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Performance of anaerobic immersed membrane bioreactor (AnIMBR) treating synthetic dairy wastewater

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ABSTRACT

The performance of a bench-scale anaerobic immersed membrane bioreactor (AnIMBR) when treating synthetic dairy wastewater was investigated. The investigation was carried out at mixed liquor suspended solid (MLSS) concentrations of 5,000, 1,0000, and 1,5000 mg/l and influent chemical oxygen demand (COD) concentrations of 2,000, 4,000, 6,000, and 8,000 mg/l. In order to avoid frequent membrane fouling, the investigation was conducted at permeate flux of about 2.2 l/m^2 h. Results of the investigation showed that maximum removal efficiencies of COD (91.4 percent) and turbidity (99.4 percent) were achieved at MLSS and influent COD values of 15,000 and 4,000 mg/l, and 15,000 and 2,000 mg/l, respectively. A maximum biogas yield of 0.17 l/g COD_r with methane content of 82 percent was obtained at an MLSS value of 15,000 mg/l. Mathematical relationships between daily biogas production and MLSS and influent COD concentrations were formulated. Throughout the investigation, sludge production was at an average of 0.022 mg VSS/mg COD_r. Results of the investigation also showed that total phosphate could be removed by more than 86 percent, which was achieved at an MLSS value of 5,000 mg/l.

Keywords: Membrane fouling; COD removal; Biogas yield; Sludge production; Phosphate removal

1. Introduction

Due to dramatic increases in population and industrial activities, food industries, particularly dairy industries, have been growing throughout the globe during the past decades. Consequently, large quantities of dairy wastewater are being produced on daily basis. On the average, a dairy factory generates 1.3–2.5 L of dairy wastewater per liter of processed milk. Wu and Zhu reported that dairy industries produce 0.2–10 L of wastewater per liter of processed milk with an average of 2.5 L [1]. Carvalho et al. reported that generation of cheese whey wastewater is roughly four times the volume of processed milk [2]. In Saudi Arabia, production of bovine milk has increased from 166 to 730 million liters between 1986 and 2012, which indicates a 340 percent increase within 26 years. Dairy wastewater is considered as a very strong wastewater in terms of chemical oxygen demand (COD), biochemical oxygen demand (BOD_5), and suspended solids (SS). COD values between 1,100 and 90,000 mg/l were reported in the published

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literature [3]. On the other hand, BOD_5 and SS values ranging between 320 and 35,000 and 900 and 56,700 mg/l, respectively, were reported [3]. Nitrogen, phosphorus, sodium, chlorides, calcium, magnesium, and potassium were also reported to present in dairy wastewater [3]. Consequently, dairy wastewater must be treated before being discharged or reused in order to protect receiving and surrounding environments. Since dairy wastewater is putrescible and can be biodegraded in efficient manner, aerobic, and anaerobic biological processes have been extensively employed in treatment of dairy wastewater [3,4]. However, enzymatic hydrolysis, electrocoagulation, advanced oxidation, electrochemical processes, adsorption, and coagulation have also been implemented to treat dairy wastewater [5–10]. Several investigators reported the instability of biological degradation of dairy wastewater [11]. Moreover, COD removal efficiency was not high enough to cope with standards and regulations pertinent to effluent discharge in some European countries [12]. Coagulation, flocculation, and sedimentation were reported to remove major portions of COD, however, supernatants were reported to be highly biodegradable and contained high amounts of nutrients such as nitrogen, calcium, magnesium, potassium, phosphorous, and organic matter [12]. Martins and Quinta-Ferreira reported that oxidation processes are not recommended to be used as sole treatment of dairy wastewater; however, these processes can be used as post-degradation treatment processes [13]. Consequently, new technologies or combinations of treatment processes are highly recommended in order to provide an efficient treatment of different types of dairy wastewater. Anaerobic membrane bioreactor (AnMBR) is a combination of anaerobic biodegradation and membrane technology. Immersed or submerged AnMBRs have the advantage of occupying less foot-prints in addition to reduced energy intake, reduced membrane cleaning frequencies, and reduced sludge production, when compared to crossflow filtration. Recently, Praneeth et al. assessed the performance and analyzed the hydrodynamic of an aerobic submerged membrane bioreactor treating dairy industrial effluent [14]. They studied the effect of operating parameters, namely, pressure of suction, degree of aeration, and transmembrane pressure (TMP) on membrane performance. Membrane performance was measured in terms of permeate flux, removal of turbidity, BOD_5, and COD as well as membrane fouling. The investigation results showed that the permeate permeability was between 108 and 115 l/m^2 h per bar of TMP. Moreover, the removal efficiency of COD and BOD_5 was in the range of 91–93 and 86–92 percent, respectively. Banu et al. studied the effect of temperature on sludge reduction of aerobic membrane bioreactors treating primary-treated dairy wastewater [15]. They operated aerobic membrane bioreactors with a mixed liquor suspended solids (MLSS) concentrations between 6,800 and 7,200 mg/l for 60 d. Part of the MLSS was collected and treated by thermochemical treatment at a temperature of 60°C and an alkali dosage in the range of 0.49 to 0.56 mg NaOH/mg MLSS. The results showed that 42 percent of COD was solubilized and 22 percent of SS was reduced. However, they concluded that sludge pre-digestion was not found to have an effect on the removal efficiency of COD in MBR processes. Hasar et. al. used submerged membrane bioreactor to treat high-strength raw whey wastewater [16]. The investigation was performed at various sludge ages (10–75 d), high MLSS concentration (50 g/dm^3), and influent COD concentrations of 60–90 g/dm^3. The results showed that the effluent was free from SS and total coliform bacteria, however, the effluent COD was 20 g/dm^3, which indicated a COD removal efficiency between 67 and 78 percent. Due its ability to reduce the pollution load, the investigators concluded that submerged MBR was found to be an effective pre-treatment system for high-strength agro-wastewater. Arros-Alileche et al. simulated membranes role in anaerobic membrane bioreactors for purification of dairy wastewater [17]. The simulation indicated that it is possible to use any type of membrane, namely, microfiltration, ultrafiltration, nanofiltration, and reverse osmosis (MF, UF, NF, and RO) to retain biomass. Microfiltration or ultrafiltration membranes require long hydraulic retention times (HRTs) or small influent concentrations and larger reactor volumes to achieve good water quality. On the other hand, nanofiltration or reverse osmosis membranes require short HRTs for highly purified water, but necessitate larger investments. From the above and up to the knowledge of the investigators, the extensive literature review revealed that there is a lack of enough and reliable information on the implementation of anaerobic immersed (submerged) membrane bioreactors in treating dairy wastewater. Consequently, the main objective of the current investigation is to study the performance of anaerobic immersed membrane bioreactors when treating synthetic dairy wastewater. In order to achieve the main objectives, the investigation was carried out at MLSS concentrations of 5,000, 10,000, and 15,000 mg/l and influent COD concentrations of 2,000, 4,000, 6,000, and 8,000 mg/l.

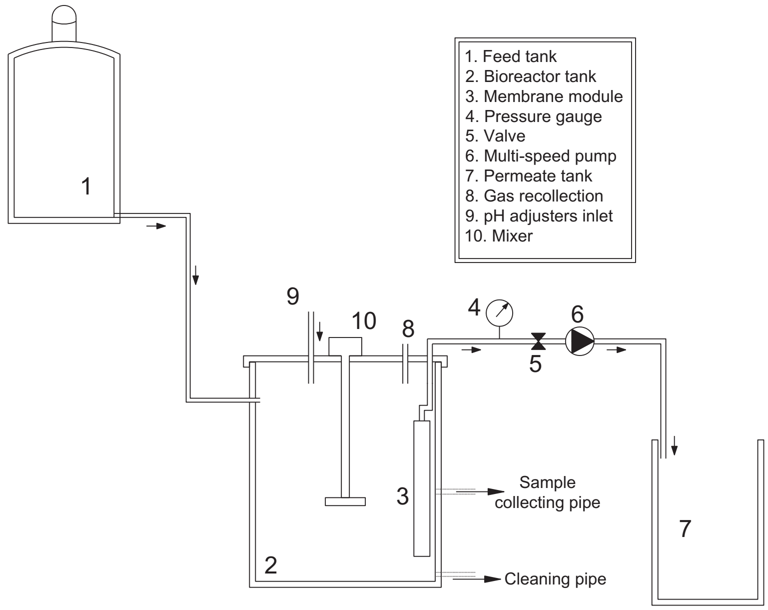

Fig. 1. Schematic diagram of the experiment setup.

2. Materials and methods

2.1. Experimental setup

Fig. 1 shows a schematic diagram of the experimental setup of the anaerobic immersed membrane bioreactor that was used throughout the investigation. The setup comprises mainly of feed tank, anaerobic reactor, membrane module, gas collection system, and permeate tank. The anaerobic reactor dimensions were 50 (L) × 20 (W) × 25 (H) cm with water volume of 20 L. Mechanical mixer was used to mix the contents of the anaerobic bioreactor, while peristaltic pump and pressure gauges were used to withdraw the permeate and measure suction and backwashing pressures, respectively. The general characteristics of the membrane module used throughout the investigation are shown in Table 1.

2.2. Synthetic dairy wastewater

Based on a thorough literature survey pertinent to characteristics of dairy wastewater, it is worth to mention that COD, BOD_5, pH, total phosphorous (TP), total Kjeldahl nitrogen (TKN), total solids (TS), SS, and total dissolved solids (TDS) beside other parameters were taken into consideration during the preparation of the synthetic dairy wastewater. The general characteristics of the prepared synthetic dairy wastewater are shown in Table 2. It is worth mentioning that powder milk was used in the preparation of the synthetic dairy wastewater.

2.3. Biogas collection

The water displacement method was used to quantify the amount of biogas produced by the anaerobic immersed membrane bioreactor. The collected biogas volume was then corrected for the bioreactor temperature (25˚C), compared with the theoretical yield at that temperature and finally expressed in liters per gram of removed COD (l/g COD_r).

2.4. Experimental design

Table 3 shows the experimental design that was implemented during the course of the investigation.

2.5. Chemical analysis

Influent and permeate samples were collected and subjected to chemical analysis in accordance with Standard Methods, as shown in Table 4 [18]. With respect to variations of pH inside the anaerobic bioreactor, all efforts were made to keep pH values between 6.8 and 7.2 by the use of 2.5 N NaOH solution.

2.6. Membrane cleaning

The investigation was performed at flux values around 2.3 l/m^2 h, therefore, membrane backwashing with distilled water twice a day was found to be very effective. Membrane backwashing was carried out for 10–30 min, depending on fouling conditions.

Table 1
General characteristics of membrane module

Parameter	Units	VFU-250a	Remarks
Water flux	l/m^2 h 100 kPa	>500	At 25˚C and 100 kPa
Molecular weight cut off	Da	250,000	Dextrane mixture
Temperature range	˚C	1–70	At pH 7 and 100 kPa
Pore size	µm	0.03–0.05	
pH range		2–10	At 25˚C
Diameter "outer side"	mm	9.2	
Length	mm	340	Only tubes
Total length	mm	400	
Total membrane area	m^2	0.04	
Permeate outlet with hose nozzle	mm	9	
Filtration direction		From outside to inside	Submerged
Type	UF tubular		
Membrane material	PVDF		
Manufacturer	Membrane Modules Systems GmbH (MEMOS)		

Table 2
General characteristics of synthetic wastewater

Constituent	Concentration (mg/l)[a]
pH	6.66
Turbidity (NTU)	1,500 ± 3
NH_4	<1
TS	1,980
TSS	1,213
TDS	767
BOD	1,341 ± 81
SCOD	940 ± 85
TCOD	2,950 ± 130
TKN	55.72 ± 1.68
Ca	227
K	69.4
Mg	62.9
Na	511
Fe	0.193
TP	8.7
PO_4^{3-}	6.24 ± 0.24

[a]Except pH and turbidity.

3. Results and discussion

3.1. Hydraulic performance

In order to study the performance of the anaerobic immersed membrane bioreactor, the investigation was performed at mixed liquor suspended solids (MLSS) concentrations of 5,000, 10,000, and 15,000 mg/l and influent COD concentrations of 2,000, 4,000, 6,000, and 8,000 mg/l, while HRT was kept at an almost constant value (10–11 d). Chronologically, the investigation was conducted at MLSS values of 10,000, 15,000, and 5,000 mg/l, however, the results will be presented in terms of increasing MLSS values (5,000, 10,000, and 15,000 mg/l). Fig. 2 shows variations of permeate flux, HRT, and membrane suction pressure with respect to investigation time. The transition phase shown refers to the time taken by the anaerobic bioreactor to increase the MLSS value from 10,000 to 15,000 mg/l. However, this phase is not shown between MLSS values of 5,000 and 10,000 mg/l since the former MLSS value (5,000 mg/l) was investigated right after the 15,000 mg/l of MLSS. Fig. 2 clearly shows that permeate flux values insignificantly varied between 2.07 and 2.29 l/m^2 h, with average values of 2.20, 2.22, and 2.18 l/m^2 h for MLSS concentrations of 5,000, 10,000, and 15,000 mg/l, respectively. These values are relatively low, however, values between 1.8 l/m^2 h and to more than 100 l/m^2 h were reported in the literature, which clearly indicates that investigated flux values were within those reported in the published literature [19]. It is worth to mention that flux values were selected in order to minimize membrane fouling. However, flux stability resulted in producing an almost constant HRT (10–11 d) as shown in the figure. In the published literature, HRT values from 2 h to 60 d were reported [20]. The published literature clearly showed that by increasing MLSS values, production of soluble microbial products (SMPs) would increase which results in higher fouling rates of membranes [21]. Moreover, at higher SRTs, extracellular polymeric compounds (EPS) are not high enough to promote particle flocculation and, therefore, membranes become more vulnerable to fouling. Wang et al. reported that sludge concentration had no obvious correlations with membrane fouling rate,

Table 3
Experimental design

Stages	Days											
	Stage I				Stage II				Stage III			
	1–6	7–11	12–16	17–22	30–35	36–40	41–45	46–50	51–55	56–60	61–66	67–72
MLSS (mg/l)	5,000				10,000				15,000			
COD (mg/l)	2000	4,000	6,000	8,000	2000	4,000	6,000	8,000	2000	4,000	6,000	8,000
Flux (l/m^2 h)	2.07–2.3											
HRT (d)	10–11											

Table 4
Standard analytical procedure

Parameter	Method	Equipment	Frequency
pH	Potentiometric—SM-4500H+B	JENWAY 924005 pH-meter	Daily
Turbidity	Nephelometric—SM-2130B	HACH 2100AN Turbidimeter	Daily
COD	Closed Reflux—SM-5220C	HACH COD reactor	Daily
Phosphate	Vanadomolybdophosphoric Acid Colorimetric Method—SM-4500PC	JENWAY 6300 Spectrophotometer	Daily
TSS	Gravimetric—SM-2540D	–	Twice a day
Biogas yield	Water displacement		Daily
CH_4 content	EPA—8015	Agilent Technologies GC—6890N	3–4 times per stage

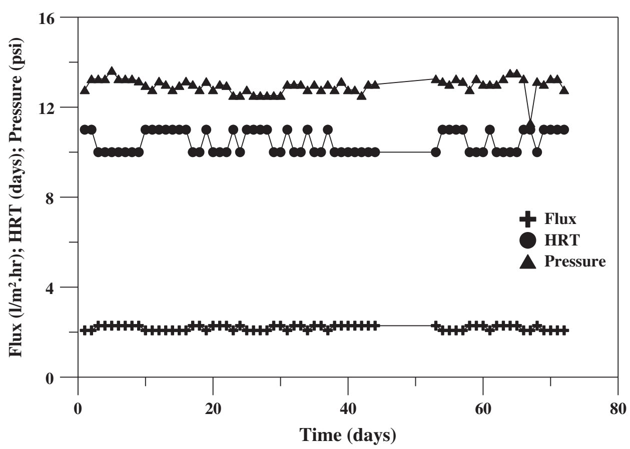

Fig. 2. Variations of permeate flux, HRT, and TMP. vs. time.

while EPS, EPSc (carbohydrates), and EPSp (proteins) were found to have clear correlations with membrane fouling [22]. Moreover, EPSp was reported to play an important role in fouling of membrane modules of MBRs. This is attributed to the fact that EPSp are hydrophobic in nature, while EPSc are more hydrophilic. It is worth mentioning that SMPs are produced across a wide range of molecular weights (MWs) (from less than 0.5 kDa to more than 50 kDa). Moreover, molecular weight distributions were reported to be significantly affected by the operating conditions, where higher molecular weight compounds were found to present at higher sludge retention times (SRTs) (more than 15 d for anaerobic systems) [23]. SMPs were reported to exhibit mono-dispersed distribution of size ranging from 100 to 200 nm, while soluble EPSs have bi-dispersed distributions (200–400 nm and 700–2,000 nm). Hence, the size of soluble EPSs was reported to be larger than that of SMPs. Since the membrane module used in the current investigation was made of hydrophilic polyvinylidene fluoride (PVDF), membrane fouling results could indicate that EPSp compounds, which are hydrophobic in nature, were the dominant type of EPS presented in the bioreactor.

It is very well documented that membranes are operated at either constant-flux or constant-pressure mode. In the current investigation, the process was operated at constant-flux mode and, therefore, suction pressure was left to increase. Fig. 2 shows that suction pressure varied between 12.77 and 13.63, 12.52 and 13.14, and 11.30 and 13.51 psi for MLSS concentrations of 5,000, 10,000, and 15,000 mg/l, respectively. The pressure drop on day 67 was due to rupture of pump tubing. It is worth to mention that pressure values between 0.1 and 15 psi were reported in the published literature for tubular membranes [24].

Membrane pressure and permeate turbidity are strictly linked to membrane fouling, therefore, membrane fouling is responsible for the increase in TMP values that could result in decreasing the permeate turbidity due to the formation of cake layer at the beginning of the treatment period. Fig. 3 shows that permeate turbidity fluctuated between 12 and 26 NTU (with an average value of 21 NTU), for an MLSS concentration of 10,000 mg/l. For an MLSS of 15,000 mg/l, the permeate turbidity was found to have an average value of 15 NTU. Moreover, permeate turbidity was found to increase with the increase in the influent COD. This could be attributed to the fact that in order to prepare a synthetic dairy wastewater with higher COD values, more powder milk was used, which resulted in increasing the number of particulates presented in the synthetic dairy wastewater that increased the membrane vulnerability to fouling. However, at an MLSS concentration of 10,000 mg/l, permeate turbidity was not found to increase with the increase in the influent COD values. At an MLSS concentration of 5,000 mg/l, the permeate turbidity was found to fluctuate between 20 and 159 NTU with an average value of 49 NTU. The maximum permeate turbidity obtained on the second day of the investigation resulted in fouling of the membrane, however, after chemical cleaning with nitric acid, the permeate turbidity was found to decrease to stable values. Furthermore, the figure shows that permeate turbidity was decreasing with the increase in the anaerobic bioreactor MLSS concentrations. Saddoud et al. who investigated treatment of cheese whey reported an average permeate turbidity of 14.5 NTU [25]. However, values between 2 and 226 NTU were reported

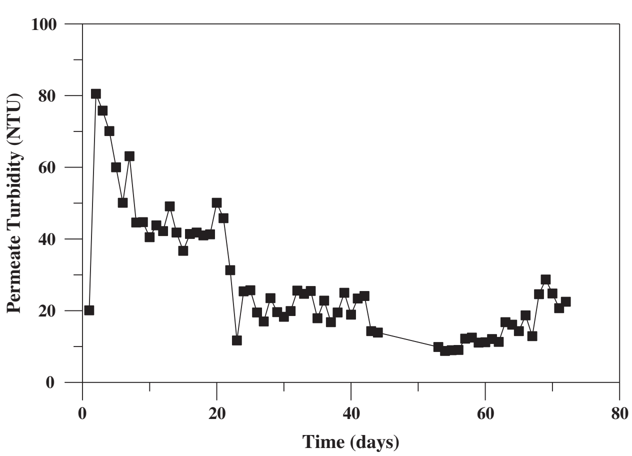

Fig. 3. Variations of permeate turbidity vs. time.

by Mota et al. who treated sugarcane vinasse using a two-phase anaerobic system coupled with a filtration unit [26]. Analysis of permeate samples showed that the permeate turbidity was produced by the presence of micro-colloidal compounds having particle sizes in the range of 0.01–0.03 μm, which explains the reasons for obtaining high turbidity values during the first stage of the investigation (MLSS of 5,000 mg/l). As mentioned before, Barker and Stuckey reported that SMPs are produced in very wide ranges of molecular weights and molecular weight distributions, which were significantly affected by operating parameters [23]. The figure clearly indicates that higher permeate turbidity values were obtained at higher SRTs. Moreover, turbidity of the synthetic dairy wastewater, used throughout the investigation, was more than 1,500 NTU, therefore, the removal efficiency was more than 95 percent for the first stage (MLSS value of 5,000 mg/l) and above 99 percent for the last two stages (MLSS values of 10,000 and 15,000 mg/l).

3.2. COD removal

To assess the performance of the AnIMBR when treating synthetic dairy wastewater, both COD removal efficiency and biogas production were evaluated at different combinations of organic loading rates (OLRs) and MLSS concentrations. As mentioned earlier, the investigation was carried out at MLSS values of 5,000, 10,000, and 15,000 mg/l and influent COD concentrations of 2,000, 4,000, 6,000, and 8,000 mg/l. Fig. 4 shows influent and effluent COD values throughout the investigation duration. The figure clearly demonstrates that effluent COD was increasing with increasing OLR (influent COD) during all stages of the investigation. Moreover, effluent COD was found to stabilize during all combinations of the investigation. The figure clearly demonstrates that effluent (permeate) COD concentrations were between 230 and 5,020 mg/l. Sharp increases in permeate COD values are attributed to sudden increases in influent COD concentrations, which was taking place at times of changing influent COD concentrations (OLRs). The figure clearly shows that at initial stages of increasing OLRs, permeate COD concentrations were increasing due to the incapability of micro-organisms to instantaneously cope with sudden increases in influent COD concentrations (OLRs). However, after sometime, the permeate COD concentrations were found to decrease and reach stable values (steady-state conditions). It is very well documented that temperatures of bioreactors influence COD removal efficiencies and improve methanogenesis, where higher temperatures were reported to yield better results [27]. Moreover,

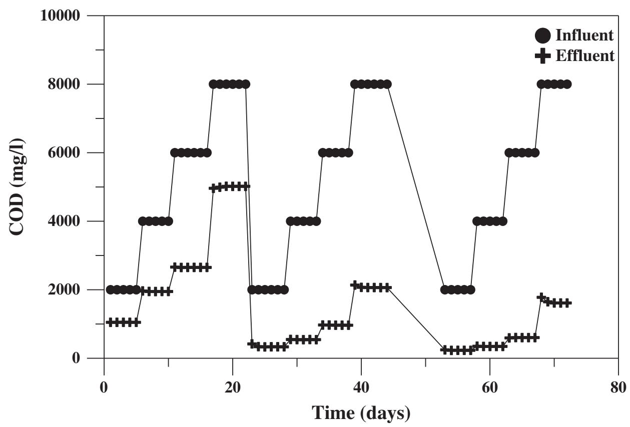

Fig. 4. Variations of influent and effluent COD concentrations vs. time.

working at thermophilic temperatures, the AnMBRs could be operated at higher OLRs than mesophilic. Therefore, at higher OLRs, COD removal efficiency is negatively affected due to reduced microbial activities at lower temperatures. Furthermore, volatile fatty acids (VFAs) may accumulate that will result in deteriorating the process performance [28]. On the other hand, with respect to removal efficiencies of COD for all combinations of MLSS and OLR, the results showed that at an MLSS concentration of 5,000 mg/l, COD removal efficiencies were in the range of 47.5–55.8 percent for influent COD values of 2,000, 4,000, and 6,000 mg/l. However, when influent COD was increased to 8,000 mg/l, the COD removal efficiency was found to decrease to 37.3 percent. When the MLSS concentration was increased to 10,000 mg/l, the results showed that average COD removal efficiencies were 83.2, 86.4, and 83.9 percent for influent COD values of 2,000, 4,000, and 6,000 mg/l, respectively. However, when the influent COD was increased to 8,000 mg/l, the COD removal efficiency decreased to an average value of 74.2 percent. When the bioreactor MLSS concentration was further increased to 15,000 mg/l, the results showed a COD removal efficiency trend that is similar to that obtained with an MLSS of 10,000 mg/l. At this stage of MLSS, COD removal efficiencies ranged between 88.4 and 91.4 percent for the first three influent COD values (2,000, 4,000, and 6,000 mg/l) and when the influent COD value was further increased to 8,000 mg/l, the COD removal efficiency was found to drop to 79.8 percent. The results clearly showed that COD removal efficiencies of the anaerobic membrane bioreactor were ranging between 37 and 91 percent. Variations of COD removal efficiency throughout the investigation period can be attributed to the same reasons given above. In the published literature, COD removal efficiencies were reported to vary between 76 and 99 percent [29]. Zwain et. al. who investigated the use of anaerobic baffled reactor (MABR) for the treatment of recycled paper mill wastewater reported a maximum COD removal efficiency of 71 percent, which indicates the agreement of the results of the current investigation with those reported in the published literature [30].

3.3. Biogas production

Fig. 5 shows the biogas production in liters per day and the cumulative biogas production in liters for the different combinations of MLSS and influent COD values. Generally, the figure shows that gas daily production was increasing with the increase in influent COD concentrations. As an example, at an MLSS of 5,000 mg/l, the biogas daily production was found to range between 0.35 and 0.4 L, 0.6 and 0.75 L, 1.05 and 1.15 L, and 1.5 and 1,6 L for influent COD concentrations of 2,000, 4,000, 6,000, and 8,000 mg/l, respectively. Moreover, the figure shows that the cumulative biogas production was also increasing with increasing MLSS concentrations, where 21.3, 30.3, and 35.6 liters were produced at MLSS values of 5,000, 10,000, and 15,000 mg/l, respectively. This is attributed to the fact that by increasing either the OLR (substrate) or MLSS (biomass), anaerobic assimilation of available organic matter (COD) will increase and, consequently, production of biogas will increase due to the consumption of available substrate. It is worth mentioning that the decrease in biogas daily production at an MLSS value of 10,000 mg/l and influent COD value of 8,000 mg/l was due to a leakage in the gas collection system that was detected and sealed. Generally, the obtained results are in total agreement with those reported in the published literature [31]. Fig. 6 shows the biogas yield expressed in liters per gram of removed COD (l/g COD_r). At an MLSS value of 5,000 mg/l, the figure clearly shows that the maximum biogas yield was varying between 0.066 and 0.104 l/g COD_r with an average value of 0.088 l/g COD_r. It is worth mentioning that the maximum biogas yield (0.104 l/g COD_r) was produced at an influent COD of 8,000 mg/l. When the biogas was collected and analyzed, concentrations of methane (CH_4) were found to vary between 16 and 24 percent. When the MLSS was increased to 10,000 mg/l, a maximum biogas yield of 0.17 l/g COD_r was obtained at an influent COD of 2,000 mg/l. Methane concentration found to be about 29 percent of the collected biogas during this stage of the investigation. However, when the value of the MLSS was further increased to 15,000 mg/l, a maximum biogas

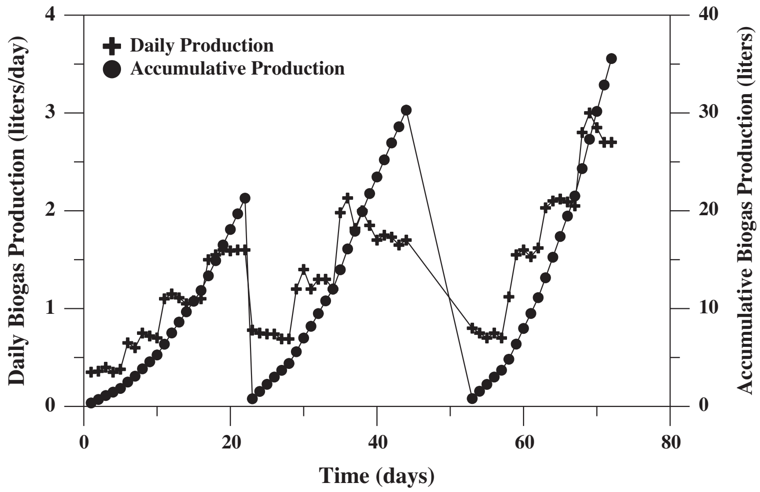

Fig. 5. Daily and cumulative production of biogas vs. time.

yield of 0.18 l/g COD_r was produced at influent COD values of 4,000 and 6,000 mg/l. Chemical analysis of the collected biogas revealed that methane concentration varied between 62 to 82 percent. In the published literature, methane yield and concentration were reported between 0.003 and 0.33 l/g COD_r and 55 and 90 percent, respectively [30,32]. It is very clear that the reported methane yield is lower than the theoretical yield (0.382 l/g COD_r), which could be attributed to methane solubility [33]. Methane solubility is highly dependent on operational temperatures and inhibitors associated with anaerobic processes such as organics, sulfide, ammonia, light and heavy metal ions. Solubility of methane is around 1.5 times higher at 15˚C than that at 35˚C for a 70 percent methane-containing biogas.

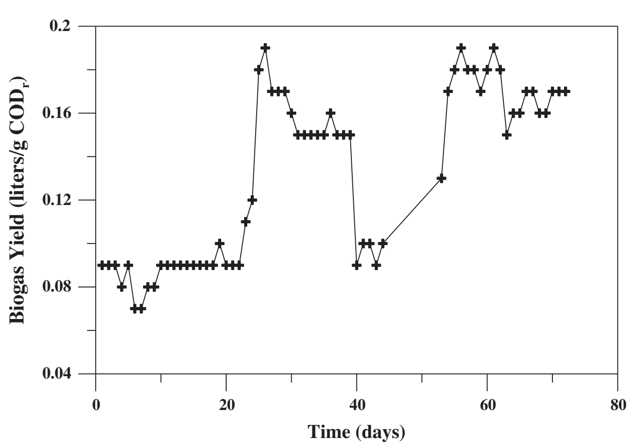

Fig. 6. Variations of biogas yield vs. time.

Fig. 7 shows the effect of MLSS and influent COD values on the daily production of biogas. The figure clearly indicates that biogas production was increasing with the increase in MLSS values, at fixed values of influent COD values. Moreover, the figure also shows that daily biogas production was increasing with increase in influent COD values, at fixed MLSS values. For example, at an MLSS value of 5,000 mg/l, biogas daily production rates were 0.37, 0.72, 1.1, and 1.6 l/d for influent COD values of 2,000, 4,000, 6,000, and 8,000 mg/l, respectively. On the other hand, at an influent COD of 4,000 mg/l, biogas daily production rates were 0.72, 1.27, and 1.58 l/d for MLSS values of 5,000, 10,000, and 15,000 mg/l, respectively. These results have already been justified and supported by results from the published literature. It is worth noticing that at an MLSS of 10,000 mg/l and an influent COD of 8,000 mg/l, biogas daily production was found to be less than expected, which was attributed to gas-leakage in the gas-collection system that was detected and sealed. If that point was ignored, the relationship between biogas daily production and MLSS was found to be in the form of:

$$\text{Biogas daily production}\left(\frac{\text{l}}{\text{d}}\right) = A \times \text{MLSS}\left(\frac{\text{mg}}{\text{l}}\right) \quad (R^2 = 0.96-0.99) \tag{1}$$

where A is a constant that is a function of influent COD. Constant A was found to be:

$$A = 2.6 \times 10^{-8} \times (\text{COD}_\text{i}) \quad (R^2 = 0.99) \tag{2}$$

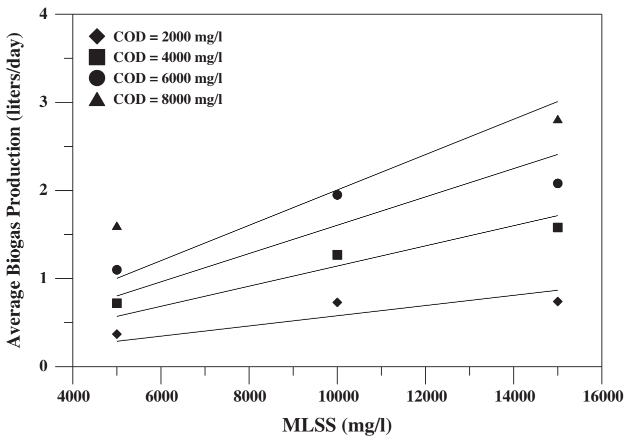

Fig. 7. Effects of MLSS and influent COD concentrations on biogas production.

where COD_i is the influent COD, therefore, Eq. (1) becomes:

$$\text{Biogas production}\left(\frac{l}{d}\right) = 2.6 \times 10^{-8} \times COD_i\left(\frac{mg}{l}\right) \times MLSS\left(\frac{mg}{l}\right) \quad (3)$$

3.4. SRT and sludge production

As stated earlier, to maintain stable conditions within the AnIMBR process, proper care was taken in order to keep MLSS concentrations at constant values. Since the membrane bioreactor was performed in anaerobic conditions, cell growth is expected to be slow, however, the need to waste part of the sludge was almost a daily task. SRT is one of the important parameters that is used to control the growth rate of biomass (sludge). Fig. 8 shows fluctuations of SRT at different MLSS concentrations throughout the investigation. The figure shows that SRT varied between 60 and 500 d during the investigation period. Values of SRT vary widely from as low as 20 to 300 d or even infinite, which indicates that there is no sludge wastage. Moreover, the figure clearly indicates that SRT was affected by MLSS and OLR (influent COD) values [34].

Sludge production rate or biomass growth rate expressed in $\Delta VSS/\Delta COD$ (mg/mg) is another way of determining growth rates of micro-organisms. The results showed that sludge production was ranging between 0.007 and 0.056 mg VSS per mg COD with an average value of 0.022 mg VSS per mg COD. It is worth to mention that conventional activated sludge processes treating domestic wastewater produce 0.20–0.50 mg VSS per mg COD, with a typical value of 0.40 mg VSS per mg COD [35]. Moreover, Al-Malack who investigated the performance of aerobic immersed membrane bioreactor reported sludge production rate values between 0.00 and 0.48 mg VSS per mg COD with an average value of 0.26 mg VSS per mg COD [36]. Results obtained during the current investigation are in line with the general principles of anaerobic wastewater treatment processes where sludge production is relatively low. Furthermore, results of the current investigation are in agreement with values reported in the published literature, where sludge production rate values between 0.02 and 0.1 mg VSS per mg COD were reported [37]. With respect to the effect of MLSS concentration on sludge production rates, the results showed an increasing trend of sludge production rates with the increase in MLSS concentrations. At the first two stages of the investigation (MLSS of 5,000 and 10,000 mg/l), sludge production rates were between 0.14 and 0.2 mg VSS per mg COD removed. This can be attributed to the fact that micro-organisms were able to reproduce freely while consuming the nutrients in the feed and reducing COD values. It is believed that higher substrate and nutrients concentrations in the feed result in higher growth of biomass, which is true to some extents. When MLSS concentrations are increased, free spacings between micro-organisms can be reduced and, therefore, easy access to nutrients and substrate is affected that may lead to a non-linear relation between weight of sludge produced and weight of COD removed or consumed. This could be exactly what happened when MLSS concentration was raised to 15,000 mg/l, where higher sludge production rates were obtained, when compared to those obtained at MLSS concentrations of 5,000 and 10,000 mg/l. This can be attributed to the complexity of interactions that are taking place in bioreactors with mixed-cultures.

Effects of SRT and OLR values on sludge production rates are shown in Fig. 9. The figure clearly shows that sludge production rates were found to decrease with increasing SRT and OLR values. Logically, an increase in the OLR (available substrate) should result in an increase in the sludge production rate, however, this phenomenon was not observed in the current investigation. This could be attributed to inhibition effects on micro-organisms due to higher concentrations of available substrate in the feed. Generally, at higher ORL values, COD removal efficiencies are negatively affected due to reduction in microbial activities, which are affected by the accumulation of VFAs that result in deteriorating the process performance [28]. On the other hand, higher SRT values are

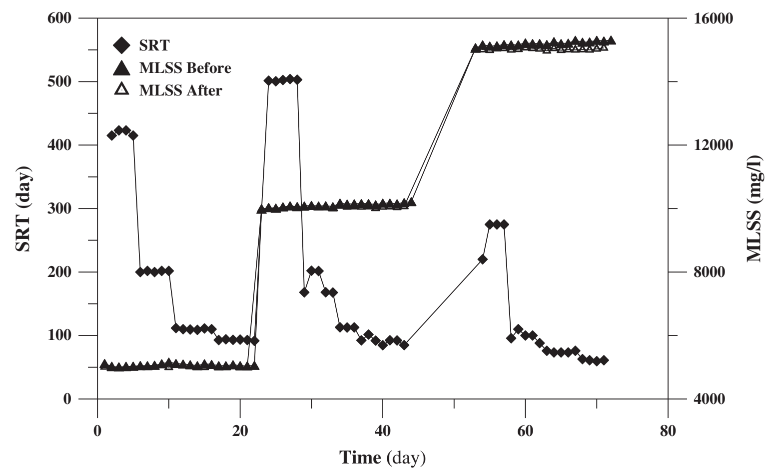

Fig. 8. SRT and MLSS before and after wasting vs. time.

expected to produce less sludge due to the presence of relatively old micro-organisms that have relatively lower growth rates. Moreover, old micro-organisms occupy interstices between new micro-organisms that results in preventing them from having an easy access to available nutrients and substrate. The results are in agreement with those reported by Al-Malack [36].

3.5. Phosphate removal

To further assess the performance of the AnIMBR, phosphate removal efficiency was investigated. Phosphate concentrations in samples collected from the bioreactor and effluent were monitored throughout the investigation period. The results showed that phosphate removal efficiency varied between 77 and 85 percent at an MLSS concentration of 5,000 mg/l. At an MLSS concentration of 10,000 mg/l, the removal efficiency of phosphate was between 70 and 80 percent. Moreover, maximum removal efficiencies were about 76, 72, 76, and 86 percent at influent COD values of 2,000, 4,000, 6,000, and 8,000 mg/l, respectively, which indicate an almost stable removal efficiency at this stage of MLSS. At an MLSS concentration of 15,000 mg/l, phosphate removal efficiency was found to vary throughout this stage of the investigation, where removal efficiencies between 52 and 82 percent were obtained. Phosphate removal can be attributed to the fact that in anaerobic bioreactors, production of low molecular weight fermentation products, such as VFAs, serves as substrates to specialized micro-organisms that have the capability to store and accumulate large quantities of phosphates such as *Acinetobacter* spp., particularly the strain *L. woffii*. Theses micro-organisms are known as phosphate-accumulating organisms (PAOs). Another reason is chemical precipitation of calcium phosphate that can take place under anaerobic conditions at pH values greater than 7. Since pH values were kept between 6.8 and 7.2 throughout the investigation, it is believed that phosphates were predominantly removed by the former mechanism. Phosphate removal efficiencies obtained throughout the current investigation were within those reported in recent published literature, where phosphate removals efficiencies of 35–94 percent were reported [38].

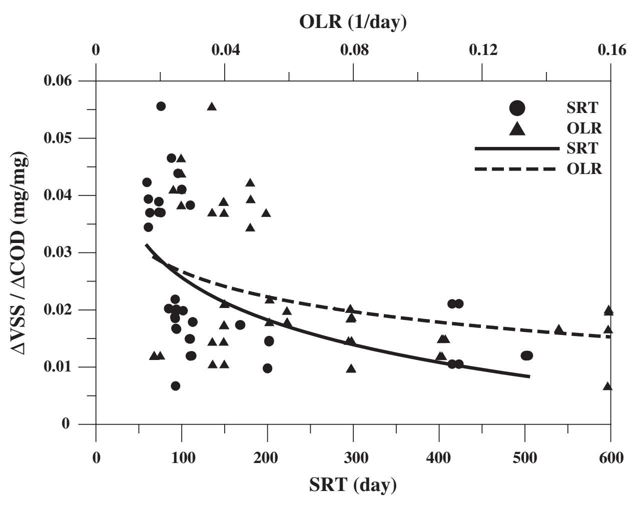

Fig. 9. Effects of MLSS and OLR on sludge production.

4. Conclusions

The effect of MLSS and influent COD on the performance of an AnIMBR when treating synthetic dairy wastewater was investigated. The investigation was performed at low permeate flux values and two backwashing cycles per day. The investigation showed that permeate turbidity was found to decrease with time except in the last two stages of the investigation when turbidity was found to increase slightly. Moreover, the results showed that effluent COD concentrations were decreasing with the increase in MLSS concentrations and increasing with the increase in influent COD values. Furthermore, cumulative biogas production was found to increase with increase in MLSS concentrations. Sludge production, which was affected by OLR and SRT values, was found to be less than that produced by aerobic processes.

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