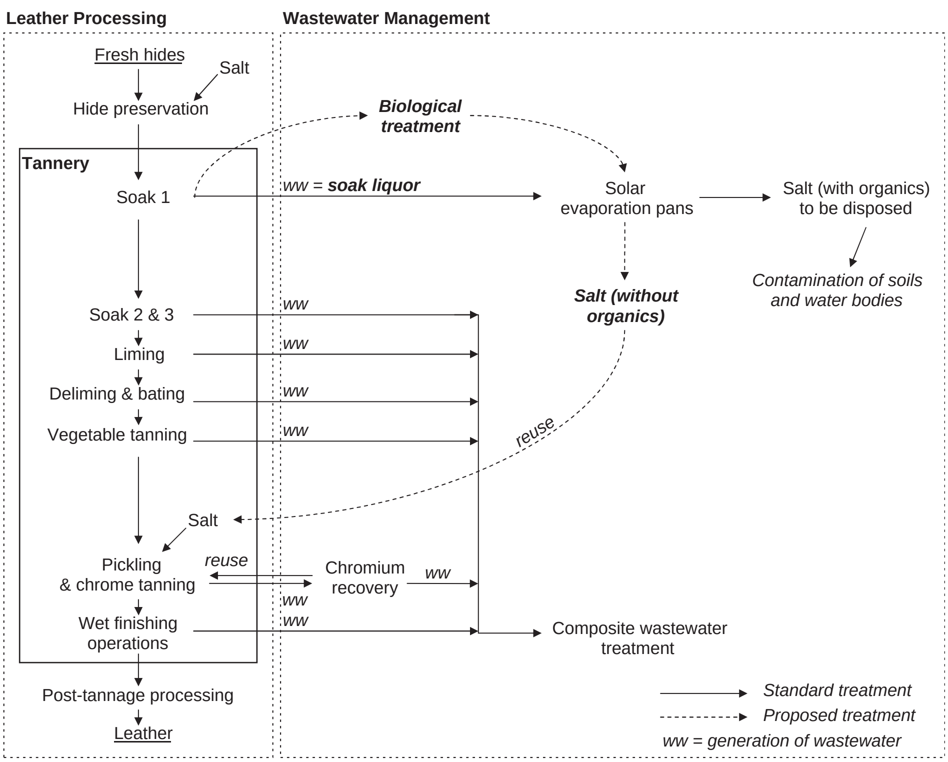

Fig. 1. Simplified leather production chain and management of the effluents associated.

be further handled without getting swelled). As the amount of salt used for the preservation of the skins exceeds the amount used for pickling, a part of the recovered salt should get another destination (e.g. neighbouring tanneries). Furthermore, improved methods of preservation of hides and skins have been developed that use less amount of salt in admixture with certain biocides and thus restrict the growth of bacteria to considerable extent. In this case, biological treatment of tannery soak liquor may become more complicated, but, as the amount of salt is reduced, the segregation of the soak liquor may not be required anymore. In some cases, the biocide alone can also be used as a preservation agent.

Degradation of synthetic substrates using halophiles has already often been studied. Panswad and Anan (1999) obtained 71% chemical oxygen demand (COD) removal efficiency using an anaerobic/anoxic/aerobic process and a synthetic wastewater containing 3% salt, provided the seeding material was acclimated to high salinity conditions. Dinçer and Kargi (2001) treated a synthetic effluent with increasing salt concentrations (0–10%), using an aerobic biological disc system, and could get more than 80% COD removal efficiency, as long as the salt concentration remained below $50\,g\,l^{-1}$. The sequencing batch reactor (SBR) is known to be a robust system that stands harsh conditions (Herzbrun et al., 1985). It is not surprising that this process has often been used in order to treat saline wastewater. Woolard and Irvine (1994) inoculated a sequencing batch biofilm reactor (SBBR) with moderate halophiles, recovered from the Great Salt Lake, in order to treat a synthetic effluent containing 150 g salt l^{-1}. The removal efficiency measured on phenol exceeded 99%. They renewed the experiment (Woolard and Irvine, 1995) with a SBR with free culture that reached an average removal efficiency of 99.5%. Uygur and Kargi (2004) used SBR to treat a saline synthetic effluent and noticed that COD removal efficiency decreased from 90% to 32% when salinity increased from 0% to 6%.

Fewer experiments have been conducted on the degradation of complex wastewater in halophily, and, once again, SBR has often been used for that purpose. Kubo et al. (2001) removed 90% of the COD contained in pickled plum production plant effluent using aerobic SBR. Moon et al. (2002) treated a 1% salt containing seafood wastewater by SBR, reaching 87.9% COD removal efficiency. Lefebvre et al. (2004) treated an agri-food effluent related to the wine industry with a SBR and obtained up to 83% COD removal efficiency, provided the pH was neutralised.

In this study, a tannery wastewater (soak liquor) was treated, using an aerobic SBR and halophilic microorganisms, in order to remove organic matter (carbon, nitrogen, and phosphorus) and SS from the effluent.

2. Materials and methods

2.1. Influent

The tannery influent (soak liquor) was collected from soak pits in a tannery around Chennai (India). Eleven different samples of soak liquor were collected and used as an influent for the bioreactor during the experimental period.

2.2. Bioreactor

An aerobic SBR was operated during 300 days to remove the organic matter from the soak liquor. The lab-scale SBR, illustrated in Fig. 2, had a volume of 10 l. Tubes were inserted into the top of the reactor to ensure the filling and withdrawal of the effluent using peristaltic pumps. An air compressor delivering airflow of $1.2\,l\,min^{-1}$ supplied aeration. The ambient temperature of the wastewater in the reactor was close to 30 °C. Each cycle lasted for 24 h: the reaction took place in 22 h, the settling in 1 h 30 min and the withdrawal and filling of the treated effluent and influent in 30 min.

The influent was delivered to the bioreactor at a flowrate of $2\,l\,d^{-1}$ until day 100, then at a rate of $3\,l\,d^{-1}$ between day 100 and 270, and finally $4\,l\,d^{-1}$ until the end of the experiment. Consequently, the hydraulic retention time (HRT) was 5 days until cycle 100, then was reduced to 3.3 days and finally to 2.5 days at the end of the experiment.

The sludge was allowed to accumulate in the reactor. However, in certain periods (between day 189 and 214, and between day 242 and 277), sludge withdrawal was done by cancelling the settling phase, thus maintaining the sludge mixed in the reactor all over the cycle. Consequently, sludge was withdrawn along with the effluent. In these periods, the sludge was then allowed to settle for 1 h 30 min in a beaker before collecting the supernatant, which was considered as the treated effluent when measuring all analytic parameters (e.g. total COD).

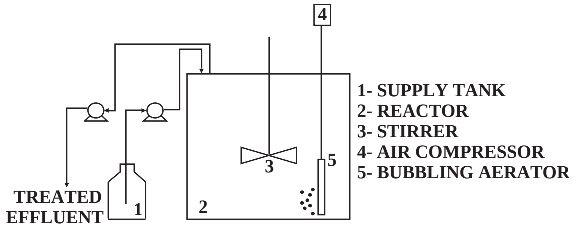

Fig. 2. Lab-scale aerobic SBR.

2.3. Inoculum

The reactor profited from a quadruple inoculation, which accelerated the installation of a halophilic microbial population and also increased the biodiversity in the reactor. The biological sludge obtained from the secondary basin of the Nesapakkam sewage treatment plant (Chennai, India) was added to the reactor on day 1. Biological sludge from the secondary basin of the common effluent treatment plant of Pallavaram (Chennai, India), treating the composite effluents of 128 tanneries, was also added on day 1. Later, a liquid sample presumably rich in halophilic bacteria was added to the reactor on day 30. This was collected from a textile effluent treatment plant in the area of Tirupur (India). Finally, sediments collected at the bottom of a salt collection basin in Kelambakkam (Chennai, India) were added on day 30.

2.4. Analysis

COD, BOD_5, TKN, N-NH_3, P-PO_4^{3-}, TDS, SS, MLVSS and pH (the abbreviations of these parameters and other terms is presented at the beginning of this paper) were analysed following APHA's Standard Methods for the Examination of Water and Wastewater (1998). Quality control was ensured using standards as well as duplicates. COD was determined by the open reflux method. Mercuric sulphate was used to eliminate the interference of chlorides when dosing COD. Sawyer and McCarty (1967) reported that this interference could be eliminated as long as a 10/1 weight ratio of mercuric sulphate to chloride is maintained. Soluble COD (CODs) was obtained after filtration using 0.45 μm glassfibre filters. Determination of ammonia was done, using the titrimetric method, and phosphates were determined with the ascorbic acid method.

3. Results and discussion

3.1. Characterisation of the soak liquor

The influent wastewater (soak liquor) was characterised with common parameters (pH, TDS, COD, TKN, etc.). The mean and standard deviations were calculated using 11 different influents during the experimental period. Main results are plotted in Table 1. The soak liquor is characterised by substantial organic matter content and high SS content, resulting in an average total COD concentration of $2200\,mg\,l^{-1}$ and a SS concentration of $5300\,mg\,l^{-1}$. Very high salinity was reflected by an average TDS concentration of $37{,}000\,mg\,l^{-1}$. TKN, N-NH_3 and PO_4^{3-} averaged 273, 153 and $21\,mg\,l^{-1}$, respectively. Finally, pH averaged 7.7. Table 1 shows great variability in the quality of the

Table 1
Characterisation of 11 influents coming from the same tannery

	Influent 1	Influent 2	Influent 3	Influent 4	Influent 5	Influent 6	Influent 7	Influent 8	Influent 9	Influent 10	Influent 11	Mean	Standard deviation
pH	—	7.7	7.8	7.9	7.7	7.8	7.7	7.5	7.5	7.6	—	7.7	0.2
TDS	57,300	35,100	25,800	27,800	33,000	51,700	25,300	30,200	38,600	45,900	34,000	36,800	8600
SS	10,300	3900	7000	6400	7700	3700	2500	3600	7600	5300	4000	5300	2400
VSS	2600	700	900	1900	1800	1700	500	700	2000	500	800	1300	700
Total COD	2000	2800	2600	3000	3600	2200	1600	1500	1900	1700	2600	2200	700
Soluble COD	600	900	600	500	1400	1100	900	800	400	900	900	800	300
Total TKN	—	300	200	310	470	350	140	140	—	—	—	270	120
Soluble TKN	—	170	160	190	230	250	90	80	—	—	—	170	70
Total NH_3	—	90	160	190	280	230	60	70	—	—	—	150	90
Soluble NH_3	—	50	130	120	190	170	40	40	—	—	—	100	60
Total PO_4^{3-}	4	15	19	21	28	23	25	41	31	18	8	21	10
Soluble PO_4^{3-}	5	13	2	6	5	11	8	11	7	6	4	7	3

influent, reflected by high standard deviation values. Great variability was observed with respect to the influent, depending on the type of hides and skins and the region from which they came, at the time of the sampling.

Some useful relationships between parameters were calculated. According to it, soluble COD averaged 37% (±14%) of total COD, which indicates that very little amount of COD is soluble. Most of it must be included in the dung that comes along with the hides and skins. The BOD_5/COD ratio was 0.3, which was very low in comparison to domestic wastewater (i.e. 0.5). Therefore, the biodegradability of the influent was found to be low, according to the criteria of Ahn et al. (1999). However, BOD_5 is a controversial parameter, when it is applied to tannery wastewater, since it contains many inhibitors of BOD_5 (Ates et al., 1997). The VSS/SS ratio averaged 0.2 ± 0.1, therefore was found to be very low due to the numerous fibres and inorganic particulate (sand, dust) escaping the soak pit. The VSS/(total COD−soluble COD) ratio averaged 1.2 ± 0.7, thus indicated that every kg of VSS contributed to 1.2 kg of particulate COD. Finally, the COD/N/P ratio averaged 200/22/2 and showed that the soak liquor contained high amounts of nitrogen but lesser amounts of phosphorus. However, no phosphorus deficiency could be identified and this ratio is close to that of domestic wastewater (i.e. 200/22/3.5).

It can then be concluded that the influent used in this experiment was highly variable and suffered from low biodegradability and high inorganic solids content (both soluble and suspended). This showed that high salt content would not be the only obstacle for the good operation of a bioreactor. Yet, the pH and COD/N/P ratio in the soak liquor enabled the bioreactor to be operated without any pH regulation and without adding nutrients such as nitrogen or phosphorus, which would have increased the running costs.

3.2. Evolution of HRT, OLR and TDS concentration

High variability in the organic content (reflected by COD concentration) and salinity (reflected by TDS concentration) of the soak liquor might make the proper operation of a biological treatment plant uneasy, causing important disturbance in the equilibrium of the microbial community. Yet, looking forward to applying the process at an industrial scale, a decision was taken not to artificially change the influent characteristics in order to make it more homogeneous. This choice resulted in frequent changes in the environmental conditions in the bioreactor. In addition, HRT was progressively decreased from 5 to 2.5 days during the experiment, as shown in Fig. 3, by increasing the influent flowrate. Consequently, OLR ranged from 0.4

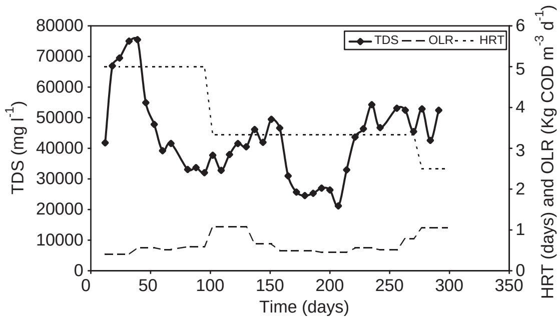

Fig. 3. Evolution of HRT, OLR and TDS concentration in the reactor during the experiment.

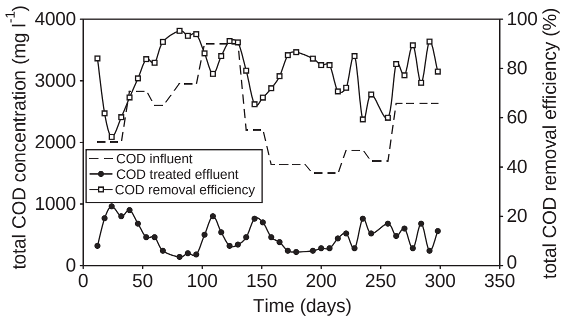

Fig. 4. Evolution of total COD concentration in the influent and treated effluent and evolution of COD removal yield during the experiment.

to 1.1 kg COD $m^{-3} d^{-1}$. TDS ranged from 21,200 to 94,300 mg l^{-1}.

3.3. COD removal

COD removal by the SBR is reported in Fig. 4, where the influent wastewater and the treated effluent concentrations are indicated. The influent concentrations are obtained from Table 2, for each influent sample used during the experiment. The starting phase, during which salinity was increased gradually to reach that of the real effluent, lasted for about 30 days. At that time, COD concentration was very high in the treated effluent (960 mg l^{-1}), leading to removal efficiencies as low as 52%. After 30 days, the removal of COD quickly increased up to day 81. At that time, HRT was 5 days, OLR was 0.6 kg COD $m^{-3} d^{-1}$ and TDS concentration was 34 g l^{-1}. Under these environmental conditions, the COD concentration in the treated effluent attained 140 mg l^{-1} (95% COD removal efficiency). This performance then stabilised over 20 days.

On day 100, the flowrate of the feed was increased from 2 to 3 l d^{-1}. Consequently, HRT decreased to 3.3 days and OLR increased to 1.1 kg COD $m^{-3} d^{-1}$.

Table 2
Effluent quality and corresponding removal efficiency for SBR operated with domestic wastewater and tannery soak liquor at two different OLRs

	Tannery soak liquor		Tannery soak liquor		Domestic wastewater	
OLR	0.6 kg COD m^{-3} d^{-1}		1.1 kg COD m^{-3} d^{-1}		0.9 kg COD m^{-3} d^{-1}	
HRT	5 d		3.3 d		0.4 d	
	Effluent concentration ($mg\,l^{-1}$)	Removal efficiency (%)	Effluent concentration ($mg\,l^{-1}$)	Removal efficiency (%)	Effluent concentration ($mg\,l^{-1}$)	Removal efficiency (%)
COD	140	95	320	91	26	81
TKN	11	96	195	54	12	83
PO_4^{3-}	1	93	2.3	92	5.8	0
SS	580	92	3280	82	15	87

Consequently, the COD removal reduced in the first 10 days, COD removal efficiency falling to 78%. Then COD removal increased again, once the acclimation to the new HRT and OLR was done. On day 123, the COD concentration in the treated effluent attained 320 $mg\,l^{-1}$ (91% COD removal efficiency). This performance then stabilised over 14 days.

On day 137, OLR decreased to 0.7 kg COD $m^{-3}\,d^{-1}$, due to a lesser COD concentrated influent wastewater (influent No. 6). It is worthy of note that, at that time (day 137), TDS concentration reached one of its highest values, i.e. 46,000 $mg\,l^{-1}$, due to the high salinity of influent No 6. This resulted in a new decrease of the COD removal. Then COD removal increased again, as a lesser saline influent wastewater (influent No. 7) was used. On day 179, good performance on COD removal could be attained again. At that time, OLR was 0.5 kg COD $m^{-3}\,d^{-1}$ and TDS concentration was 25.7 $g\,l^{-1}$, and this resulted in a treated effluent containing as less as 220 $mg\,l^{-1}$ COD (87% COD removal efficiency). This COD removal efficiency remained over 80% during the next 35 days, all environmental parameters remaining more or less constant over that period of time.

Finally, on day 214, TDS concentration started to increase again, due to a more saline influent wastewater (influent No. 9) and remained high until the end of the experiment (influents Nos. 10 and 11). This TDS raise resulted in a new disturbance that reduced the efficiency of COD removal. No stabilisation could be observed any more and it is worthy to note that a last modification done on day 277, HRT being reduced from 3.3 to 2.5 days and OLR being increased from 0.8 to 1.1 kg COD $m^{-3}\,d^{-1}$, did not affect the performance of the system. Therefore, in this last period of time, the COD concentration in the treated effluent varied from 240 to 680 $mg\,l^{-1}$ (74–91% COD removal efficiency).

3.4. Specific impact of TDS concentration on COD removal

Monitoring the performance of the SBR in removing COD over 300 days, it appeared clearly that this performance was dependent upon the environmental conditions in the reactor and overall upon the TDS concentration. The specific effect of TDS concentration on COD removal was then further analysed. Fig. 5 shows that the COD concentration in the treated effluent increased and the COD removal efficiency decreased when the TDS concentration increased in the reactor. Up to 50 g TDS l^{-1}, the COD concentration in the treated effluent averaged 390 $mg\,l^{-1}$ (82% COD removal efficiency). At TDS concentrations higher than 50 $g\,l^{-1}$, the average COD concentration was 810 $mg\,l^{-1}$ (63% COD removal efficiency). It is worthy of note that, on the contrary, no correlation was found between the COD concentration in the influent and in the treated

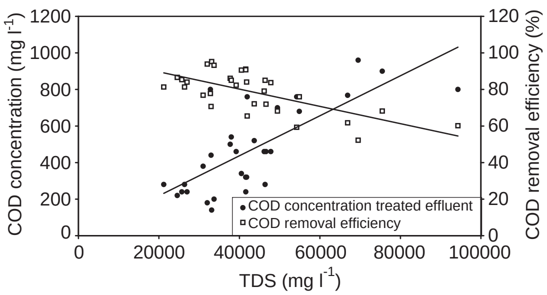

Fig. 5. Evolution of COD concentration in the treated effluent and COD removal yield with TDS concentration.

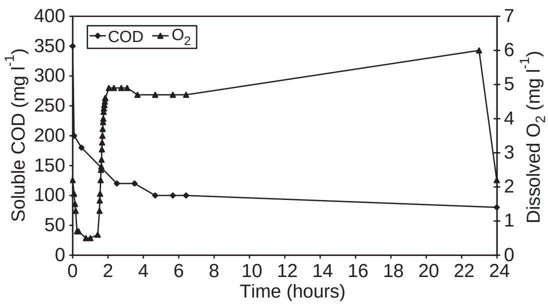

Fig. 6. Evolution of soluble COD and dissolved O_2 during one cycle of operation of the SBR.

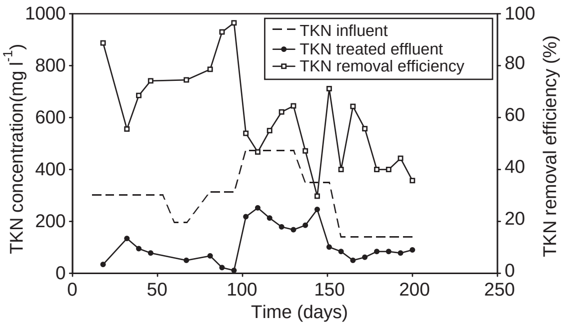

Fig. 7. Evolution of TKN concentration in the influent and treated effluent and evolution of TKN removal yield during the experiment.

effluent (data not shown). Consequently, these results show the strong inhibitor effect of the highest TDS levels on the performance of the bioreactor. The microbial consortium was unable to adapt efficiently to the highest TDS levels. Yet, the increase in biomass was not affected by TDS concentration (data not shown). As biomass was maintained, only its ability to remove COD was reduced under the highest salinity conditions. This explains why, when TDS concentration decreased again, depending on the influent used during the experiment, recovery was fast. Dinçer and Kargi (2001), who noticed a rapid deterioration of a biological disc system in removing COD as soon as salinity reached $50\,g\,l^{-1}$, have already indicated this limit value of $50\,g$ salt l^{-1}.

It has already been shown in the literature that good performance could be obtained even with more than 50 g salt l^{-1}. Woolard and Irvine (1995) could remove 99.5% of the phenol contained in a 15% salt containing wastewater in SBR. Lefebvre et al. (2004) could remove 83% of the soluble COD of a 12% salt containing wastewater. But it seems that, in our experimental conditions, under fluctuating salinity conditions, the microbial consortium was unable to adapt adequately to the strongest TDS concentrations.

3.5. Study of a SBR cycle

A study of a SBR cycle was carried out during day 250. The removal of soluble COD during this cycle in parallel with the dissolved oxygen concentration is shown in Fig. 6. In 5 min, soluble COD reduced from 350 to $200\,mg\,l^{-1}$, which indicates that 40% of the soluble COD disappeared immediately from the liquid phase and was probably adsorbed on to the biomass. After 2 h 30 min, soluble COD reduced to $120\,mg\,l^{-1}$, as the readily biodegradable COD was consumed. At the end of the cycle, soluble COD reduced to $80\,mg\,l^{-1}$, after the slowly biodegradable COD was removed.

During the first 2 h, dissolved oxygen concentration was around $0.7\,mg\,l^{-1}$, due to the consumption of the readily biodegradable soluble COD. Then, dissolved oxygen concentration quickly increased up to $5\,mg\,l^{-1}$ within 30 min and progressively reached $6\,mg\,l^{-1}$ after 23 h. This last increase was mainly due to the endogenous respiration and to the consumption of slowly biodegradable soluble COD, the last phenomenon being less than the previous one. The last hour of the cycle was dedicated to settling: no more oxygen was added to the reactor and the dissolved oxygen quickly decreased.

3.6. Phosphorus removal

After a starting phase of about 30 days, the performance of the SBR in removing PO_4^{3-} increased (data not shown). Every change in the HRT, OLR or TDS affected the removal of PO_4^{3-} in the same way as it affected the removal of COD. Consequently, the PO_4^{3-}concentration in the treated effluent ranged from 0.5 to $10\,mg\,l^{-1}$, resulting in a PO_4^{3-}removal efficiency ranging from 50% to 95%. The amount of PO_4^{3-} removed averaged 1.0 ± 0.2 mg for 100 mg of COD removed.

3.7. Nitrogen removal

Different observations can be done concerning the removal of TKN and the results are plotted in Fig. 7.

After a starting phase of about 30 days, the performance in removing TKN quickly improved up to day 100. At that time, 11 mg l^{-1} of TKN only remained in the treated effluent (96% TKN removal efficiency). After day 100, the amount of TKN in the input suddenly rose, because of the increase in the influent flowrate, and salinity increased too. This resulted in a sudden deterioration of the performances of the SBR in removing TKN. During this period, running from day 100 to 137, the amount of TKN remaining in the treated effluent averaged 195 mg l^{-1} (54% TKN removal efficiency). Then, when the quantity of TKN decreased again, after day 137, and when salinity decreased, the performance of the SBR in removing TKN did not improve. During the last period, running from day 150 to day 200, the TKN concentration in the treated effluent averaged 76 mg l^{-1} (46% TKN removal efficiency). Similar results and conclusions could be drawn with NH_4^+ (data not shown), this parameter being approximately 50–60% of TKN. The amount of TKN removed averaged 11.0 ± 0.2 mg for 100 mg of COD removed before the first shock (day 100) but only 5.1 ± 1.2 mg for 100 mg of COD removed at the end of the experiment. The amount of TKN removed at the end of the experiment (i.e. 5.1 ± 1.2 mg TKN for 100 mg of COD removed) is a typical value for assimilation of nitrogen. It can then be assumed that, before the first shock (day 100), nitrification took place but, after the shock, only assimilation occurred.

These results show that the SBR was able to achieve proper removal of TKN under weak load conditions (i.e. ammonia loading rate (ALR) = 40 mg N-NH_3 l^{-1} d^{-1}) and 32 g TDS l^{-1}. Then, when the TDS concentration and the load increased after day 100, the removal of TKN decreased. Finally, even when the salt and load were reduced again, the recovery was low, which shows that the bacterial community had suffered from the change in salt and load. Furthermore, because the excess COD was consumed (see Fig. 4) and not the excess TKN, the COD/N balance was changed, leading to a different behaviour of the bacterial community. It can be assumed that, under weak load conditions, some nitrification took place, but due to the change in the salt and load, nitrifiers then disappeared.

The inhibition of the organisms responsible for nitrogen removal (mainly nitrifiers) under highly saline conditions has already been studied: Dahl et al. (1997) found that nitrification could take place under operational conditions up to 20 g Cl l^{-1}, with a maximum nitrification rate of 2 mg N g VSS^{-1} h^{-1}. In addition, they found that a rapid increase of chloride concentration inhibited the nitrifiers. Vredenbregt et al. (1997) showed that nitrification was possible up to at least 34 g Cl l^{-1} in a fluid bed reactor, provided ALR was maintained at 15 mg NH_3 l_{bed}^{-1} h^{-1}. Panswad and Anan (1999) found that nitrification activity was reduced from 85% to 70% when salinity rose from 5 to 30 g l^{-1}, using salt acclimated seeds, and that the impact was more noticed at the low salt doses of 0–5 g l^{-1} than at the higher runs. Campos et al. (2002) showed the mixed inhibition effect of salt and ammonia on nitrification: ammonia accumulation started at an ALR of 3 g l^{-1} d^{-1} and a total saline concentration of 525 mM (13.7 g NaCl l^{-1}, 19.9 g $NaNO_3$ l^{-1} and 8.3 g Na_2SO_4 l^{-1}). In our conditions, 96% TKN removal efficiency could be attained under ALR of 40 mg N-NH_4^+ l^{-1} d^{-1} and a TDS concentration of 34 g NaCl l^{-1}. Under these highly saline conditions, a higher ALR of 84 mg N-NH_4^+ l^{-1} d^{-1} was responsible for a loss in the TKN removal efficiency and no complete recovery could be attained when ALR was reduced again.

3.8. SS removal

Evolution of solids in the inlet and outlet of the SBR is shown in Fig. 8. The first 25 days were characterised by high SS amount in the output. This was due to the starting of the experiment, when increasing salt concentration resulted in the low settling of the microorganisms and their withdrawal with the output. Then, the performance of the SBR in removing SS increased. On day 67, the SS concentration in the outlet reached 580 mg l^{-1} (92% SS removal efficiency), then stabilised over 30 days. Then, with every sudden change in OLR and TDS concentration (see Fig. 3), the performance of SBR in removing SS fluctuated. A major perturbation occurred after day 137, when the TDS concentration suddenly increased, though OLR suddenly decreased from 1.1 to 0.7 kg COD m^{-3} d^{-1}. This resulted in the withdrawal of substantial amounts of SS, as shown in Fig. 8. This resulted in higher amounts of COD (see Fig. 4) and TKN (see Fig. 5) in the treated effluent in the days following day 137. Basically, SS concentration averaged 910 mg l^{-1} in the last 100 days of experiment (79% removal efficiency), which still indicates high turbidity. Approximately 20% of the SS found in the treated effluent were VSS.

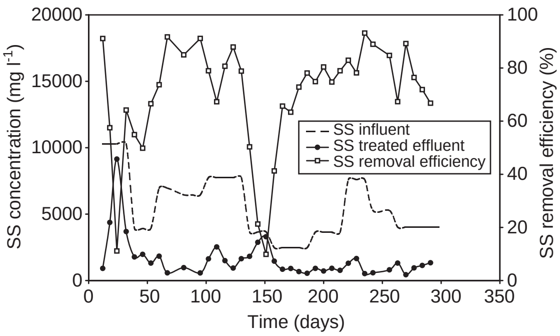

Fig. 8. Evolution of SS concentration in the influent and treated effluent and evolution of SS removal yield during the experiment.

High turbidity is very common in hypersaline effluents, as noticed in the literature. Lefebvre et al. (2004) successfully treated a $120\,g\,l^{-1}$ salt containing agri-food effluent but the SS still averaged $1800\,mg\,l^{-1}$ after treatment. Woolard and Irvine (1995) gave several reasons to explain this fact, related to the low mechanical integrity of the flocs, as well as to the high density of salt water.

3.9. Biomass production

Biomass concentration, measured as MLVSS, was followed and the results are plotted in Fig. 9. After 50 days dedicated to the starting of the experiment, including the increase in salt concentration, the accumulation of MLVSS averaged $110\,mg\,l^{-1}\,d^{-1}$ up to day 189. At that time, MLVSS concentration averaged $18\,g\,l^{-1}$. Sludge withdrawal was then initiated by cancelling the settling step, thus removing MLVSS during the withdrawal of the treated effluent. Sludge withdrawal was stopped on day 214, when MLVSS concentration was only $2\,g\,l^{-1}$ then initiated again from day 242 to day 277. After acclimation of the sludge, the sludge volume index (SVI) decreased and stabilised around $25\,ml\,g\,MLVSS^{-1}$ (see Fig. 9), which indicated a very good settleability of the sludge. This good property made it possible to retain high sludge concentration (up to $21\,g\,l^{-1}$). These results are in accordance with the literature, which shows that high salinity is not an obstacle to biomass growth. Panswad and Anan (1999) did not notice an impact of high salinity ($30\,g\,l^{-1}$) on MLSS in a bioreactor, provided the seeds are acclimated. Kubo et al. (2001) could also get proper cell growth up to 15% salinity. Furthermore, Panswad and Anan (1999) did not notice any significant impact of high salt concentrations and saline shocks on sludge settleability. Campos et al. (2002) also showed that high salt concentration do not have long-term effects on the physical properties of the sludge. They were able to maintain $20\,g\,VSS\,l^{-1}$ in an activated sludge reactor, thanks to a SVI value of $11\,ml\,g\,VSS^{-1}$. Finally, Uygur and Kargi (2004) found that SVI increased with increasing salt content, but the SVI value ($97\,ml\,g^{-1}$) obtained at 6% salt in a SBR indicated good settling properties even at high salt content.

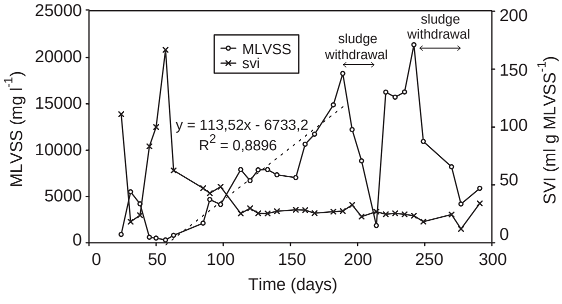

Fig. 9. Evolution of SVI and biomass concentration during the experimental period.

3.10. Comparison with a SBR treating domestic wastewater

The performance of the SBR operated in this study was finally compared to the performance of a SBR treating domestic wastewater. Ng et al. (1993) operated an aerobic SBR on domestic sewage with an OLR of $0.9\,kg\,COD\,m^{-3}\,d^{-1}$ and 0.4 days HRT. The characteristics of the influent used in that study were 331 mg total $COD\,l^{-1}$, $119\,mg\,SS\,l^{-1}$, $42\,mg\,TKN\,l^{-1}$ and $5.7\,mg\,PO_4^{3-}\,l^{-1}$. The effluent concentrations after treatment of that influent and the corresponding removal efficiencies are shown in Table 2, along with the results obtained for the treatment of tannery soak liquor at two different OLRs. It can be seen from Table 2 that the removal efficiency of all parameters can be higher for the treatment of tannery soak liquor than for the treatment of sewage. Of course, since the influent concentrations were higher in the case of tannery soak liquor than in the case of domestic wastewater, the treated effluent concentrations remained higher. It can then be concluded that, in the case of a stable halophilic system, the performance of a highly saline system can be similar to the performance of a non-saline one.

4. Conclusion

This study proved the feasibility of treating a hypersaline tannery soak liquor using halophilic bacteria in order to remove the organic matter from the effluent. A SBR was operated during 300 days on tannery soak liquor and the evolution of the reactor in removing different parameters (COD, TKN, PO_4^{3-}, and SS) was monitored. The main conclusions are as follows:

(1) The characteristics of the tannery soak liquor showed low biodegradability, high inorganic suspended solids, high nitrogen content but fairly low phosphorus content. In addition, this effluent appeared to be highly variable depending on the origin and the nature of the hides.
(2) The salt concentration appeared to be the main factor that affected the reactor's performance. The COD, PO_4^{3-}, TKN and SS removal efficiencies decreased when salinity increased. Fifty grams of NaCl per litre appeared to be a limit value for the proper operation of the system.
(3) Optimum removal efficiencies were attained under a low OLR of $0.6\,kg\,COD\,m^{-3}\,d^{-1}$, 5 days HRT and

34 g NaCl l^{-1}. COD, PO_4^{3-}, TKN and SS removal efficiencies attained 95%, 93%, 96% and 92%, respectively.

(4) The organisms responsible for nitrogen removal appeared to be the most sensitive to the environmental changes that occurred in the reactor. Other organisms presented adequate recovery capabilities after a salt or load shock.

(5) Biomass growth was not affected by the high salt concentrations, neither was the settleability of the sludge.

(6) The SBR technology appeared to be an adequate solution for the treatment of tannery soak liquor, removing organic matter, as well as the odour of the liquor. After biological treatment, this liquor may be sent to evaporation pans and the improved quality of the salt obtained could allow it to be reused.

(7) The performance of a highly saline system can be similar to the performance of a non-saline one.

Acknowledgements

This study was conducted in the Centre for Environmental Studies, Anna University, Chennai (India), thanks to cooperation between Anna University and the French National Institute for Agronomic Research (Institut National de la Recherche Agronomique, INRA), under the framework of the Indo-French Cell for Bioprocesses on Environment (IFCBE). The authors want to thank the laboratory assistance provided by Mrs. J. D'Silva during the study.

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