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Treatability and kinetics studies of mesophilic aerobic biodegradation of high oil and grease pet food wastewater

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Abstract

In this work, batch activated sludge studies were investigated for the treatment of raw pet food wastewater characterized by oil and grease concentrations of 50,000–66,000 mg/L, COD and BOD concentrations of 100,000 and 80,000 mg/L, respectively, as well as effluent from an existing anaerobic digester treating the aforementioned wastewater. A pre-treatment process, dissolved air flotation (DAF) achieved 97–99% reduction in O&G to about 400–800 mg/L, which is still atypically high for AS. The batch studies were conducted using a 4-L bioreactor at room temperature (21 °C) under different conditions. The experimental results showed for the DAF pretreated effluent, 92% COD removal efficiency can be achieved by using conventional activated sludge system at a 5 days contact time and applied initial soluble COD to biomass ratio of 1.17 mg COD/mg VSS. Similarly for the digester effluent at average oil and grease concentrations of 13,500 mg/L, activated sludge affected 63.7–76.2% soluble COD removal at 5 days. The results also showed that all kinetic data best conformed to the zero order biodegradation model with a low biomass specific maximum substrate utilization rate of 0.168 mg COD/mg VSS day reflecting the slow biodegradability of the wastewater even after 99% removal of oil and grease.

Keywords: Mesophilic aerobic; Activated sludge; Food industry wastewater; Oil and grease; Biokinetics constants; Batch reactors

1. Introduction

The presence of high-strength oil and grease in industrial wastewaters poses serious challenges for both aerobic and anaerobic biological treatment systems [1]. The developments in rendering industries high-strength wastewater treatment during the last 10 years were summarized by Johns [2]. The latest applications and developments for different treatment processes were evaluated below. While a series of primary treatment procedures, such as screening, settling, etc. have been explored for pre-treatment of high oil and grease wastewater. Dissolved air flotation (DAF) is still considered to be the best due to its high oil and grease reduction efficiency, which can be up to 99% [3].

Anaerobic treatment of high-strength wastewater has been achieved by using low rate covered anaerobic ponds and high rate anaerobic systems, as well as the traditional uncovered anaerobic ponds and low rate anaerobic systems [2]. 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 [4,5], 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. Application of a large covered anaerobic pond to treat pork-processing wastewater achieved BOD_5 removal efficiency of 85–90% [6]. The anaerobic contact (AC) reactor was also considered as a high rate anaerobic technology. AC reactor systems have

Abbreviations: AS, activated sludge; AnRBC, anaerobic rotating biological contactor; BOD, biological oxygen demand; COD, chemical oxygen demand; DAF, dissolve air flotation; DO, dissolve oxygen; HRT, hydraulic retention time; O&G, oil and grease; RAS, returned activated sludge; RBC, rotating biological contactor; SBOD, soluble BOD; SCOD, soluble COD; SP, soluble phosphorus; SRT, solid retention time; TBOD, total BOD; TCOD, total COD; TP, total phosphorus; TSS, total suspended solid; UASB, upflow anaerobic sludge blanket; VSS, volatile suspended solid

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Nomenclature

K maximum substrate consumption specific rate
K_s Monod half velocity concentration
S_0 initial substrate concentration
U_{max} maximum specific growth rate
X biomass concentration in reactor
X_0 initial biomass concentration
$Y_{X/S}$ biomass growth yield coefficient

achieved better than 84% COD, 93% BOD_5 and 75% TSS removal in slaughterhouse wastewater treatment [2]. While anaerobic processes have been successful for the treatment of soluble organic waste [7], their success in dealing with high oil and grease wastewater has been limited. For example, in treating wool-scouring wastewater with high O&G strength, the thermophilic anaerobic process allowed a COD degradation of about 40% at an HRT of 10 days [8].

For aerobic biological wastewater treatments at high O&G concentrations, an activated sludge system treating oil and grease at concentrations of 400 and 600 mg/L, achieved COD removal efficiencies of 86 and 75%, respectively, while at 800 mg/L oil and grease concentration in feed, the COD removal efficiency of the bioreactor dropped markedly [9]. Thus it is apparent that the treatment of high-strength oil and grease wastewaters is very challenging and novel technologies utilizing either aerobic or anaerobic processes have not been very successful. The conventional AS treatability study of high oil and grease and COD wastewater under mesophilic condition or even at room temperature has seldom been investigated before [10]. While aerobic thermophilic processes have been used for the treatment of high oil and grease wastewater including liquid pig manure [11], potato-processing wastewater [12,13], these systems are often plagued by foaming problems, solids separability concerns, and volatilization of ammonia necessitating air phase treatment.

This project addresses the treatment of raw wastewater from rendering operations prior to and post treatment by a full-scale completely mixed mesophilic anaerobic digester. The objective of this study is to investigate the aerobic batch activated sludge treatment of high oil and grease wastewater with O&G concentration as high as 800 mg/L. The research will also delineate the kinetics of organic removal under such conditions. During this AS study, different contact time and different initial applied substrate to biomass ratios (S_0/X_0) were investigated in order to determine the optimal organic loadings.

2. Methodology

2.1. Existing system description

The treatment system at this rendering facility in southern Ontario consists of an anaerobic digester that provides a hydraulic retention time of 30 days at the average flow rate of 60 m^3/day. The wastewater characteristics are shown in Table 1 together with the anaerobic digester effluent. The very high COD and suspended solids concentrations in both 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 100,000 mg/L. Gas production from the digester was minimal while COD reduction was at approximately 30% well below normal for a wastewater with a BOD-to-COD ratio of >0.7.

2.2. Activated sludge experiment setup

2.2.1. Batch scale system setup

The activated sludge reactor using in this study is a batch scale complete mixed reactor model as shown in Fig. 1. The bioreactor system was made from glass with a working volume of 4 L. It was aerated through an air diffuser and mechanically mixed by a magnetic stirrer (Corning Plate Stirrer PC-351). Under these conditions, the dissolved oxygen concentration in the reactor was kept between 2 and 3 mg/L. The batch aerobic treatability studies were conducted at room

Table 1
Raw and pre-treated wastewater characteristics

Parameters (mg/L)	Raw waste (before digester)		Anaerobic digester effluent		DAF pretreated 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

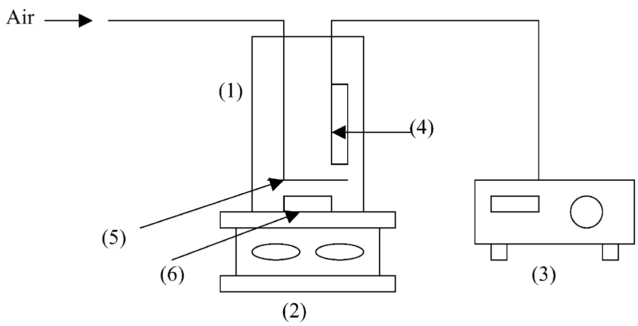

Fig. 1. Batch activated sludge experimental setup: (1) 4 L bioreactor, (2) magic stirrer (Corning Plate Stirrer PC-351), (3) DO meter (YSI Dissolve Oxygen Meter Model 50), (4) DO probe, (5) air diffuser, (6) mixing bar.

temperature (21 °C) under different initial food to microorganism ratio (S_0/X_0). The wastewater samples used in AS reactor were the raw waste, DAF pre-treated waste, and also from the aeration tank of an on-site pilot scale activated sludge system, which is described later in Section 2.2.2. Wastewater was mixed with a typical concentrated returned activated sludge (RAS) collected from Adelaide municipal wastewater treatment plant in London, Ontario, which employs conventional activated sludge system for BOD removal and nitrification. The concentrated sludge was obtained by settling the regular RAS to 1/3 of the total volume. The concentrated sludge had the following characteristics: TSS = 9900–12,400 mg/L, VSS = 7000–9130 mg/L, TCOD = 12,800–16,200 mg/L.

In the batch scale study, the system was initially operated at different reaction times to determine the optimum contact time from an SCOD removal standpoint. Grab samples of the mixed liquor were collected daily, filtered through 0.45 μm filter paper to determine TSS, VSS, and SCOD. The results showed that SCOD reduction dropped remarkably when the reaction time was longer than 5 days. Therefore, the maximum reaction time of the selected batches was controlled at 5 days.

2.2.2. On-site pilot scale reactors setup

Subsequent to the laboratory scale batch studies, an on-site pilot batch scale system was set up. The system consisted of a 20 L DAF tank, a 150 L storage tank and a 28 L activated sludge reactor. Fig. 2 shows the schematic of the pilot system. All the vessels are made from stainless steel with a glass observation window. DAF pretreated waste from a storage tank was pumped (Milton Roy LMI metering pump, 24.4 GPD at 125 psi) into AS reactor. The AS reactor was then aerated by pressurized air through tube type air diffusers. The pressurized air for both DAF and AS reactor provided by a 5 hp air compressor. The operational conditions were similar to lab scale batch conditions with batches running for 6 days and grab samples of the mixed liquor were collected daily as well.

2.2.3. Analytical methods

During the batch sample analysis, mixed liquor samples were withdrawn from the reactor once a day and analyzed for total suspended solid (TSS), volatile suspended solid (VSS), dissolved oxygen (DO), total COD (TCOD), soluble COD (SCOD), ammonia nitrogen (NH_3-N), nitrate nitrogen (NO_3-N), total phosphorus (TP), soluble phosphorus (SP) and oil and grease (O&G).

Portions of the samples were collected daily from the mixed liquor in the bioreactor, were filtered through a 45 μm fiber glass filter paper (Whatman, 47 mm 1822 047) in order to analyze the soluble wastewater characteristics as well as TSS and VSS using Standard Method (No. 2540D for TSS and No. 2540E for VSS [14]). Dissolved oxygen was constantly monitored by a DO meter (YSI Dissolved Oxygen Meter Model 50). Oil and grease testing was sent out to a certified commercial laboratory, while all the other parameters were determined by HACH equipment (*HACH Odyssey Analyzer and COD heating reactor*) using standard HACH testing kits for different analyses.

2.3. Kinetics modeling

The kinetics modeling used in this study were based on basic Monod model. Two limiting cases of the Monod model were considered.

2.3.1. Zero order model

In the cases of constant biomass concentrations with low biomass change, i.e., $\Delta X \ll X_0$, and high substrate concentration ($S \gg K_s$), Monod equation can be reduced to a zero

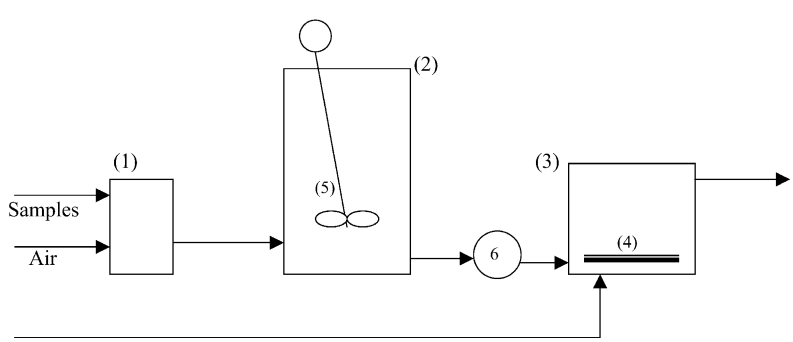

Fig. 2. Pilot activated sludge experimental setup: (1) 20 L pressure tank, (2) 150 L storage tank, (3) 28 L AS bioreactor, (4) air diffuser, (5) motor mixer, (6) booster pump (Milton Roy LMI).

order reaction [15]:

$$\frac{dS}{dt} = kX \quad (1)$$

Therefore, the kinetics constants 'kX' can be measured by zero order linear regression using substrate S versus time plot, with the slope being equal to the product of 'k' and X. Thus 'k' is the slope of the zero order coefficient versus biomass (X) concentration.

2.3.2. First order model

On the other hand, based on the same constant biomass concentration condition, with $K_s \gg S$, Monod equation can be simplified to a first order reaction:

$$\frac{dS}{dt} = \frac{kXS}{K_s} \quad (2)$$

Therefore, the first order biodegradation kinetics coefficient 'kX/K_s' can be determined from $\ln(S/S_0)$ versus time plot. The slope of the first order biodegradation coefficient versus biomass is thus k/K_s.

3. Results and discussion

3.1. Overall performance

The temporal variation of soluble COD in the batch scale operated with DAF effluent wastewater at initial substrate to microorganism ratio of 1.17 is depicted in Fig. 3. As apparent from Fig. 3, SCOD removal was accomplished within 4 days, and no further reduction in SCOD was observed between day 5 and day 9, with the steady state SCOD stabilizing at 300–500 mg/L after day 5. Thus it was decided that all batches would be run for 5 days. Furthermore, the results of this test clearly show that approximately 10% of the initial soluble COD was non-biodegradable even after 10 days of treatment.

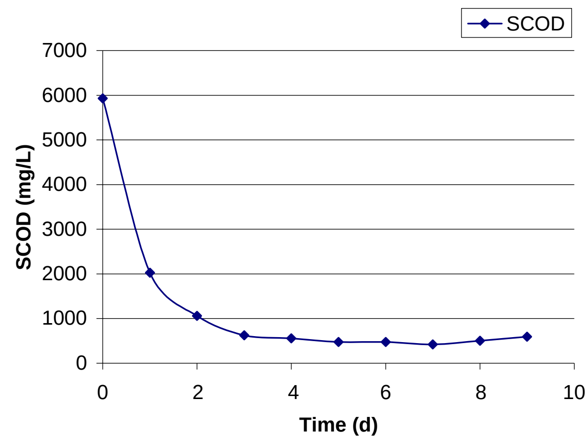

Fig. 3. Soluble COD batch removal kinetics.

Table 2 summarizes the initial O&G, substrate (as SCOD) and biomass concentrations and SCOD removal efficiencies for the various waste streams investigated. It is noteworthy that COD removal efficiencies for the DAF pretreated effluents both in lab and pilot scale studies were based on soluble COD since it accounted for over 70% of the total COD, while the soluble fraction of the BOD was 0.87. For the particulate-laden digester effluent, COD removals have been based on both soluble and total COD data. It is conceded however that the total COD removal efficiencies are affected by the distribution of particulate COD between biomass and substrate.

The initial substrate to biomass (S_0/X_0) has been calculated using the initial measured VSS, which includes particulate COD, and the initial VSS originating from the seed

Table 2
Initial conditions in different activated sludge batches

Batch name	S_0 (SCOD) (mg/L)	X_0 (VSS)[a] (mg/L)	S_0/X_0 (VSS)[a]	X average (VSS)[a] (mg/L)	X_0 (X)[b] (mg/L)	S_0/X_0 (X)[b]	O&G[c] (mg/L)	COD removal (%)
DAF 1	5930	5060	1.17	5208	4565	1.30	>600	92.0
DAF 2	2485	2110	1.18	2625	1750	1.42	>600	92.0
DAF 3	10100	4125	2.45	5861	1160	8.71	>600	64.4
DAF 4	7850	2833	2.77	3375	2455	3.20	>600	60.8
DAF 5	7565	5200	1.45	5562	4055	1.87	>600	70.8
DAF stored 1	7600	3700	2.05	4295	2455	3.10	660	47.6
DAF stored 2	7740	6430	1.20	5643	4055	1.91	660	70.8
Digester effluent 1	10500 (35600)[d]	13900	0.76	17314	4565	2.30	13500	63.7 (18.9)[e]
Digester effluent 2	12600 (27100)[d]	13600	0.93	16270	4565	2.76	13500	76.2 (44.2)[e]
Digester effluent 3	9450 (30600)[d]	19000	0.50	22130	3043	3.11	13500	69.3 (37.2)[e]
On-site 1	12750	5130	2.49	7045	5130	2.49	664	88.7
On-site 2	8530	4830	1.77	6388	3830	2.23	664	78.4

[a] These values were calculated based on VSS values being identical to biomass concentration.
[b] These values were calculated based on assuming only seed sludge VSS as biomass concentration.
[c] O&G parameter values were not measured in each batch, while the samples were collected and tested periodically. The above shown O&G values were measured during selected batch experiments.
[d] The numbers in parentheses are the initial values of total COD for the batches.
[e] The numbers in parentheses are the total COD removal efficiencies.

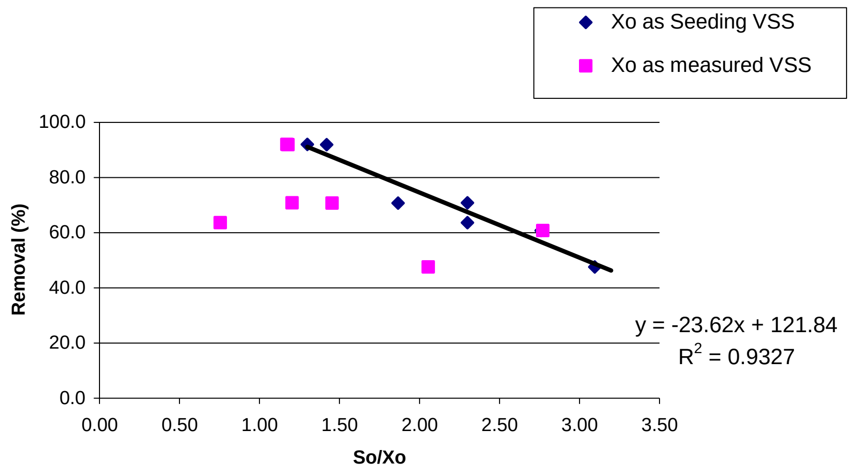

Fig. 4. Soluble COD removal efficiencies in different batches.

sludge obtained from the municipal wastewater treatment plant. Perhaps the most remarkable observation is that the activated sludge affected 63.7–76.2% soluble COD removal and 18.9–44.2% total COD removal at O&G concentrations of 13,500 mg/L. The reproducibility of the data is evident since all three batches were at S_0/X_0 values within 10–20% of each other and also affected close removal efficiencies. This is contradictory to the findings of other researchers [9] who reported that oil and grease concentrations above 600 and 800 mg/L affected significant reductions in COD removal. While the reasons for these discrepancies are largely unknown, it is postulated that the nature of oil and grease in this rendering wastewater being predominantly of animal origin rather than mineral, is not only non-inhibitory but also biodegradable. The principal mechanism by which oil and grease adversely impacts aerobic biological systems is by coating the biological floc and hindering oxygen transfer.

Based on the five laboratory batches conducted with DAF pretreated wastewater from the anaerobic digester, COD removal efficiencies varied widely from 60.8 to 92% at S_0/X_0 values of 1.3 to 8.71 with removal efficiency generally decreasing with the increase in S_0/X_0. The relationship between the COD removal efficiencies for the DAF pretreated digester effluent and the initial substrate to biomass ratio is depicted in Fig. 4. It is evident that generally removal efficiency decreased with an increase in S_0/X_0 with the peak SCOD removal efficiency of 92% occurring at S_0/X_0 in the range of 1.3–1.42 mg COD/mg VSS. Since in this study all batches were run for the same time, the S_0/X_0 is therefore synonymous with food to microorganism ratio (F/M) and

Table 3
Comparative performance of various treatment processes

Wastewater type	Treatment methods	Influent COD (mg/L)	Oil and grease (mg/L)	Substrate removal (%)	Ref.
Previous studies					
Beer brewery	Thermophilic aerobic reactor (50 °C)	–	–	67	[23]
Slaughterhouse	Anaerobic lagoons	2291	624	79	[17]
Slaughterhouse	Anaerobic reactor	3600	1700	33–52	[17]
Slaughterhouse	UASB	1610	–	57	[17]
Dairy	AnRBC	–	–	60–81	[24]
High strength	AnRBC	12000	–	71	[19]
Food processing	UASB	4700	–	80–85	[25]
Wool scouring	Thermophilic aerobic reactor (65 °C)	77000	1100	40	[20]
Wool scouring	Mesophilic anaerobic reactor	40000	–	40	[8]
Dairy	Activated sludge	2521	400	86	[9]
			600	75	
			800	0	
Dairy	Pre-hydrolysis + activated sludge	2521	400	93	[9]
			600	92	
			800	82	
Meat processing	UASB	1544	144	56	[18]
Meat processing	UASB + RBC	1544	144	91.5	[18]
Current study					
Pet food	Conventional activated Sludge	13700	404–820	70–92	–

accordingly the observed pattern of COD removal with increasing S_0/X_0 or F/M is typical [16]. This is to be excepted since any organic loading above the maximum microbial uptake will be untreated.

A similar trend was observed for the stored DAF pretreated and the raw wastewater with COD removal efficiencies decreasing from 70.8 to 47.6% with an increase in S_0/X_0 from 1.91 to 3.1 mg COD/mg VSS in the case of stored DAF pretreated and from 76.2 to 69.3% at S_0/X_0 values of 2.76 and 3.11 mg COD/mg VSS for the raw wastewater. For the two on-site batches, the COD removal efficiency increased mildly from 78.4 to 88.7% with the increase in S_0/X_0 from 2.23 to 2.49 mg SCOD/mg VSS. It is unlikely that the on-site batch would exhibit substantially different trends than the laboratory ones and this slight discrepancy may be attributed to experimental errors.

Table 3 compares the performance of various aerobic and anaerobic treatment processes for food processing wastes. As evident from the table, COD removal efficiencies achieved in this study using the activated sludge processes are at the high end of literature values. For example, at similar O&G concentrations anaerobic lagoons achieved 79% [17] at much lower influent COD concentrations. Upflow anaerobic sludge blanket reactors [17,18] as well as anaerobic rotating biological contactors [19] achieved 56–70% COD removal. Thermophilic aerobic process, which can operate at very high oil and grease concentrations [20] due to solubilization of oil, achieved highly variable removal efficiencies in the range of 40–90%. Thus while anaerobic processes offer the advantages of low energy consumption, sludge production, and nutrient requirements, their vulnerability to high oil and grease concentrations is notable. The relative advantages of aerobic thermophilic processes are offset by inconsistent performance, and operational problems i.e., foaming and the need for off-gas to treatment for ammonia. Based on the findings of this study and that of Jung et al. [9], the activated sludge process can effectively treat wastewater at oil and grease concentrations of up to 800 mg/L. In fact it has been shown that membrane bioreactor (MBR), which is a modification of the conventional activated sludge system can achieve 94–96% COD reduction at influent oil concentration of 500–3000 mg/L at a hydraulic retention time of 13.3 h with sludge and oil concentration in the MBR as high as 48 and 30 g/L, respectively [21]. This study clearly demonstrates that biomass retention and long sludge ages are critical to the performance of activated sludge systems.

3.2. Biokinetic modeling

As elaborated upon earlier, both limiting cases of the Monod model i.e., zero order and first order kinetics were investigated. A summary of the zero order and first order coefficients for the various batches is listed in Table 4 together with the various correlation coefficients. Figs. 5 and 6 illustrate graphically the fit of the data from both lab and on-site batches to the zero order and first order kinetic models, respectively. It is apparent from the data that both model

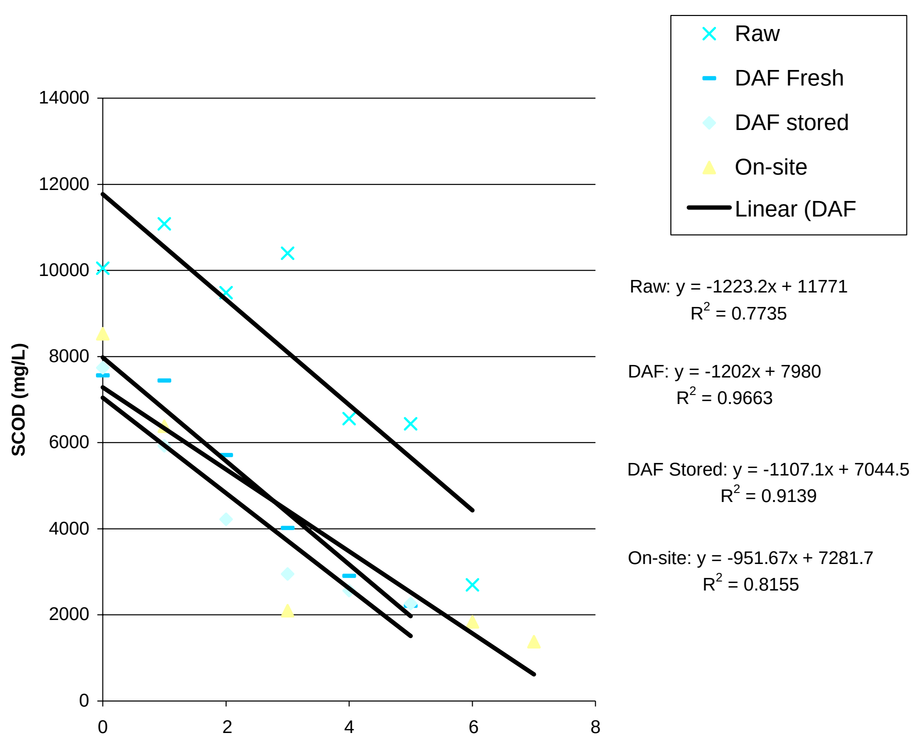

Fig. 5. Zero order soluble COD removal kinetics.

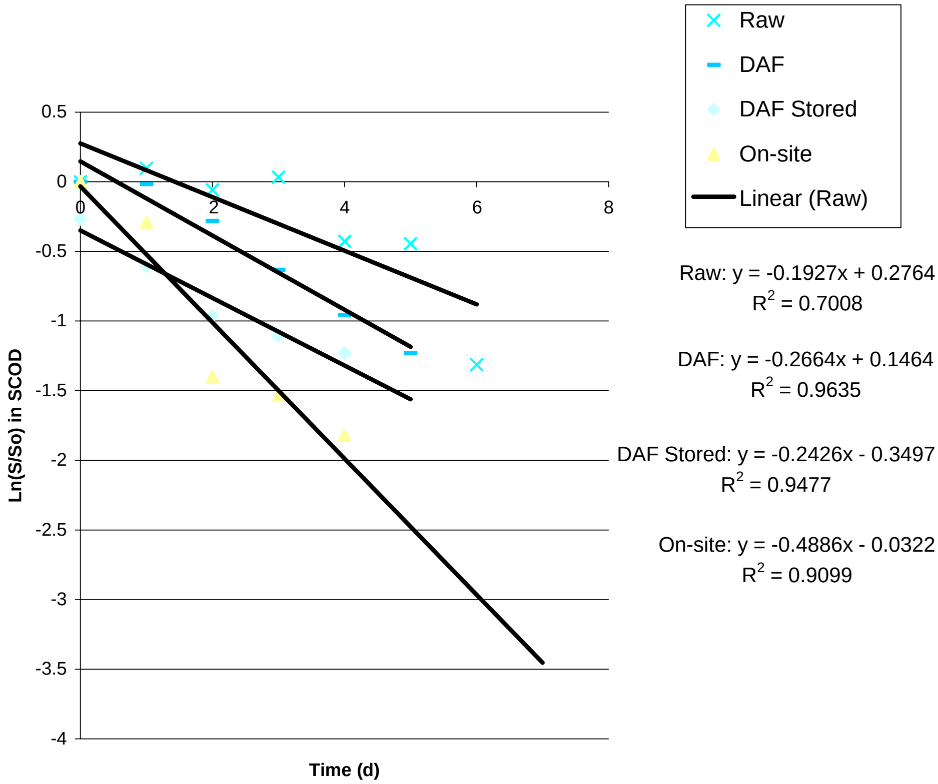

Fig. 6. First order soluble COD removal kinetics.

fit the data well, with R^2 values of zero order kinetics for the DAF pretreated wastewater ranging from 0.66 to 0.97. High correlation coefficients were also observed for all other waste streams. By comparison, similar R^2 values were observed for the first order kinetics. The goodness fit of the data to both first and zero order kinetics is rather intriguing and need further investigations.

The maximum specific substrate utilization rate, 'k' for the DAF pretreated digester effluent was obtained by linear regression of the zero order coefficient and the initial biomass concentration, X_0 as reflected by the VSS measurement as shown in Fig. 7. The high R^2 value of 0.634 reflects the reliability of the estimated value of k of 0.168 mg COD/mg VSS day. This value is much lower than municipal wastewater values of 4.3–28.7 mg COD/mg VSS day [22], which reflects the very slow biodegradability of the wastewater even after removing oil and grease. It is noted from Fig. 7 that the plot of

Table 4
Kinetics of zero order and first order modeling

Batch	Zero order kinetics		First order kinetics	
	k' (kX) (mg/L day)	R^2	k'' (kX/K_s) (1/day)	R^2
DAF 1	917.5	0.660	0.486	0.882
DAF 2	439.6	0.825	0.526	0.924
DAF 3	1120	0.899	0.156	0.897
DAF 4	1019	0.916	0.215	0.906
DAF 5	1202	0.966	0.266	0.964
DAF stored 1	750	0.815	0.128	0.839
DAF stored 2	1107	0.914	0.243	0.938
Digester effluent 1	1223	0.774	0.193	0.701
Digester effluent 2	2217	0.787	0.347	0.898
Digester effluent 3	1995	0.516	0.352	0.635
On-site 1	1708	0.693	0.823	0.848
On-site 2	951.7	0.816	0.489	0.909

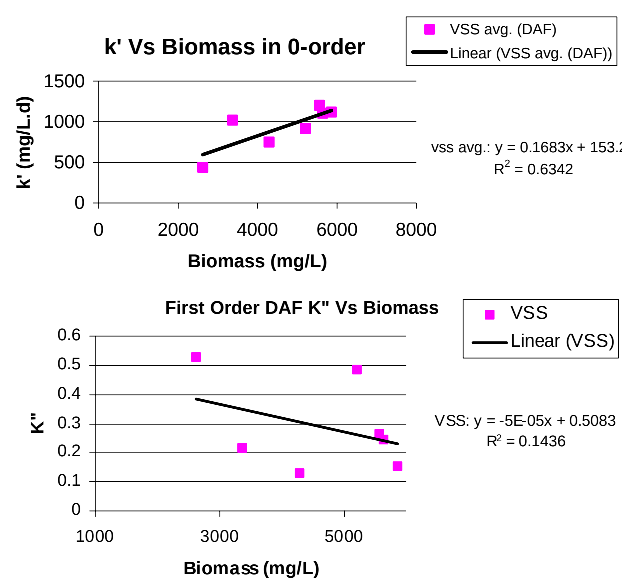

Fig. 7. Variation of zero order and first order biodegradation coefficients with biomass.

the first order biodegradation coefficient versus biomass concentration did not yield a straight line relationship with a positive slope of k/K_s (L/mg VSS day) as expected. The reasonably good fit of the data to both zero order and first order models approximations may be explained by a varying biomass concentration or prevalence of wide various in substrate concentrations within the vicinity of this K_s value in any given batch. A comparison of the initial and average biomass concentration for the DAF pre-treatment digester effluent indicates that generally the discrepancies between these two values were mostly in the 4–25% with the exception of the on-site batches. While these values clearly reflect some changes in the biomass concentration, which undermine the zero order and first order models, such changes are mostly within the expected variability for VSS measurement of 10% [14] and thus the delineation of biokinetic constants is not compromised.

By examining the initial and final SCOD presented in Table 2 for the DAF effluent and the on-site batches, which essentially treated DAF-pretreated effluent. It is evident that the initial SCOD was mostly in the 7565–12,750 mg/L and the final SCOD were in the 1500–4000 mg/L. The fit of the data to both models may suggest a value of K_s, i.e., the batches are zero order initially and first order towards the end. The fact that in general the zero order fit was overall better than the first order particularly for the on-site batches, and also correlated better with biomass concentration indicated that the initial rates were indeed the maximum substrate utilization rates, i.e., the value of K_s is much lower than the 7565–12,750 mg/L and is close to the 1500–4000 mg/L. The same remarks can be made regarding the raw digester effluent where initial SCOD ranged from 9450 to 12,600 mg/L with final SCOD ranging from 2900 to 3700 mg/L.

4. Summary and conclusions

Based on the batch activated sludge studies conducted the high-strength pet food wastewater at a low temperature of 21 °C, the following conclusions can be drawn:

- High oil and grease wastes can be treated aerobically with favorable kinetics in conventional activated sludge systems. More than 90% COD removal efficiency can be achieved at oil and grease concentrations as high as 660 mg/L at contact time of 5 days.
- At 13,500 mg/L of oil and grease and total COD concentrations of 77,300 mg/L, activated sludge can still achieve respectable soluble COD removals in the 63.7–76.2% range at 5 days contact time.
- Soluble COD removal efficiencies from the DAF pretreated digester effluent peaked at an initial substrate to biomass concentration of 1.17 mg COD/mg VSS and decreased almost linearly beyond that.
- Although both zero order and first order models fit the biokinetics data for the batch studies, the zero order was deemed more pertinent with an estimated maximum biomass specific substrate utilization 0.17 mg COD/mg VSS day.

Acknowledgements

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