Journal of Hazardous Materials B102 (2003) 243–255

Journal of Hazardous Materials

www.elsevier.com/locate/jhazmat

Anaerobic treatability of high oil and grease rendering wastewater

George Nakhla*, Mustafa Al-Sabawi, Amerjeet Bassi, Victor Liu

Department of Chemical and Biochemical Engineering, The University of Western Ontario, London, Ont., Canada N6A 5B9

Received 3 April 2003; received in revised form 18 June 2003; accepted 18 June 2003

Abstract

This study evaluated the use of a new biosurfactant, BOD-Balance^{TM}, derived from cactus for the treatment of oil-and-grease-laden rendering wastewater anaerobically. Batch laboratory experimental results and preliminary full-scale data are presented. The biosurfactant affected a significant increase in the COD degradation rate for the raw wastewater. However, after reduction of the oil and grease (O&G) by dissolved air flotation, the biosurfactant did not exhibit any advantages. Modeling of the data indicated that various COD fractions, i.e. both soluble and particulate as well as total COD at various testing conditions conformed well to both zero-order and first-order models. The biosurfactant affected a 164–238 and 164–247% increase in COD and particulate COD biodegradation rate for the raw wastewater. The reduction of O&G concentration to <800 mg/l increased total and soluble COD degradation rates by 106%. Results from the full-scale mesophilic anaerobic digestion system indicated that the addition of the biosurfactant at doses of 130–200 mg/l decreased O&G concentrations from 66,300 to 10,200 mg/l over a 2-month-period.

Keywords: Rendering wastewater; Anaerobic treatment; Biosurfactant; Mesophilic low-rate digestion; Biokinetic modeling

1. Introduction

The presence of high strength oil and grease (O&G) in industrial wastewaters poses serious challenges for biological treatment systems, often necessitating costly modifications by inclusion of physio-chemical processes such as flotation, sedimentation, flocculation and membrane filtration. In aerobic systems, high oil and grease has a detrimental impact on oxygen transfer efficiency [1]. Under anaerobic conditions, long-chain fatty acids, such as oleic

* Corresponding author. Tel.: +1-519-661-2131; fax: +1-519-661-3498.
E-mail address: gnakhla@eng.uwo.ca (G. Nakhla).

0304-3894/$ – see front matter © 2003 Elsevier B.V. All rights reserved.
doi:10.1016/S0304-3894(03)00210-3

acid, the product of lipid hydrolysis are well-known inhibitors of anaerobic systems [2]. Oil and grease found in pet food wastewater is highly resistant to biodegradation and contributes to the high COD levels. Anaerobic treatment alone is not very efficient at eliminating oil and grease as verified by Wahaab and El-Awady [3], who showed that the levels of oil and grease in meat processing wastewater did not comply with regulatory discharge standards for the industrial wastewater into the sewage network after anaerobic wastewater treatment using anaerobic sludge. Alternative methods to deal with high O&G such as thermophilic processes and use of surfactants facilitate the biodegradation of O&G primarily by increasing solubility. Recently, aerobic thermophilic processes have been validated at the laboratory level for the treatment of various food processing wastewaters such as liquid pig manure [4], slaughterhouse wastewater [5], potato-processing wastewater [6], and beer-brewery wastes [7]. Becker et al. [8] have demonstrated the treatability of wool-scouring wastewater with average COD, TSS, and lipid concentrations of 77,200, 26,200, and 17,000 mg/l, respectively, in a thermophilic aerobic bioreactor utilizing a newly isolated strain *Bacillus thermoleovorans* IHI-91 with COD and lipid removal efficiencies of 15–20 and 20–30% at short residence times of about 10–20 h. Full-scale thermophilic aerobic systems have been used for the treatment of food processing wastewater at O&G concentrations of 1500–2000 mg/l in Taiwan [9,10]. In their review of thermophilic aerobic systems, Lapara and Alleman [11] have concluded that the biology of such systems differs from conventional activated sludge systems in that nitrifying bacteria, floc-forming organisms and higher organisms which aid flocculation are not present. Thus, it appears that the separability of biomass from the treated effluent is a major concern with thermophilic aerobic processes. Other aerobic treatment processes such as the activated sludge are generally not considered as an economically favorable treatment option for high-strength wastes because of energy requirements.

Anaerobic treatment processes can favorably compete with aerobic processes for the treatment of high O&G food industry wastewater provided that the wastewater is high in strength and is at high temperatures [12–14], particularly at thermophilic ranges where the solubility of oils is high. The use of surfactants to aid in the emulsification and removal of oils from wastewaters have been explored for the treatment of wool-scouring wastewater, which is characterized by very high COD and high O&G, very similar to the high strength pet food wastewater described in this study. Since wool grease is also resistant to biodegradation [15,16], the use of a chemical surfactant is needed to remove the oil and grease from the wool scouring effluent. The separation of bulk grease from the wool scouring effluent will produce a degreased liquor which is easily treated by conventional anaerobic processes [17]. Thus, the application of a surfactant can be utilized in the case of high oil and grease pet food wastewater, in order to emulsify grease.

Analogous to the treatment of wool-scouring effluents under anaerobic biological conditions, which causes grease bioflocculation rather than grease degradation [18,19], the use of a biosurfactant may enable the enhancement of anaerobic biodegradability of rendering wastewater with high levels of oil and grease by solubilizing the oil and grease. Surfactants used for greasy wool scouring wastewater have been non-ionic, of the alkyl phenol or ethylene oxide type [20] and thus require an additional coagulation-flocculation step. On the other hand, biosurfactants can easily be incorporated directly in the anaerobic digestion process, thus eliminating the need for additional processes and resulting capital and operational cost increases. Recently, Lugowski et al. [21] have demonstrated the effectiveness of a biosurfactant, BOD-Balance^{TM}, a proprietary formulation (US patent pending) derived from cactus, in improving anaerobic digestion of municipal sludges. The main objective of this study is to investigate the efficiency of the aforementioned biosurfactant in anaerobic treatment of high strength oil and grease laden pet food wastewater at mesophilic temperature ranges.

2. Methodology

2.1. Existing system description

This rendering facility processes a variety of meat and foo processing by-products to produce animal feed, animal feed ingredients, and animal feed flavorings. The facility runs its complete processing operations 5 days per week 24 h a day, and operates a clean-up shift and skeleton processing operation on Saturdays. The processing operations include freezing of meat by-products for storage prior to processing into feed, coarse grinding of meat by-products, washing of chicken viscera to remove chicken manure, cooking chicken viscera washwater to remove fat and tallow, centrifuging chicken viscera washwater to remove meat particles and high melting fats, cooking meat by-products, emulsifying (fine grinding), mixing feed ingredients and freezing finished feed, waste effluent is produced from equipment and floor cleaning in the processing areas and process washing operations. The most significant source of wastewater originates from the washing chicken viscera to remove the chicken manure. The other major source of wastewater originates from the cleaning of freezer plates, with minor wastes generated from washing the cookers, mixers, grinders and emulsifiers.

The wastewater treatment system is depicted in Fig. 1. Subsequent to oil recovery, and centrifugation of the chicken washwater, this “hot” stream is mixed with “cold” wastewater from the freezers washing, screened using a rotary screen, and stored prior to feeding to the anaerobic digester. The digester provides a hydraulic retention time of 30 days at the average flow rate of 60 m^3 per day. The wastewater characteristics are shown in Table 1 together with the anaerobic digester effluent prior to the use of the biosurfactant. The very high COD (inclusive of the contribution of the scum layer) and suspended solids concentrations in both

Table 1
Raw and pre-treated wastewater characteristics

Parameters (mg/l)	Raw waste (before digester)		Treated digester effluent		DAF effluent	
	Range	Average	Range	Average	Range	Average
TSS	17300–61700	36857	11400–17200	14467	1160–2250	1685
VSS	15180–59800	34383	10600–17100	13867	1060–1850	1500
TCOD	74925–154100	96660	52300–98525	77300	16940–20500	18810
SCOD	13125–18450	16757	13150–23375	18855	11060–16940	13700
TBOD			77800	77800	11800–13200	11900
SBOD			8820	8820	8800–10500	10000
NH_3–N	197.5–400	328	680–1485	1353	674–1348	1186
PO_4^{3-}	500–830	665	240–355	286	210–360	249
O&G	38800	38800	5942–21500	13500	404–820	668

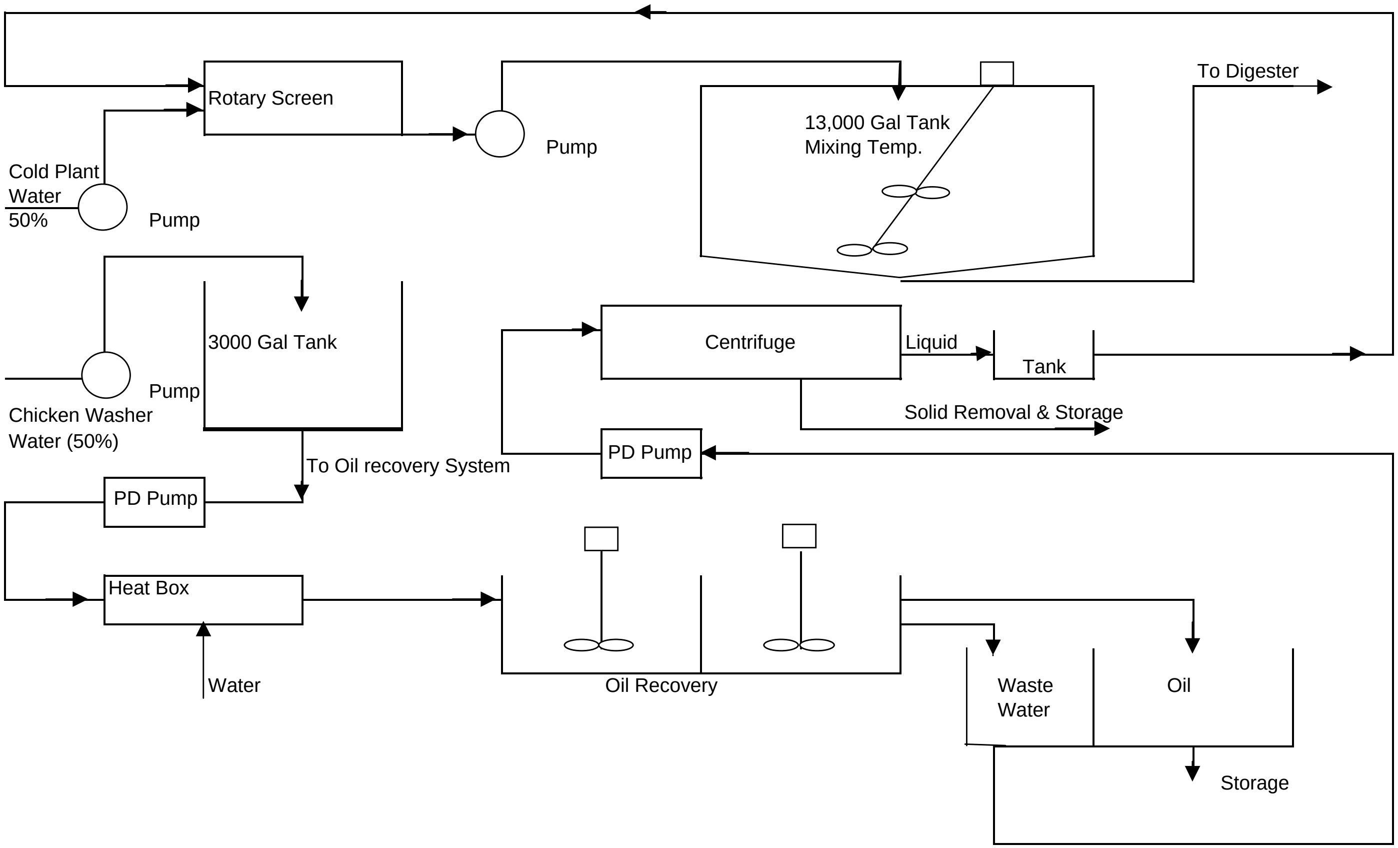

Fig. 1. Existing wastewater treatment system.

the raw wastewater and digester effluent are noteworthy, despite the 60–70% reduction in SS achieved in the digester. It should be noted that oil and grease concentrations in the scum layer, which constituted well over 50% of the digester volume exceeded the 100,000 mg/l. Gas production from the digester was minimal while COD reduction was at approximately 20% well below normal for a wastewater with a BOD-to-COD ratio of >0.7. Due to the development of an extensive scum layer, mixing in the system was compromised and thus the digester was modeled experimentally as a low-rate anaerobic digester, i.e. batches were conducted without continuous complete mixing.

2.2. Experimental set-up

2.2.1. Anaerobic treatability without biosurfactant

Raw wastewater, as well as wastewater emanating after laboratory-scale dissolved air flotation treatment, were both used in the batch anaerobic studies conducted. A gauge pressure of 65 lb/in.^{2} and a pressurization time of 3 min for DAF simulation provided on average 79.5 and 90% removals of O&G and TSS from the raw wastewater reducing their concentrations to 61 and 1700 mg/l, respectively.

In order to demonstrate the efficiency of low-rate anaerobic digestion of wastewater, 2 l batch anaerobic treatability studies were conducted using a 1:1 mixture of raw wastewater and municipal anaerobic sludge and using a 1:1 mixture of DAF-treated wastewater and anaerobic sludge. Both reactors were held at mesophilic temperature (35 °C) and were intermittently mixed. Samples from each batch reactor were taken for the first 5 days and every 3 days thereafter. Each sample was analyzed and COD levels were obtained.

2.2.2. Biosurfactant testing

Batch anaerobic treatability studies were also conducted using the biosurfactant BOD-Balance™ to determine its effectiveness on oil and grease found in pet food wastewater. In an anaerobic laboratory scale experiment, three 2 l batch reactors were set-up containing DAF-treated wastewater and anaerobic sludge. Different doses of BOD-Balance™ were added to each of the reactors, with reactor 1 containing 250 mg/l of the biosurfactant, and reactor 2 receiving a 100 mg/l dose. Reactor 3 did not contain any of the biosurfactant. These batch reactors were kept at 35 °C under low-rate anaerobic conditions without continuous mixing. The initial total COD levels for reactors 1, 2, and 3 were 17,560, 15,560, and 15,800 mg/l, respectively, and the initial soluble COD levels were 6680, 8480, and 8520 mg/l.

BOD-Balance™ was also tested on raw wastewater containing an extensive amount of oil and grease. The raw wastewater was mixed with anaerobic sludge and a 500 mg/l dose of the biosurfactant was added to this mixture. The batch anaerobic reaction was held at 35 °C without continuous mixing. The TCOD and SCOD levels were initially at 31,440 and 11,200 mg/l.

2.3. Analytical methods

Wastewater was analyzed for total and filtered (through 0.45 μm filter paper) COD using the Hach Apparatus. Total and volatile suspended solids (TSS, VSS) were analyzed in accordance with Standard Methods [22]. Methane content of the gas was occasionally measured with a gas chromatograph, Varian Model No. 3800 (Varian, Inc., USA). The detector was a Flame Ionization Detector (FID) and was operated at 250 °C. During gas analysis, the column oven temperature was initially at 40 °C and was increased at a rate of 5 °C/min to a final temperature of 200 °C.

3. Results and discussions

3.1. Existing system performance and pre-treatment

The characteristics of the raw wastewater, the anaerobic digester effluent and the DAF pretreated digester effluent are depicted in Table 1. The extremely high COD and oil and grease in the raw wastewater and anaerobic digester are noteworthy. Scrutiny of the raw wastewater characteristics indicated that the average total COD of 96,660 mg/l was mostly particulate with a soluble fraction of around 17% only. Using the typical COD equivalent of VSS of 1.42 gCOD/gVSS reveals that filterable organic solids accounted for only 60% of the particulate COD (pCOD) being calculated as total COD minus soluble COD (SCOD) minus COD equivalent of VSS. Since TSS and VSS were measured by filtration through 0.45 μm filters, it is evident that colloidal organic particles coarser than the 0.45 μm accounted for about 40% of the pCOD or 32,000 mg/l. It is interesting to note that PCOD coarser than 0.45 μm in the digester effluent was about 38,000 mg/l. Table 1 reveals that the digester affected no reduction of SCOD, less than 20% total COD reduction, 60% reduction of VSS and TSS, and 65% reduction in O&G concentrations. This is highly unusual since soluble COD is more readily biodegradable than particulate COD. It is possible that soluble COD was simultaneously biodegraded and generated from the hydrolysis of particulate COD, to affect a minimal overall net reduction in SCOD. Gas production from the full-scale anaerobic digester was minimal which combined with the anomaly between COD and VSS removals indicates that mixing in the digester was poor. The efficiency of the batch lab scale simulated DAF system is noted since it affected 95.1% removal of O&G, 76% reduction of TCOD, 85% reduction of SBOD, and 89% removal of TSS. Chemical addition including alum, ferric chloride, and an organic polymer did not improve DAF efficiency, indicating that most of the O&G existed as free oils.

3.2. Biosurfactant testing

The results of the anaerobic treatability studies conducted on the raw wastewater are presented in Fig. 2. As apparent from Fig. 2, despite the high oil and grease concentration in the raw wastewater even after the 1:1 dilution by anaerobic sludge in the batch, anaerobic biodegradation was not completely inhibited. At the end of the 16-day study, total and soluble COD in the raw wastewater decreased from 31,440 and 11,200 mg/l, respectively, to 20,750 and 7050 mg/l. The BOD-Balance^{TM} applied at 500 mg/l to the raw wastewater affected a significant improvement in overall anaerobic biodegradability with TCOD and SCOD reduction of 62 and 74%, respectively, to 11,500 and 3000 mg/l, respectively.

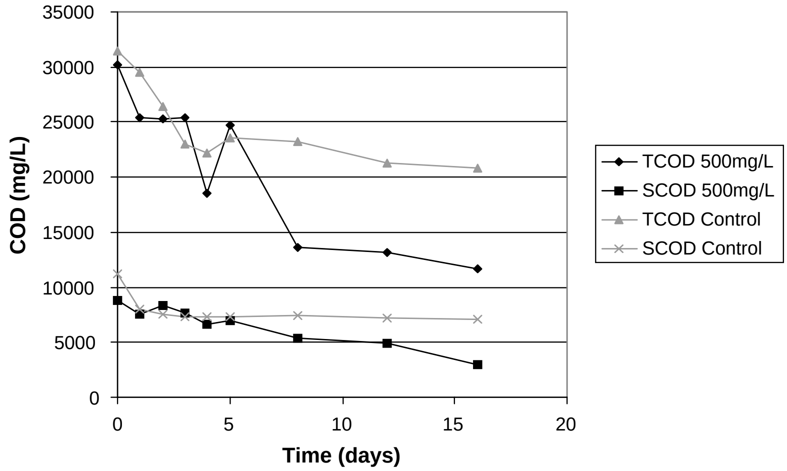

Fig. 2. Total and soluble COD removal in raw wastewater.

Details of initial and final COD fractions for all batch studies are presented in Table 2. By comparison, pCOD removal efficiency increased by 96% from 32 to 59% while SCOD reductions improved by 100% from 37 to 74% due to BOD-Balance^{TM} addition. The increase in pCOD removal is primarily explained by the reduction in surface tension that helps solubilize hydrophobic organic including O&G as well as colloidal organics. It should be emphasized that the SCOD increase with the BOD-Balance^{TM} is about 5% only and therefore the marked improvements in SCOD removal are not attributable to the rapid biodegradability of the biosurfactant. It is postulated that biodegradation of some of the slowly biodegradable SCOD may have been enhanced either directly or indirectly through co-metabolism with particulate substrates.

A comparison of the final VSS concentrations with and without BOD-Balance^{TM} indicates that the biosurfactant only affected a marginal improvement in VSS destruction.

Table 2
Characteristics of anaerobically treated digester effluent and DAF treated wastewater with and without biosurfactant

	TCOD (mg/l)		SCOD (mg/l)		PCOD (mg/l)		TSS (g/l)		VSS (g/l)	
	Initial	Final	Initial	Final	Initial	Final	Initial	Final	Initial	Final
Raw WW with 500 mg/l BOD-Balance^{TM}	31440	11500	11200	3000	20240	8500	15.1	11.7	12.5	9.1
Raw WW without BOD-Balance^{TM}	31440	20840	11200	7040	20240	13800	15.5	12.4	12.9	10.4
DAF WW with 250 mg/l BOD-Balance^{TM}	17560	9880	6680	1080	9880	8800	10.9	9.9	8.1	7.1
DAF WW with 100 mg/l BOD-Balance^{TM}	15560	8080	8480	1240	7080	6840	8.9	7.6	7.1	4.8
DAF WW without BOD-Balance^{TM}	15800	8160	8520	1320	7280	6840	8.1	7.2	6.3	5.8

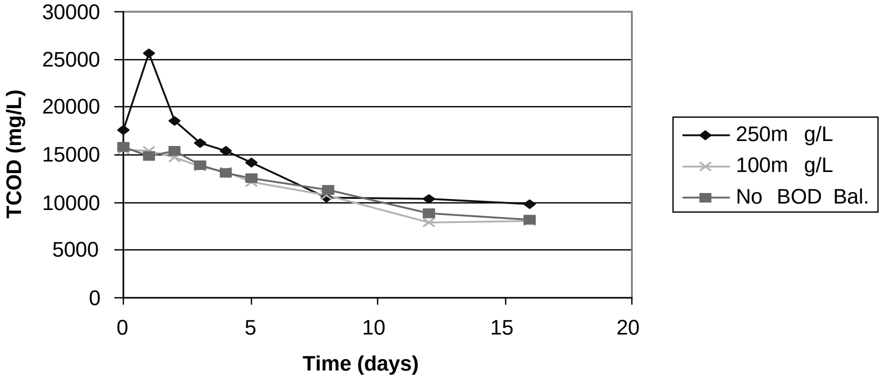

Fig. 3. Total COD removal for DAF treated wastewater with and without BOD-Balance™.

However, considering the substantial enhancement in COD reduction, it appears that the biosurfactant may have reduced the anaerobic yield, resulting in methane production. Although gas flow measurements were not routinely undertaken, sampling of the gas indicated 73% methane content.

Figs. 3 and 4 illustrate the impact of BOD-Balance™ to the DAF pretreated digester effluent on TCOD and SCOD, respectively, while the detailed initial and final concentrations are listed in Table 2. Both figures indicated that there is minimal, if any impact of the biosurfactant. As shown in Table 2, there was essentially no difference between the control and the 100 mg/l BOD-Balance™ with respect to removal efficiencies as well as final concentrations, with both removing 240–440 mg/l of pCOD and 7200–7240 mg/l of SCOD after 16 days. At the 250 mg/l level the biosurfactant removed 1080 mg/l of pCOD and SCOD over the 16 days.

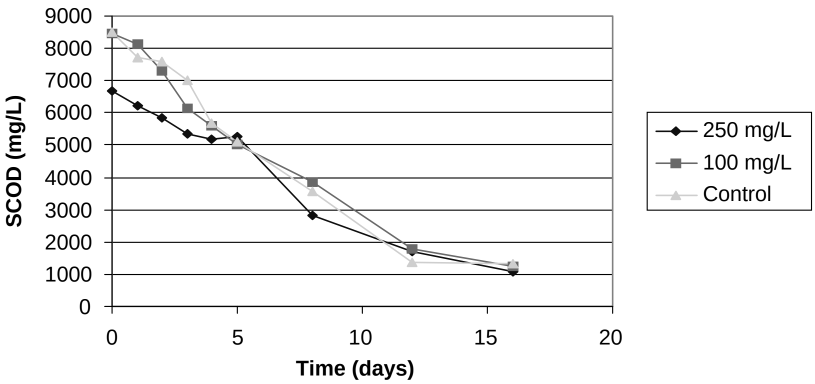

Fig. 4. Soluble COD removal for DAF treated wastewater.

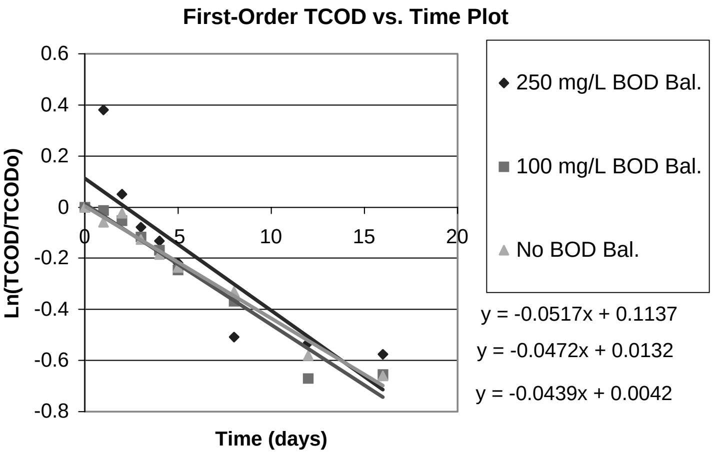

Fig. 5. First-order total COD removal kinetics.

3.3. Biokinetic modeling

Biokinetic data were analyzed using both the zero-order and first-order kinetics models. Fig. 5 illustrates graphically some of the first-order fits of the data generated using the DAF pretreated digester effluent while a detailed comparison of the two models for the various COD fractions is presented in Table 3. The correlation coefficient for the various fractions using both models were generally in the 80–90% with the exception of pCOD for DAF pretreated effluent and SCOD in the raw wastewater without BOD-Balance^{TM}. Given that the initial and final concentrations were generally very high, it was anticipated that the zero-order could fit better than the first-order. However, first-order kinetics appeared to fit the data slightly better than zero-order as reflected by higher R^2 values, even though it is quite evident that both models fit the data well.

The impact of BOD-Balance^{TM} on raw wastewater treatability is very conspicuous as the overall improvement in TCOD biodegradation rates increased by 238% (based on first-order) and 164% (based on zero-order). Similarly, particulate COD biodegradation rates improved by 247% (based on first-order) and 166% (based on zero-order). Unfortunately, while as discussed above, significant improvement in SCOD removal was observed, the kinetics can not be fairly compared due to poor fit of the SCOD for the raw wastewater only to both models. For the DAF pretreated anaerobic digester, BOD-Balance^{TM} at 100 mg/l affected only a 75% (first-order) and 5% (zero-order) improvement in TCOD removals. However, kinetics for SCOD removal were greatly enhanced by 55–80% (based on first-order) and deteriorated by 4–13% (based on zero-order). It is therefore apparent that BOD-Balance^{TM} only improves performance at high oil and grease concentration of >1000 mg/l and it is therefore postulated that it solubilizes oil and grease, thus improving accessibility to microorganisms. Additionally, for this particular wastewater, improvement of particulate organics and O&G biodegradation has been concomitant with enhanced soluble COD kinetics.

Table 3
Comparison of zero-order and first-order kinetics for total COD (TCOD), soluble COD (SCOD) and particulate COD (PCOD) reduction at 35 °C

	Zero-order kinetics for TCOD reduction (rate constant (mg/l per day))	First-order kinetics for TCOD reduction (rate constant (per day))	Zero-order kinetics for SCOD reduction (rate constant (mg/l per day))	First-order kinetics for SCOD reduction (rate constant (per day))	Zero-order kinetics for PCOD reduction (rate constant (mg/l per day))	First-order kinetics for PCOD reduction (rate constant (per day))
Raw WW & 500 mg/l BOD-Balance™	−1406.6	−0.0721	−328.96	−0.0533	−1077.6	−0.0832
Raw WW without BOD-Balance™	−533.45	−0.0213	−128.58	−0.0149	−404.87	−0.024
DAF WW & 250 mg/l BOD-Balance™	−998.36	−0.0517	−429.72	−0.1015	−528.83	−0.0493
DAF WW & 100 mg/l BOD-Balance™	−530.03	−0.0472	−472.17	−0.1181	−57.855	−0.0084
DAF WW without BOD-Balance™	−504.51	−0.0185	−491.9	−0.0658	−12.607	−0.0018

The impact of the high O&G concentration in the 5900–21,500 mg/l range on the anaerobic biodegradability is readily discernible from a comparative evaluation of the biokinetic constants for raw wastewater and DAF pretreated effluent without BOD-Balance^{TM}. The reduction of O&G increased first-order TCOD biodegradation raters by 106%, primarily due to better utilization of SCOD. As mentioned earlier, SCOD biokinetics can not be fairly compared due to the poor fit in the case of raw wastewater. But the data in Table 2 reflects that in the presence of high O&G 40% reduction in SCOD occurred over a 16 days period as compared with an 85% at low O&G concentrations.

The kinetics of anaerobic biodegradation of pet food wastewater using BOD-Balance^{TM} are comparable to alter studies. Mercz and Cord-Ruwish [13] achieved 30% grease reduction of wool scouring effluent containing 9000 mg/l of grease, 29,000 mg/l COD, 9700 mg/l BOD, and 11,400 mg/l TSS, by anaerobic bioflocculation in a pilot plant after 8 days. Using the first-order rate coefficient for TCOD in the raw waste of 0.072 per day, 30% reduction can be achieved in an estimated 5 days only. On the other hand, much faster kinetics were obtained for two-stage bioflocculation of high strength wool scouring wastewater with grease level above 15,000 mg/l with 90% reduction at HRT of 10 days [17] as opposed to an estimated 30 days using the biokinetics of this study.

3.4. Full scale trials

Based on the results of the batch-scale testing, addition of BOD-Balance^{TM} at a dose of 130–200 mg/l to the full-scale anaerobic digester was initiated in June 2002. The addition of BOD-Balance^{TM} stimulated anaerobic biological activity, which was reflected both by a dramatic increase in gas production as well as a pH drop, which was redressed by the addition of alkalinity in the form of sodium bicarbonate. The results of the two-month monitoring are presented in Table 4. It should be noted that the initial O&G reported in Table 4 of 20,300 mg/l is an anomaly since the three consecutive samples on Days 2, 37, and 44 were much higher. Accordingly, the O&G concentration of 66,300 mg/l on Day 2 is more reflective of the initial conditions in the digester at the beginning of the test. It is apparent that O&G decreased from 66,300 to 10,200 mg/l while COD was reduced from 59,175 to 35,000 mg/l. Thus, COD removal efficiency increased from 20% to a respectable 64%. The economic viability of using the biosurfactant at US$ 7–9/l versus removal of O&G using a DAF or a centrifuge will be influenced by two principal factors, namely, the

Table 4
Full-scale performance of digester with BOD-Balance^{TM}

Date	Time (day)	Alkalinity ($CaCO_3$) (mg/l)	NH_3–N (mg/l)	TBOD (mg/l)	SBOD (mg/l)	TCOD (mg/l)	SCOD (mg/l)	Oil & grease (mg/l)	TKN (mg/l)	TP (mg/l)
3 June 2002	1		680	33000	13000	59175	13150	20300		1140
4 June 2002	2			10000	32000			66300		
9 July 2002	37	3700	1230	36900	8820	56000	15000	30200	1850	180
16 July 2002	44	5700	1300	4390	1190	29000	14000	21500	1700	227
29 July 2002	57	4300	990	44100	9000	84000	19000	10200	1400	220
8 August 2002	67	7100	1500	29900	10200	35000	19000	10200	1900	330

disposal and processing cost of DAF sludge and the potential for recycling of oil. It must be emphasized that the biosurfactant dose in this case is particularly high due to the very high O&G concentration as well as the past accumulation of O&G in the digester, and accordingly long-term dosage may be lower than employed in this study.

4. Summary and conclusions

Batch scale anaerobic treatability studies were conducted to evaluate the feasibility of using a biosurfactant, BOD-Balance^{TM} to treat high oil and grease pet food wastewater at the mesophilic temperature range. Raw wastewater with average COD and O&G concentrations of 96,660 and 38,800 mg/l, respectively, as well as DAF pretreated wastewater with average COD and O&G concentration of 18,810 and 670 mg/l, respectively, were tested. Three doses of the biosurfactant, i.e. 100, 250, 500 mg/l were evaluated. The major findings of the study are summarized below:

- The addition of biosurfactant to the raw wastewater improved pCOD removal by 96–59% and SCOD removal by 100–74% with final concentration of 11,500 and 3000 mg/l, respectively, after 16 days.
- At the 100 mg/l in the DAF pretreated wastewater the addition of the biosurfactant exhibited no improvement while at 250 mg/l, particulate COD removal increased by 150–1080 mg/l after 16 days.
- Particulate and soluble COD degradation confirmed well to both zero-order and first-order biokinetic models.
- Biosurfactant addition to the high O&G wastewater affected a 164–238% increase in total COD biodegradation rate coefficient and a 164–247% increase in particulate COD rate coefficient.
- Removal of O&G by dissolved air flotation increased total COD degradation rate coefficient by 106%, with almost 85% reduction in soluble COD after 16 days.

It can thus be concluded that anaerobic treatment of high oil and grease wastewater can be accomplished by the use of biosurfactants. The results of full-scale application confirmed the operability of the mesophilic digestion with BOD-Balance^{TM} at O&G concentration in the 10,200–66,300 mg/l range.

Acknowledgements

The financial support for this study, provided by CRESTech under grant no. WRPF022, as well as by National Science and Engineering Research Council of Canada in the form a scholarship to Mustafa Al-Sabawi, is gratefully appreciated.

References

[1] P. Gurlois, G. Alric, J.P. Poroclion, G. Bridoux, J. Manem, The elimination of fats by anaerobic biological treatment, Tech. Sci. Meth. (In French) 5 (1993) 247–251.

[2] I. Angelidaki, B.K. Ahring, Effects of free long-chain fatty acids on the thermophilic anaerobic digestion, Appl. Micorbiol. Biotechnol. 37 (1992) 808–812.
[3] R.A. Wahaab, M.H. El-Awady, Anaerobic/aerobic treatment of meat processing wastewater, The Environmentalist 19 (1999) 61–65.
[4] R. Beaudet, C. Gagnon, J.G. Bisaillon, M. Ishaque, Microbiological aspects of aerobic thermophilic treatment of swine wastes, Appl. Environ. Microbiol. 56 (1990) 971–976.
[5] D. Couillard, S. Zhu, Thermophilic aerobic process for the treatment of slaughterhouse effluents with protein recovery, Environ. Pollut. 79 (1993) 121–126.
[6] B. Malladi, S.C. Ingham, Thermophilic aerobic treatment of potato-processing wastewater, World. J. Microbiol. Biotechnol. 9 (1993) 45–49.
[7] R. Zvauya, W. Parawira, C. Mawadza, Aspects of aerobic thermophilic treatment of Zimbabwean tradition opaque-beer brewery wastewater, Bioresource Technol. 48 (1994) 273–274.
[8] P. Becker, D. Koster, M.N. Popov, S. Markossian, G. Anlianileian, H. Markl, The biodegradation of olive oil and treatment of lipid-rich wool scouring wastewater whole anaerobic thermophilic conditions, Water Res. 33 (1999) 653–660.
[9] C.F. Chiang, C.J. Cu, L.K. Surg, Y.S. Wu, Full-scale evaluation of heat-balance for autothermal thermophilic anaerobic treatment of food processing wastewater, Water Sci. Tech. 43 (2001) 251–258.
[10] A.F. Rozich, D. Strom, Applications of modified thermophilic aerobic reactors for treating high strength wastes and sludges, in: Proceedings of WEFTEC Asia, Singapore, 1998, pp. 5435–5440.
[11] T.M. Lapara, J.E. Alleman, Thermophilic aerobic biological wastewater treatment, Water Res. 33 (1999) 895–908.
[12] H. Sixt, H. Sahm, Biomethanation, in: J.M. Sidwich, R.S. Holdom (Eds.), Biotechnology of Waste Treatment and Exploitation, Ellis Horwood, Chichester, UK, 1987, pp. 147–172.
[13] T.I. Mercz, R. Cord-Ruwisch, Treatment of wool scouring effluent using anaerobic biological and chemical flocculation, Water Res. 31 (1997) 170–178.
[14] S. Di Berardino, S. Costa, A. Converti, Semi-continuous anaerobic digestion of a food industry wastewater in an anaerobic filter, Bioresource Technol. 71 (2000) 261–266.
[15] R.G. Cail, J.P. Barford, R. Lichacz, Anaerobic digestion of wool scour wastewater in a digester operated semi-continuously for biomass retention, Agric. Wastes 18 (1986) 27–38.
[16] D. Isaac, R. Cord-Ruwisch, Anaerobic degradability of wool scour effluent, in: Proceedings of the Presentation of Poster Papers of IAWPRC International Conference on Appropriate Waste Management Technologies, Institute for Environmental Science, Murdoch University, Perth, Western Australia, 1991.
[17] C. Wipa, G. Ho, R. Cord-Ruwisch, Anaerobic bioflocculation of wool scouring effluent: the influence of non-ionic surfactant on efficiency, Water Sci. Technol. 34 (1996) 1–8.
[18] W. Lapsirikul, R. Cord-Ruwisch, G.E. Ho, Anaerobic bioflocculation of wool scouring effluent, Water Res. 28 (1994) 1743–1747.
[19] W. Lapsirikul, G.E. Ho, R. Cord-Ruwisch, Treatment of wool scouring effluent by anaerobic bioflocculation, Water Sci. Technol. 30 (1994) 375–384.
[20] R.G. Stewart, Woolscouring and Allied Technology, second ed., Caxton Press, New Zealand, 1985.
[21] A.J. Lugowski, G.F. Nakhla, G. Palmateer, J. Purcell, Performance of anaerobic digesters using bioenhancers, in: Proceedings of the 72nd Annual Water Environment Federation Conference, October 1999, New Orleans.
[22] American Public Health Association, American Water Works Association, and Water Environment Federation, Standard Methods for the Examination of Water and Wastewater, 17th ed., Washington, DC, 1989.