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Anaerobic digestion of tannery soak liquor with an aerobic post-treatment

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Abbreviations:
BOD_5biochemical oxygen demand (5 days)
CODchemical oxygen demand
HRThydraulic retention time
(ML)SS(mixed liquor) suspended solids
(ML)VSS(mixed liquor) volatile suspended solids
OLRorganic loading rate
SBRsequencing batch reactor
TAtotal alkalinity
TDStotal dissolved solids
UASBupflow anaerobic sludge blanket
VFAvolatile fatty acids.

ABSTRACT

The leather industry occupies a place of prominence in the Indian economy due to its massive potential for employment, growth and exports. The potential environmental impact of tanning is significant. This study focuses on tannery soak liquor, generated by the soaking of hides and skins, which is characterised by high organic load and high salinity. For these reasons, the soak liquor should be segregated and pre-treated separately before being mixed with the composite wastewater, made of all other streams mixed together. The anaerobic digestion of tannery soak liquor was studied using a UASB. COD removal reached 78% at an OLR of 0.5 kg COD $m^{-3}d^{-1}$, a HRT of 5 days and a TDS concentration of 71 g l^{-1}. The combination of the UASB with an aerobic post-treatment enhanced the performance of the overall wastewater treatment process and the COD removal efficiency of the combined anaerobic/aerobic treatment system reached 96%. However, for effective operation, the system had to be operated at very low OLRs, which affects the economic viability of such a process.

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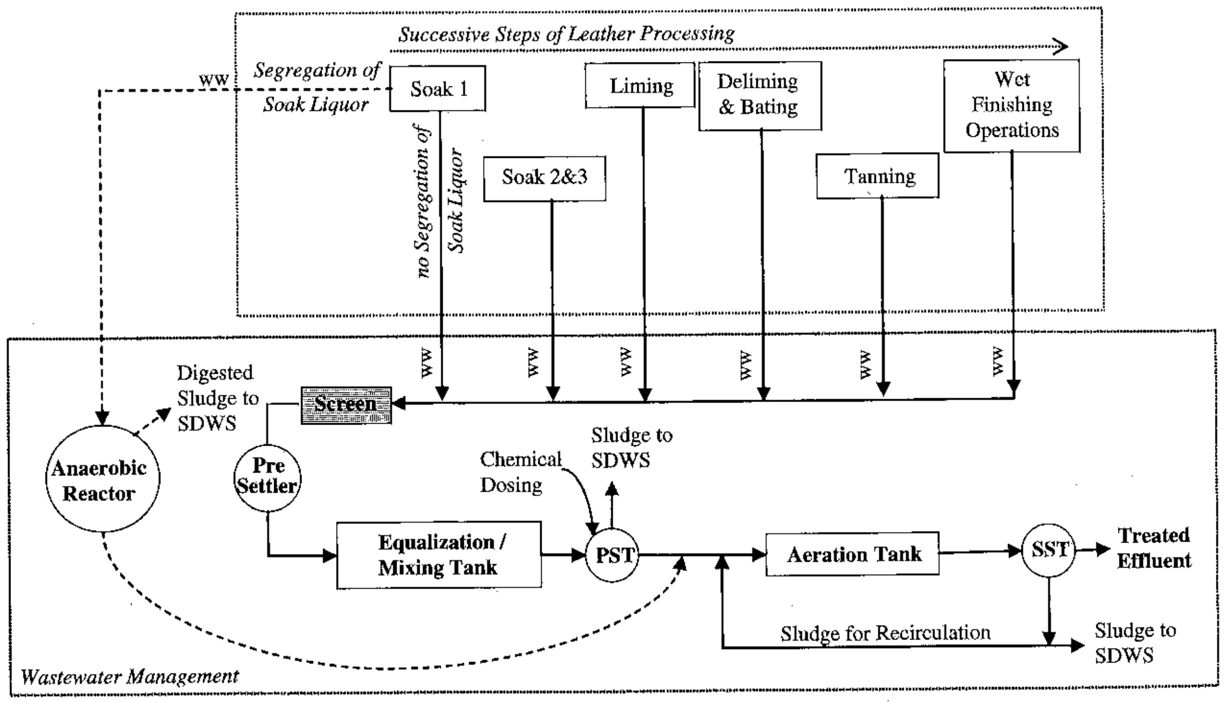
1. Introduction

Hypersaline effluents are generated by various industrial activities. Such 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). The use of halophilic bacteria is required (Larsen, 1962). The number of studies dealing with the biological treatment of hypersaline wastewater is increasing rapidly.

Among the industries generating hypersaline effluents, tanneries are prominent in India. Tanning is one of the oldest professions in India, with 2000 industrial 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 phases 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 the upper part of Fig. 1, entitled “Successive steps of leather processing”. Salt (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, a high level of suspended solids (sand, lime, hair, flesh, dung, etc.) and high salinity. The soak liquor is usually mixed with the other streams generated by leather processing to form the composite wastewater, which is screened, equalised, physically and chemically treated, and then biologically treated, as indicated in the lower part of Fig. 1, entitled “Wastewater management”.

There would be several advantages in segregating the soak liquor and treating it anaerobically, before mixing it with the composite wastewater, as proposed in Fig. 1. Firstly, sulphates are known to inhibit anaerobic treatment—as sulphates are reduced into sulphide by sulphate-reducing bacteria, which retards the anaerobic treatment of carbon—and the composite wastewater contains between 1000 and 3500 mg sulphates l^{-1}, whereas the soak liquor does not contain sulphates. Thus, anaerobic digestion of the soak liquor is likely to be more efficient if segregated. Secondly, biochemical oxygen demand (BOD_5) is likely to be higher in the soak liquor than in the composite wastewater, which makes the soak liquor particularly suitable for anaerobic digestion. Thirdly, application of anaerobic digestion to the segregated soak liquor could be used as a pre-treatment before aerobic treatment (such as lagooning or with activated sludge). The anaerobically treated soak liquor could be mixed with the composite wastewater after physico-chemical treatments. Thus, the cost of the treatment would be reduced because fewer chemicals would be used during primary treatments, less oxygen would be required for aeration and less sludge would be generated by aerobic treatment.



PST : Primary Settling Tank
SST : Secondary Settling Tank
SDWS : Sludge Dewatering System
ww : generation ofwastewater
→ Standard treatment
--→ Proposed treatment

Fig. 1 – Simplified overview of tanning process and tannery effluent management.

Table 1 – Characteristics of nine influents coming from the same tannery

	pH	TDS (gl^{-1})	SS (mgl^{-1})	VSS (mgl^{-1})	COD (mgl^{-1})
Influent No. 1	7.5	30.2	3600	700	1500
Influent No. 2	7.5	38.6	7600	2000	1900
Influent No. 3	7.6	45.9	5300	500	1700
Influent No. 4	–	34.0	4000	800	2600
Influent No. 5	7.8	63.2	4200	2300	3700
Influent No. 6	7.8	32.9	5100	1600	2600
Influent No. 7	7.0	50.5	10,700	1500	4400
Influent No. 8	7.7	58.2	5100	1400	2200
Influent No. 9	7.6	72.3	9600	2400	2300
Mean	–	47.3	6100	1500	2500
Std. Dev.	–	14.8	2600	700	900

High salt content is considered to have an inhibitory effect on anaerobic digestion, mainly due to cations. A sodium content exceeding $10\,gl^{-1}$ has already been reported as inhibiting methanogenesis (Kugelman and McCarty, 1965; Rinzema et al., 1988; Gourdon et al., 1989). However, Omil et al. (1995) could not show any clear toxic effect of a seafood-processing effluent, with salinity similar to sea water, on an anaerobic contact system pilot-plant. It was therefore proven that the adaptation of an active methanogenic biomass to the salinity of the effluent was possible. They concluded that the efficiency of such a process depended on an adequate adaptation strategy of the biomass to salinity. Feijoo et al. (1995) specified that sodium toxicity on sludge depended on several factors such as the antagonism effect, due to other ions at adequate concentrations, the nature and the adaptation of the sludge and the methanogenic substrate used.

The scope of this work was to study the anaerobic digestion of hypersaline tannery soak liquor using an upflow anaerobic sludge blanket (UASB) reactor. A UASB was selected because it has already been used successfully for the biological treatment of tannery composite wastewater (Wiegant et al., 1999; Boshoff et al., 2004). The efficiency of an extensive aerobic post-treatment process was also considered. In order to reduce the cost of such a post-treatment as much as possible, an extensive process was selected, i.e. activated sludge reactor without recirculation of the sludge, to simulate an aerobic lagoon. Finally, the performance of such a treatment was compared to that of an aerobic sequencing batch reactor (SBR) treating similar wastewater (Lefebvre et al., 2005).

2. Materials and methods

2.1. *Influent*

The tannery influent (soak liquor) was collected from soak pits in a tannery around Chennai (India). Nine different samples of soak liquor were collected and used as an influent for the UASB reactor during the experimental period. The average characteristics of the nine samples are reported in Table 1. The high standard deviation values reflect the high variability of tannery soak liquor. The characterisation of tannery soak liquor has already been detailed in a previous study (Lefebvre et al., 2005).

2.2. *Bioreactors*

2.2.1. *Upflow anaerobic sludge blanket (UASB)*

A 5 l lab-scale UASB, fed with soak liquor, was operated for more than 300 days. Influent was continuously provided to the UASB using a peristaltic pump. Temperature was ambient (close to 30 °C), which made the treatment mesophilic. The device most characteristic of a UASB is the phase separator. This device is placed at the top of the reactor and divides it into a lower part, the digestion zone, and an upper part, the settling zone. The wastewater is introduced as uniformly as possible over the reactor bottom, passes through the sludge bed and enters into the settling zone via the aperture in the phase separator. Thus, the presence of a settler on top of the digestion zone enables the system to maintain a large sludge mass in the UASB reactor, while an effluent free of suspended solids is discharged. The biogas bubbles are released into the gas phase at the liquid–gas interface. The influent flowrate equalled $1\,l\,d^{-1}$ initially, then increased to $1.5\,l\,d^{-1}$ on day 110, decreased to $0.8\,l\,d^{-1}$ on day 213 and finally increased again to $1\,l\,d^{-1}$ on day 244.

2.2.2. *Aerobic post-treatment*

A 3 l lab-scale activated sludge reactor was connected to the outlet of the UASB. Thus, the influent used for this reactor was already pre-treated anaerobically. An illustration of the lab-scale combined anaerobic/aerobic treatment process is provided in Fig. 2. Aeration was supplied through an air compressor. The temperature of the wastewater in the reactor was close to 30 °C. A clarifier was connected to the outlet of the reactor to ensure the clarification of the effluent before discharge. The particularity of the reactor used in this study was the absence of recirculation of the sludge. This made it a hybrid system close to the lagoon in the sense that, operationally, the hydraulic and solids retention times were the same and equalled 3 days in this study. Consequently, the biomass maintained in the reactor was less than that commonly found in activated sludge reactors (i.e. $3–4\,gMLSS\,l^{-1}$) and was much closer to that found in lagoons (i.e. $100–400\,mgMLSS\,l^{-1}$) (Metcalf and Eddy, 2003).

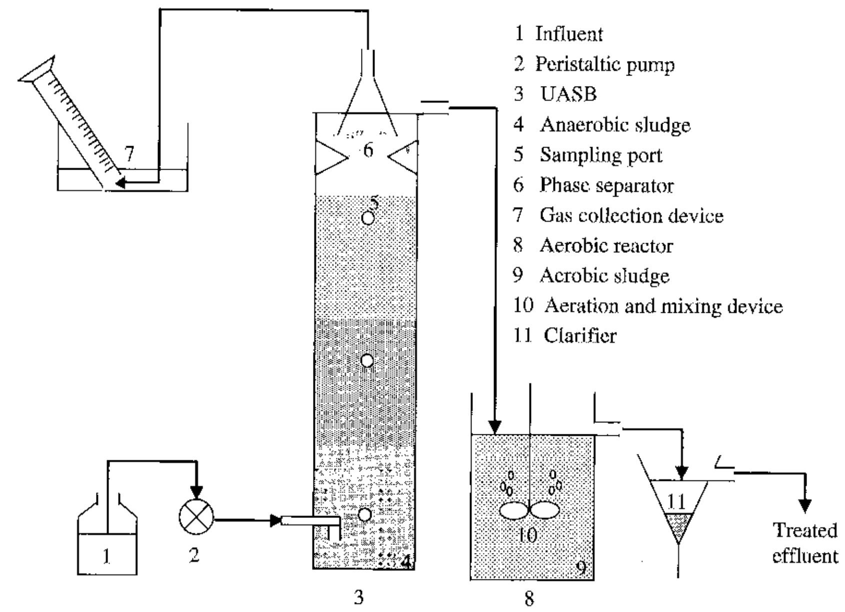


Fig. 2 – Lab-scale combined anaerobic/aerobic treatment process.

2.3. *Inoculum*

The UASB reactor profited from the inoculation of granular sludge collected from a pilot-scale UASB treating composite tannery effluent. The MLSS and MLVSS concentrations of this inoculum were 19 and $5\,gl^{-1}$, respectively. The addition of this inoculum was likely to reduce the start-up time (Maat and Habets, 1987) and to introduce an anaerobic population used to treating tannery effluents components. In addition to this inoculum, a permanent addition of bacteria occurred, as the tannery soak liquor that was used as an influent contained some amounts of bacteria and even sometimes protozoans. The aerobic reactor was inoculated with aerobic sludge collected from a common effluent treatment plant purifying domestic wastewater from the city of Chennai.

2.4. *Analysis*

COD, TDS, suspended solids (SS), volatile suspended solids (VSS), total alkalinity (TA), volatile fatty acids (VFA) and pH (the abbreviations of these parameters and of 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) (APHA, 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. Determination of VFA used the distillation method, in which the results are measured as mg volatile acids as acetic acid l^{-1}.

3. Results and discussion

3.1. *Performance of the UASB*

The UASB reactor was fed with tannery soak liquor for more than 300 days. Due to the influent's high variability, which has been described previously, the operational conditions of the bioreactor were subject to frequent and rapid changes, as shown in Fig. 3, which reports the respective evolution of the TDS concentration, OLR and HRT applied to the reactor.

The analysis of Fig. 3 has permitted the division of the experiment into four distinct phases: Phase 1 (days 1–110) corresponds to the starting phase of the reactor and the conditions of its operation at a low OLR, constant HRT and a TDS concentration always less than $50\,gl^{-1}$. Phase 2 (days 110–173) corresponds to a rapid hardening of the environmental conditions, with a reduction of HRT and an increase of OLR, along with increasing TDS concentrations. Thus, the operation of a UASB under extreme conditions, in the context of an industrial complex influent (soak liquor) subject to abrupt variations, was analysed during phase 2. Phase 3 (days 173–213) was characterised by a return to the conditions of phase 1, thanks to a sudden decrease of OLR and TDS concentrations. It was therefore possible to test the recovery capabilities of the process after the shock that occurred during phase 2. Finally, phase 4 (days 213–307) was characterised by an increase of salinity in stages, while OLR was maintained at low values and HRT at high values. The impact of increasing TDS concentrations on the performance of the process could therefore be studied. In addition, MLVSS concentration,

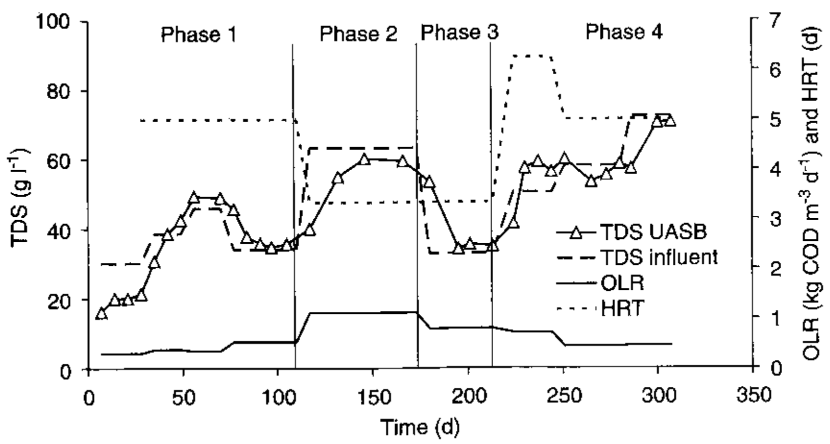


Fig. 3 – Evolution of the environmental operational parameters applied to the UASB reactor treating tannery soak liquor.

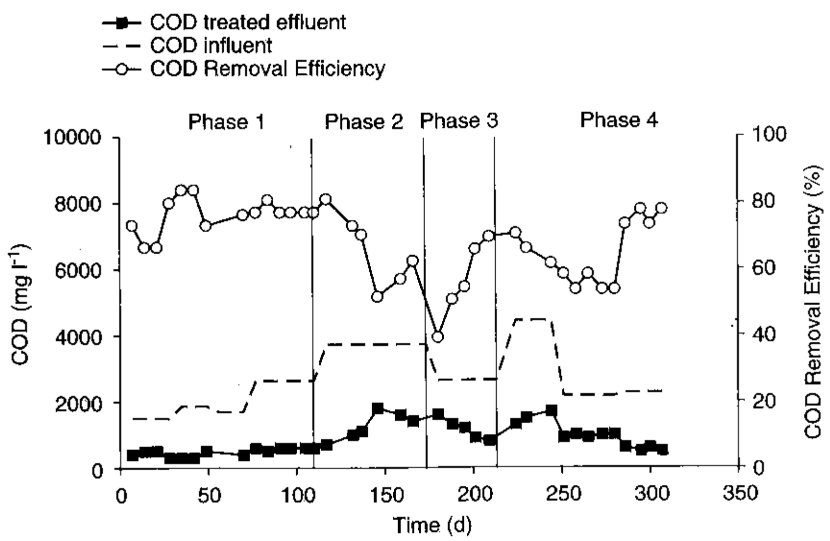


Fig. 4 – COD concentration in the influent, treated effluent and COD removal efficiency of the UASB reactor treating tannery soak liquor.

measured in the lower zone of the reactor, increased linearly from 1.4 $g\,l^{-1}$ on day 97, at the end of phase 1, to 12.2 $g\,l^{-1}$, on day 307, at the end of phase 4.

3.1.1. *Phase 1(days 1–110): operation of the UASB under low OLR*

During phase 1, the UASB was operated at a low OLR, ranging from 0.3 $kg\,COD\,m^{-3}\,d^{-1}$ to 0.5 $kg\,COD\,m^{-3}\,d^{-1}$, and a HRT of 5 days, as shown in Fig. 3. It also appears from the same figure that the TDS concentration in the UASB increased constantly during the first 70 days of operation until it reached that of influent No. 3 (i.e. 46 $g\,TDS\,l^{-1}$). Then, between days 70 and 110, the TDS concentration decreased until it reached the TDS concentration of influent No. 4 (i.e. 34 $g\,TDS\,l^{-1}$). On day 91, under an OLR of 0.5 $kg\,COD\,m^{-3}\,d^{-1}$, HRT of 5 days and 36 $g\,TDS\,l^{-1}$, the COD in the treated effluent reached 600 $mg\,l^{-1}$, with a corresponding COD removal efficiency of 77%, as can be seen in Fig. 4, where the COD values in the influent and in the treated effluent are reported, along with the corresponding COD removal efficiencies. This performance then stabilised until the end of phase 1, showing that the reactor functioned under steady state conditions.

TA, VFA and pH are efficient indicators of the stability of the reactor and of the correct balance between acidification and methanogenesis. Methanogenesis, in particular, is known to become unstable when the alkalinity ratio (VFA/TA) is above 0.3 (Mosquera-Corral et al., 2001). Furthermore, optimal methanogenesis is known to take place at a neutral pH. An inhibition of methanogenesis generally results in an increase of VFA concentration and a sudden drop in alkalinity and pH. At the end of phase 1, the alkalinity ratio was 0.25. The pH was also monitored and averaged 8.0, which corresponds to the pH of the influent but is slightly alkaline and may inhibit methanogenesis. Yet, the amount of biogas produced during phase 1 averaged 750 $ml\,d^{-1}$, thus 470 $ml\,g^{-1}$ of COD removed. This value appeared to be low, which indicated a gas leakage.

The concentration of VFA (measured as acetic acid) was also determined and represented in Fig. 5. It can be seen that, at the end of phase 1, the concentration of VFA was maintained below 300 mg acetic acid l^{-1}. This shows that

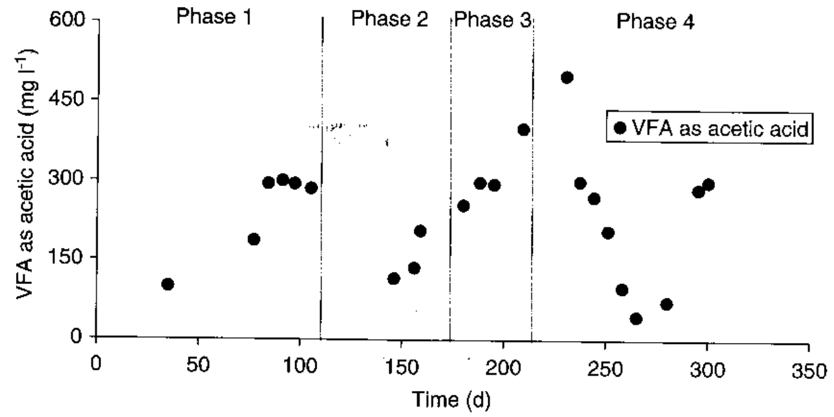


Fig. 5 – Evolution of VFA in the UASB reactor treating tannery soak liquor.

the process of hydrolysis and acidification of the organic matter took place in proper conditions.

3.1.2. *Phase 2 (days 110–173): operation of the UASB under extreme conditions*

On day 110, the flowrate increased from 1 to 1.5 $l\,d^{-1}$ and, consequently, HRT decreased to 3.3 days and OLR increased to 1.1 $kg\,COD\,m^{-3}\,d^{-1}$ (see Fig. 3). At the same time, TDS increased at a fast rate due to the higher salinity of influent No. 5 (63 $g\,TDS\,l^{-1}$). This resulted immediately in a shock and consequent destabilisation of the system, with COD values in the treated effluent reaching 1800 $mg\,l^{-1}$ on day 146, and corresponding COD removal efficiency falling to 52%. Then, it seems that an acclimation process started, as the COD removal efficiency increased once again. Fig. 5 clearly indicates that this increase of COD in the treated effluent during phase 2 was not due to an increase of VFA. Therefore, it seems that the hydrolysis and acidification processes had been overloaded.

Such overloading of the process at a low OLR could be explained by the high salinity that inhibited the microbial metabolism. In addition, the high influent SS concentration might also have disturbed the operation of the UASB reactor. Indeed, Lettinga and Hulshoff Pol (1991) have already reported that, beyond a certain influent SS concentration and depending on the characteristics of the SS, an anaerobic treatment system like the UASB becomes less feasible. The alkalinity ratio averaged 0.09±0.03 and pH averaged 8.4±0.1 during phase 2.

3.1.3. *Phase 3 (days 173–213): recovery of the UASB after an environmental shock*

In an industrial scenario, a bioreactor will frequently be exposed to environmental shocks lasting for several days. Therefore, it should be able to withstand variable conditions. In the leather industry especially, the characteristics of the soak liquor are likely to change weekly or monthly, depending on every batch of hides and skins that is supplied to the tannery. The recovery capability of the UASB after exposition to variable load and salt conditions was therefore studied during phase 3. In comparison to influent No. 5, influent No. 6, which was used throughout this phase, was characterised by a lower organic matter content (2640 $mg\,COD\,l^{-1}$) and a lower TDS concentration (33 $g\,TDS\,l^{-1}$), as shown in Table 1. Consequently, OLR was lower than in the previous phase and the TDS concentration in the UASB reactor started to decrease after day 173 (see Fig. 3). As a result, the environmental conditions became more favourable to anaerobic digestion and the COD concentration in the treated effluent started to decrease, as can be seen in Fig. 4. As a consequence, the COD removal efficiency started to increase quickly and reached 70% on day 209. At this time, the TDS concentration was 35 $g\,l^{-1}$ and OLR was 0.8 $kg\,COD\,m^{-3}\,d^{-1}$, levels similar to the same parameters at the end of phase 1 prior to the shock. VFA concentration increased regularly during phase 3 (see Fig. 5) and reached 400 $mg\,l^{-1}$ at the end of phase 3, which shows that acidification could take place properly again and that methanogenesis became the limiting factor once more, as it had already been the case at the end of phase 1. It can thus be concluded that the bioreactor was capable of good and fast recovery after a shock, as soon as the environmental conditions improved. This proves that the biomass could survive during the shock; only its ability to degrade COD was affected in extreme environmental conditions. The recovery phenomenon was accompanied by a decrease in pH that averaged 7.7±0.2 at the end of phase 3. The alkalinity ratio averaged 0.15±0.04 at the same time. This result is in agreement with the experiment undertaken by Gangagni Rao et al. (2005), who exposed an anaerobic fixed-film reactor treating saline (i.e. 20 $g\,TDS\,l^{-1}$) pharmaceutical wastewater to organic shock loads and showed that, after a temporary drop, COD removal efficiency could be restored within a week, as soon as the OLR was reduced again.

3.1.4. *Phase 4 (days 213–307): adaptation of the UASB under increasing salt concentration*

Influent No. 7 was characterised by a very high COD concentration (4440 $mg\,l^{-1}$), as shown in Table 1. In order to avoid renewed overloading of anaerobic digestion, a decision was taken to reduce the flowrate on day 213. Thus, HRT was increased again and OLR was maintained around 0.5 $kg\,COD\,m^{-3}\,d^{-1}$. Influent Nos. 7, 8 and 9 were also extremely saline and contained as much as 50, 58 and 72 $g\,TDS\,l^{-1}$, respectively. As a consequence, the TDS concentration in the UASB increased in stages during phase 4. During a first period, the performance of the UASB was altered. The COD concentration in the treated effluent increased from 800 to $1700\,mg\,l^{-1}$ between day 209 and 244, thus the corresponding COD removal efficiency decreased from 70% to 58%. Then, a second period at the end of the experiment was characterised by an enhancement of the reactor performance again, which was due to an influent with lower COD concentration and, probably, a higher biodegradability. Consequently, on day 307, the COD concentration in the treated effluent attained $500\,mg\,l^{-1}$ and the COD removal yield reached 78%, at an OLR of $0.5\,kg\,COD\,m^{-3}\,d^{-1}$, a HRT of 5 days and 71 g TDS l^{-1}. These performances are similar to the performances obtained at the end of phase 1, under similar environmental conditions, apart from salinity which was much higher at the end of phase 4. This shows that sludge can still be active at a salinity level over $70\,g\,l^{-1}$. Fig. 5 shows that the increase in the TDS concentration first resulted in a decrease in the VFA concentration, then VFA concentration started to increase again. This is a sign that the first consequence of increasing salinity was an inhibition of acidification, which was followed by a recovery after adaptation occurred. It can be concluded, then, that very high salinity is not an obstacle to anaerobic digestion, provided that the process is progressively adapted to high salt concentrations and OLR is maintained at a low level. At the end of phase 4, the alkalinity ratio averaged 0.24 ± 0.07 and pH averaged 7.7 ± 0.1.

3.2. *Solids characterisation and management*

The evolution of solids in the inlet and outlet of the UASB was also studied (data not shown) and showed very little SS removal. During the experiment, SS removal efficiency seldom exceeded zero. High turbidity problems are very common in hypersaline effluent treatment systems. Woolard and Irvine (1995), in particular, explained that systems treating hypersaline effluents invariably have high concentrations of effluent SS, due to the high density of salt water and to the salt-induced cell lysis phenomenon. Moreover, the nature of the influent itself, with a high inorganic SS concentration, may be responsible for the high SS concentration in the treated effluent. It has indeed already been shown that, in tannery wastewater containing high amount of salt and SS, the settling rate of the raw solids is reduced (Song et al., 2000). Consequently, as most of SS contained in tannery soak liquor are unlikely to be retained or degraded inside the anaerobic reactor, they will probably remain in the treated effluent. Therefore, in order to remove the excess of SS from tannery soak liquor, the use of physico-chemical pre-treatment should be considered, before applying anaerobic digestion. Mishra et al. (2004), for instance, used as a flocculant fenugreek mucilage, a polysaccharide extracted from a leguminous plant grown in India, to remove nearly 85% of SS from tannery effluent within 1 h, at a flocculant dose of $0.08\,mg\,l^{-1}$ and neutral pH. Yet, the effect of such a pre-treatment on the structure and composition of the sludge and, consequently, its impact on the performance of subsequent anaerobic treatment has to be tested.

At the end of the experiment, MLSS and MLVSS were measured in the upper, middle and lower zones of the reactor.

Table 2 – Mixed liquor solids concentration at different zones of the UASB reactor treating tannery soak liquor, measured at the end of the experiment (day 307)

	Upper zone	Middle zone	Lower zone
MLSS ($g\,l^{-1}$)	9.3	17.2	44.9
MLVSS ($g\,l^{-1}$)	2.1	2.3	12.2
MLVSS/MLSS	0.23	0.13	0.27

Results are compiled in Table 2. High amounts of MLSS and MLVSS were measured, especially at the bottom of the reactor. The MLSS/MLVSS ratio showed that 73% to 87% of the solids that were found in the UASB reactor were inorganic and were probably introduced in the reactor with the influent that contained between 3600 and $10{,}700\,mg\,l^{-1}$ of SS. The higher concentration of MLSS and MLVSS in the lower zone of the reactor can be explained by the low upward velocity (between 14 and $21\,cm\,d^{-1}$), which favoured solids sedimentation and accumulation at the bottom of the reactor. Guerrero et al. (1997) noted that MLSS and MLVSS concentrations were higher at the bottom of an upflow anaerobic filter. They explained that this phenomenon could be due to the higher abundance of hydrolytic-fermentative bacteria, which have higher cellular yields, in the zone closest to the inlet of the reactor.

It has been shown that a sludge blanket developed at the bottom of the UASB reactor, but the observation of the biomass revealed the absence of the granular sludge typically found in UASB. This shows that, although the reactor was operated as a UASB and was inoculated with granules, the maintenance of stable granular sludge was made impossible in this reactor due to high salinity. Consequently, the sludge blanket that accumulated at the bottom of the reactor did not consist of granules. Actually, it has already been mentioned that, in thermophilic cultures of *Methanosarcina thermophila*, high sodium concentrations inhibited the microbial production of extracellular polysaccharides, therefore disrupting the granules (Sowers and Gunsalus, 1988). Granule disaggregation could also be due to the change of influent between the pilot plant where the sludge originated from (i.e. tannery composite wastewater) and the lab-scale reactor where they were inoculated.

3.3. *Aerobic post-treatment*

An aerobic post-treatment was set up after the UASB reactor on day 260. Because of no sludge recirculation, the activated sludge biomass was quickly reduced from $3.5\,g\,MLVSS\,l^{-1}$ (initial value after seeding on the starting day of operation) to $0.4\,g\,l^{-1}$. Then, biomass slightly increased again and stabilised around $1.5\,g\,l^{-1}$ (data not shown). This biomass value is less than the values usually reported in the literature for activated sludge processes and is closer to these commonly found in lagoons (Metcalf and Eddy, 2003). The operating conditions of this activated sludge process, in the absence of sludge recirculation, made it close to an aerobic lagoon, as the

Table 3 – Performance of biological reactors operated on tannery soak liquor

	COD influent ($mg\,l^{-1}$)	OLR ($kg\,COD\,m^{-3}\,d^{-1}$)	HRT (d)	TDS ($g\,l^{-1}$)	COD treated effluent ($mg\,l^{-1}$)	COD removal (%)
Aerobic SBR (low OLR)	2950	0.6	5.0	35	140	95
Aerobic SBR (moderate OLR)	3600	1.1	3.3	40	320	91
UASB (phase 1)	2630	0.5	5.0	36	600	77
UASB (phase 4)	2270	0.5	5.0	71	500	78
UASB+aerobic post-treatment	2270	0.3	8.0	71	100	96

hydraulic and solids retention times were the same, equalling 3 days. Nevertheless, the COD in the treated effluent, after aerobic treatment, attained $100\,mg\,l^{-1}$ after one month of operation. Thus, the combined anaerobic/aerobic process made it possible to remove 96% of the initial COD contained in the influent, under a total OLR of $0.3\,kg\,COD\,m^{-3}\,d^{-1}$ ($0.5\,kg\,COD\,m^{-3}\,d^{-1}$ for UASB and $0.2\,kg\,COD\,m^{-3}\,d^{-1}$ for the post-treatment), a total HRT of 8 days (5 days for UASB and 3 days for the post-treatment) and a TDS concentration of $71\,g\,l^{-1}$. Therefore, it appears that the aerobic reactor formed an efficient post-treatment that attained very low COD values in the final treated effluent, at the cost of an increase of HRT and a decrease of OLR.

3.4. *Comparison with an aerobic sequencing batch reactor treating tannery soak liquor*

The performance of the UASB reactor operated in this study was compared to the performance of an aerobic SBR fed with the same influent in a previous study (Lefebvre et al., 2005). The optimal stable performance of SBR, UASB and combined anaerobic/aerobic treatment are compiled in Table 3.

It appears from Table 3 that, whereas the aerobic SBR was able to remove 95% of the COD of the soak liquor at a low OLR of $0.6\,kg\,COD\,m^{-3}\,d^{-1}$, a HRT of 5 days and $35\,g\,TDS\,l^{-1}$, the UASB was able to remove only 77% of the COD of the soak liquor under similar conditions in phase 1 (i.e. OLR of $0.5\,kg\,COD\,m^{-3}\,d^{-1}$, HRT of 5 days and $37\,g\,TDS\,l^{-1}$). Thus, the aerobic SBR could remove more organic matter than the UASB, which shows the superiority of aerobic treatment over anaerobic treatment at a similarly low OLR. Furthermore, the aerobic SBR could withstand a higher OLR than the UASB and remove up to 91% of the COD at a moderate OLR of $1.1\,kg\,COD\,m^{-3}\,d^{-1}$, a HRT of 3.3 days and $40\,g\,TDS\,l^{-1}$. At a similar OLR, the UASB was overloaded and no stable performance could be achieved.

The combination of anaerobic digestion with an aerobic post-treatment was able to achieve a COD removal efficiency of 96% at a total OLR of $0.3\,kg\,COD\,m^{-3}\,d^{-1}$, a total HRT of 8 days and $71\,g\,TDS\,l^{-1}$. Thus, very little COD remained in the final treated effluent (i.e. $100\,mg\,COD\,l^{-1}$) and the quality of this effluent was similar to that obtained after aerobic treatment in the SBR at a low OLR (i.e. $140\,mg\,COD\,l^{-1}$), but OLR was higher and HRT lower in the case of aerobic treatment used alone, which makes it more competitive.

4. Conclusion

The aim of this study was to check the advantage of segregating tannery soak liquor from the composite tannery wastewater, in order to treat it separately by anaerobic digestion. The anaerobically pre-treated soak liquor could then be mixed with the composite wastewater to undergo aerobic treatment. The anaerobic digestion of the tannery soak liquor was studied using a UASB reactor over more than 300 days. The conclusions are as follows:

(1) The optimal performance of the UASB reactor treating tannery soak liquor, obtained during the first phase (start-up period), was 77% of COD removal efficiency at an OLR of $0.5\,kg\,COD\,m^{-3}\,d^{-1}$, a HRT of 5 days and a TDS concentration of $36\,g\,l^{-1}$.
(2) Higher OLR and TDS concentrations resulted in a destabilisation of the system.
(3) The UASB showed good recovery capabilities, therefore proving itself able to withstand environmental shocks that always occur in industrial applications.
(4) The UASB showed good adaptability to increasing salt concentrations and achieved 78% COD removal efficiency at $71\,g\,TDS\,l^{-1}$, provided HRT is constant and OLR is maintained at a low level.
(5) No stable granular sludge could be maintained in the reactor. The operation of the reactor under more stable conditions may favour the formation and maintenance of such granules, yet, this hypothesis has to be tested.
(6) The COD removal efficiency of a combined anaerobic/aerobic treatment system reached 96% after one month of operation at an OLR of $0.5\,kg\,COD\,m^{-3}\,d^{-1}$, HRT of 8 days and TDS concentration of $71\,g\,l^{-1}$.
(7) The comparison of anaerobic and aerobic treatment of tannery soak liquor showed the superiority of aerobic treatment, which can withstand a higher OLR and thus remove more COD from the influent.

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