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Digestion of linoleic acid using an anaerobic fluidized bed reactor

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ABSTRACT

Edible oil industries generate wastewater consists of long-chain fatty acids (LCFA), such as linoleic acid, which causes inhibition during anaerobic digestion. In the current study, the performance of a laboratory-scale anaerobic fluidized bed reactor (AFBR) was investigated for the treatment of linoleic acid under anaerobic digestion. The AFBR was fabricated with a plexi glass column (60 mm diameter, 160 cm height, and volume of 2.95 L). The amount of biomass was increased within the AFBR using polyvinyl chloride (PVC) chips as a carrier medium. During the start-up, the AFBR was operated at hydraulic retention time (HRT) of 24 h, OLR = 0.50 g/L/d, flowrate 5 L/d, and an up-flow velocity of 9×10^{-4} m/min. The chemical oxygen demand (COD) values were decreased up to 76 mg/L, with a removal efficiency of 65.4%. However, the optimized conditions were achieved during the operational period when the influent flowrate was set at 15 L/d, and HRT was set at 6 h, corresponding up-flow velocity of 4.4×10^{-3} m/min and organic loading rate of 1.13 g/L/d. The values of COD were reduced up to 51.5 ± 1 mg/L. Consequently, the reactor efficiency was increased from 65.4% to 82.6% in terms of COD removal. Moreover, different linoleic acid concentrations were spiked in the AFBR (i.e., 100, 150, 200, and 250 mg/L) during the optimized condition and the linoleic acid removal was observed up to 91.2%. Therefore, the AFBR with utilized biomass media (PVC chips) seems to have the promising potential of the high strength wastewater treatment by the degradation of LCFA and the reduction of organic pollutants.

Keywords: Linoleic acid; Anaerobic fluidized bed reactor; Edible oil wastewater

1. Introduction

Long-chain fatty acid (LCFA) accumulation in sludge is a major cause of hindrance in anaerobic treatment systems [1–5]. LCFA cause inhibition to acetoclastic methanogenesis even at low concentrations. Consequently, methane production decreases in a continuous bioreactor [1,4–10]. The impediment of lipid break-down is majorly caused by LCFA [11,12]. The adsorption of LCFA onto sludge limits substrate transfer within reactors and escalates other operational problems such as sludge floatation and washout [13,14]. Moreover, LCFA in wastewater can cause blockage in pipelines and sewers [15]. These issues can be managed by the degradation of LCFA [4,5].

Anaerobic fluidized bed reactors (AFBRs) is one of several techniques used to treat LCFA present in wastewater. AFBR effectively handles high organic loading rates (OLRs) at lower hydraulic retention times (HRTs) [16,17], provides a large surface area for microbial biomass attachment and retention [18–21], and overcomes clogging and short-circuiting [22]. It has good mass transfer capability and can treat high-strength wastewater [19,22]. The AFBR can

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typically remove at least 65% and up to 90% of chemical oxygen demand (COD) in wastewater treatment [21,23–25].

Among various LCFA, linoleic acid is present in the composition of different edible oils such as sunflower, soybean, mustard, palm, and coconut [26]. Maize oil is one of the edible oils, which consists of 56% linoleic acid, which makes it a vital component of maize oil [27,28]. The linoleic acid has two double bonds and 18 carbon chain [29,30]. An earlier study has reported that linoleic acid could inhibit acetoclastic methanogenesis completely, even at a concentration of 30 mg/L [1]. Although AFBR has been used to treat industrial and edible oil wastewaters, the degradability of LCFAs, such as linoleic acid, has been found low. For instance, although higher COD removal was observed when AFBR was used for the treatment of edible oil effluents, such as palm oil mill [23] and terephthalic acid, the applied OLR was low at relatively higher HRT values. The biomass carrier used in previous studies was also cost-intensive. We premise that the degradation of LCFAs can be enhanced in an AFBR by adding inexpensive polyvinyl chloride (PVC) chips as bio-carrier. In the current study, an inexpensive waste material (PVC chips) was utilized as biomass carrier media.

Moreover, the AFBR was operated at higher OLR, along with at a low value of HRT. This study aimed to investigate the feasibility of AFBR for edible oil wastewater treatment. We investigated a lab-scale AFBR operated at two different HRTs (24 and 6 h) and two different OLRs (0.50 and 1.13 g COD/L/d). Also, linoleic acid was spiked into the AFBR at optimized conditions to observe its degradation.

2. Materials and methods

2.1. Reactor configuration, start-up, and operation

A plexi glass column was used to fabricate the reactor of 60 mm diameter, 160 cm height, and a volume of 2.95 L, as shown in (Fig. 1). A gas–solid separator was attached at the top of the reactor to collect the biogas, having a volume of 1.48 L. The column of the reactor comprised six sampling ports. Influent and effluent pumps were used to feed the reactor and collect the discharge, respectively. The recycling pump was attached to the uppermost point to recycle the flow. The column of the reactor was filled with 1.5 kg of plastic bottle chips diameter of 1.5–2 mm was used as biofilm material. After the start-up, the reactor was operated at various OLRs, HRT's, up-flow velocity, and flowrates to obtain the optimized condition of the reactor. The start-up and operational phase of the reactor continued for 110 d and was divided into three phases. Phase one is also called the start-up phase of the reactor. In phase one, the acclimatization of microorganisms took place. The reactor was operated at HRT of 24 h at a flowrate of 5 L/d with an up-flow velocity of 0.0009 m/min and OLR = 0.50 g/L/d. This stage continued for 2 months. In phase (operational phase), linoleic acid was added in the feed for 1 month.

During phase two, the reactor was operated at a flowrate of 15 L/s, OLR 1.13 g/L/d, HRT 6 h, and up-flow velocity 0.0044 m/min to achieve the optimized conditions. In phase three, the reactor was continued to operate for 15 d without spiking of linoleic acid, at HRT of 6 h, (OLR) of 1.13 g/L/d, and up-flow velocity of 0.0044 m/min (at a flowrate of 15 L/s) to monitor the reactor performance.

The reactor was inoculated with the sludge obtained from anaerobic digester located in Khaskheli village, Hyderabad, Pakistan. The reactor was filled with 2,000 mL of sludge with mixed liquor suspended solid 5.8 g/L. The reactor was operated with synthetic feed. The synthetic feed for 1 L was prepared by using following chemicals: sodium acetate (CH_3COONa); 280 mg/L, glucose ($C_6H_{12}O_6$); 70 mg/L, yeast 20 mg/L, calcium chloride ($CaCl_2$); 50 mg/L, manganese sulfate ($MnSO_4$); 50 mg/L, magnesium sulfate ($MgSO_4$); 50 mg/L, ferric chloride ($FeCl_3$); 50 mg/L, sodium hydrogen carbonate ($NaHCO_3$); 600 mg/L, ammonium sulfate ($(NH_4)_2SO_4$); 200 mg/L, T buffer; 264 mg/L, micronutrients; 125 mg/L. These chemicals were used for the ideal growth of microorganisms in the biofilm. All chemicals were purchased from Daejung Chemicals and Metals Co., (Shiheung, Korea). The synthetic feed was fed to the reactor every day. After a 2-month start-up period, the operational phase continued for another 45 d (1.5 months). During this, the linoleic acid was injected for one month in the synthetic feed. The operational parameters are tabulated in Table 1.

The COD of the injected synthetic feed was maintained to be 300 mg/L regardless of flowrate for the start-up period and operational period. The total influent COD of the synthetic feed was made up of 35% of glucose and 75% of sodium acetate to support the growth of microorganisms. During the operational period, four various concentrations, that is, 100, 150, 200, and 250 mg/L of linoleic acid, were injected into the reactor. The reactor was run for 25 d along with various linoleic acid concentrations. The linoleic acid in a sample of the effluent was separated by solvent extraction technique and derivatized (processed) to be analyzed in gas-chromatograph (GC).

2.2. Analytical methods

COD, total suspended solids (TSS), volatile suspended solids (VSS), and biochemical oxygen demand (BOD) were tested according to the standard methods (APHA 1998). pH was measured by a pH meter (model no: PH-8414). COD test was conducted daily for the filtered and unfiltered sample treated by the reactor. The samples were taken out from the bottom and top ports of the reactor every day to analyze the COD of the filtered sample. The sample was passed through the filter to separate the particulates from the sample, and the impurities were removed. The analysis of COD was conducted by the closed reflux colorimetric method (5220 D). The COD vials were placed in the digester at 150°C for 2 h. After heating, the samples were allowed to cool down at room temperature. The COD in the sample was measured with the help of a spectrophotometer. To measure TSS/VSS

Table 1
Operational conditions during start-up and operational phase

Parameters	Start-up	Operational phase
HRT	24 h	6 h
OLR	0.50 g/L d	1.13 g/L d
Flowrate	5 L/d	15 L/d
Up-flow velocity	9×10^{-4} m/min	4.4×10^{-3} m/min

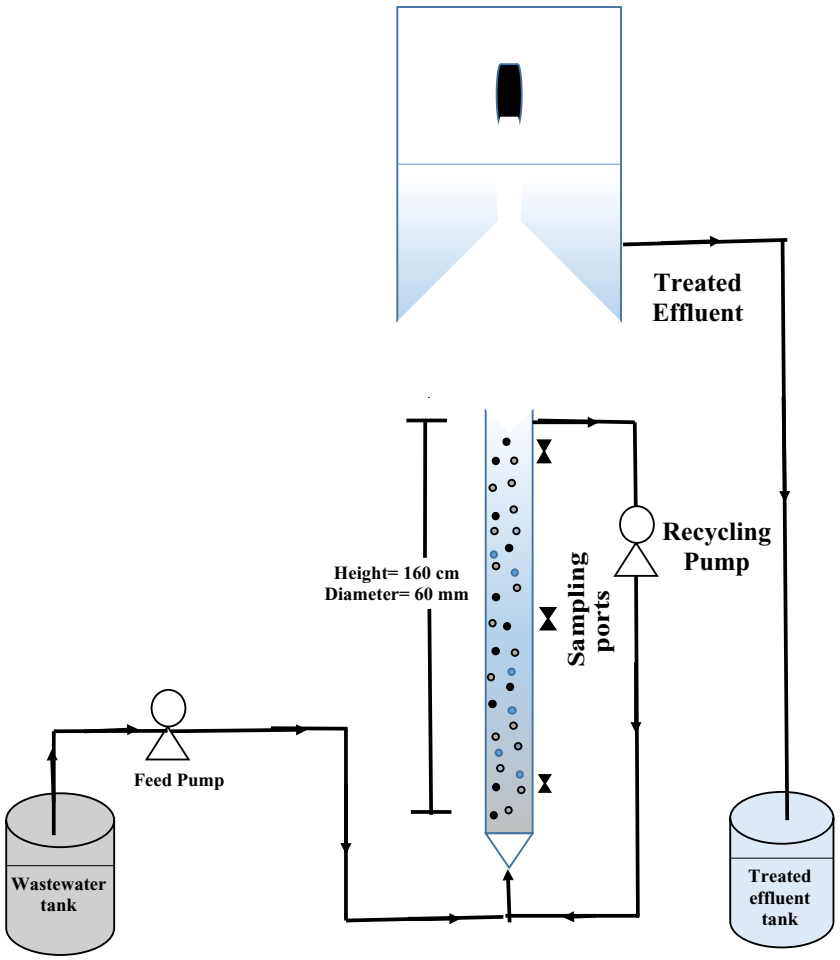

Fig. 1. Schematic diagram of anaerobic fluidized bed reactor.

inside the rector from start-up and onwards, samples were collected from the sampling ports of reactor divided into two sections, that is, port 1 (bottom) and port 2 (top). The analysis of TSS was performed by the gravimetric method (2540 D). The samples were filtered through filter paper and were transferred in the drying oven at 105°C for 1 h. The dried sample was transferred to the desiccator to cool down at room temperature and weighed on the analytical balance. The VSS values were measured by subjecting the residue obtained during TSS analysis (2540 D) to ignition at a constant temperature of 550°C. The remaining solids represent the fixed total, dissolved, or suspended solids, while the weight loss on ignition is the volatile solids. The residue was ignited in a muffle furnace at a temperature of 550°C for 15–20 min (2540 E). The BOD analysis was conducted at the 5 d BOD test (5210 B). The dissolved oxygen (DO) concentrations were measured in a BOD bottle filled with sample and seeded dilution water before and after the incubation period. The DO was measured by using multi 9630 IDS (Water Treatment Works) meter.

To analyze the linoleic acid by GC, the sample preparation was carried out by using the liquid–liquid extraction technique. The wastewater sample from the reactor was shaken, mixed dichloromethane for 10 min in a separator funnel, and kept steady for a half-hour to separate the organic layer (repeated twice). The clear part of the settled organic layer was separated in a dry beaker and further dried using anhydrous magnesium sulfate. A filter paper (Whatman 125 mm) was used to filter out the extract and heated on a hot plate to concentrate the filtrate. Now, the sample volume of 1 μL was taken to be injected in GC [31]. The analysis of LCFA in treated wastewater samples was analyzed by gas chromatography (GC) incorporated with SHIMADZU GC-2010 (Tokyo, Japan) chromatograph and attached with flame ionization detector (FID) at 250°C, injector at 250°C and a 30 m, 0.25 mm internal diameter SHIMADZU (Tokyo, Japan) column. Nitrogen was used as carrier gas at a flowrate of 5 mL/min., with oven temperature 90°C for 0.5 min, with a 20°C per min ramp to 180°C and a final hold at 180°C for 9 min [1].

3. Results and discussion

3.1. Treatment performance in the AFBR reactor

The AFBR had a start-up period of 2 months and an operational period of 3 months. The injected COD was maintained to be 297.6 ± 6 mg/L. The COD was gradually reduced from 297.6 ± 6 to 76 ± 3 mg/L with

a reactor efficiency of 65.4% ± 12% at HRT of 24 h, an OLR = 0.50 g/L/d, flowrate 5 L/d, and the up-flow velocity of 0.0009 m/min, respectively. During operational period, the flowrate was increased from 5 to 15 L/d along with HRT of 6 h, the up-flow velocity of 0.0044 m/min and OLR of 1.13 g/L/d; the COD was reduced up to 51.5 ± 1 mg/L along with a reactor efficiency of 82.6% ± 1%. Thus, the performance of the reactor was step-wise enhanced. The COD removal is supposed to occur due to the optimized conditions and proper time given to microorganisms to nurture at optimized reactor operations.

The pH of the influent and effluent is illustrated in Fig. 2. The pH of the influent is maintained to be in the range of 7.6 ± 0.1 during the start-up and operational period. The pH of the effluent was found to be in the range of 8.5–8.7. Thus, significant variations of pH have not been found during the operational phase. In this study, the pH was not affected by the addition of linoleic acid. It is essential to stabilize the pH of both influent and effluent; to have optimized conditions for microorganisms, particularly methanogens, as the formation of methane is impossible below a pH of 4.5 [32].

In this study, sodium bicarbonate was used in synthetic feed to stabilize the pH. The effect of pH was mainly influenced by the quantity of two chemicals used to make feed, that is, sodium hydrogen carbonate and ammonium sulfate. One of the stages of the anaerobic process includes acetogenesis, which is responsible for decreasing the pH inside the reactor. With the optimized amount of sodium hydrogen carbonate and ammonium sulfate, the pH of the effluent was maintained. It was necessary to maintain pH in the spectrum of 7–9 for both influent and effluent for the anaerobic process. The pH was maintained within a range of 7.4–7.7 during the operational period of the anaerobic reactor for the treatment of LCFA [33]. Whereas in a previous study, the anaerobic acidogenisis was maintained in a specific pH range 6–8 [34]. The pH 6.0–6.5 produces impedimental environment on LCFA to be decomposed by microorganisms [35].

3.2. Biomass concentration

The concentration of TSS and VSS represent biomass activity inside the reactor. VSS/TSS ratio plays a significant role in sludge characteristics determination, whether the suspended solids present in the wastewater can be digested completely under anaerobic conditions or not. The TSS/VSS was monitored from the start-up period and onwards. It was intended to keep the sludge in suspension by running the reactor at sufficient flowrates before the start-up period. The biomass concentration is illustrated in Fig. 3. The TSS and VSS values in the column were found to be in the range of 17,354 ± 125 and 5,784 ± 91 mg/L, respectively. A gradual decline in TSS is observed because a thick layer of sludge covered the plastic particles used as biofilm media, that is, 15.33 mg/L TSS was found on 200 g of plastic media and 0.1 mg/L in suspension.

The solids inside the column always circulated in fluidized motion. Moreover, as a result of the increased up-flow velocity from the start-up and operational period, the average biomass was decreased. Due to the increase in up-flow velocity, the bed porosity increased, which resulted in a lower concentration of bio-particles and formed a lower biomass concentration. Besides, shear forces are produced on the biofilm by the fluid were increased. Thus, consequently, a lower biomass concentration was observed [36].

3.3. Organic loading rate

The COD of the influent and effluent were analyzed during the start-up and operational period of the reactor. COD removal values are illustrated in Fig. 4a. The injected COD of the influent was maintained to be 297 ± 6 mg/L. During start-up, COD of the effluent was reduced up to 76 ± 3 mg/L, and the COD of the filtered effluent was found to be up to 56.4 ± 10 mg/L when the reactor was operated at HRT of 24 h at a flowrate 5 L/d with an up-flow velocity of 0.0009 m/min for 2 months.

Moreover, during the operational phase, as the reactor was stable; the concentration of COD kept declining and reached 51.5 ± 1 mg/L, whereas the COD of the filtered effluent was decreased to 2.5 ± 3 mg/L when the flowrate was increased to 15 L/d with HRT of 6 h. The corresponding up-flow velocity was 0.0044 m/min, and an OLR was 1.13 g/L/d. The COD of the filtered effluent was less than the unfiltered sample of the effluent due to the separation

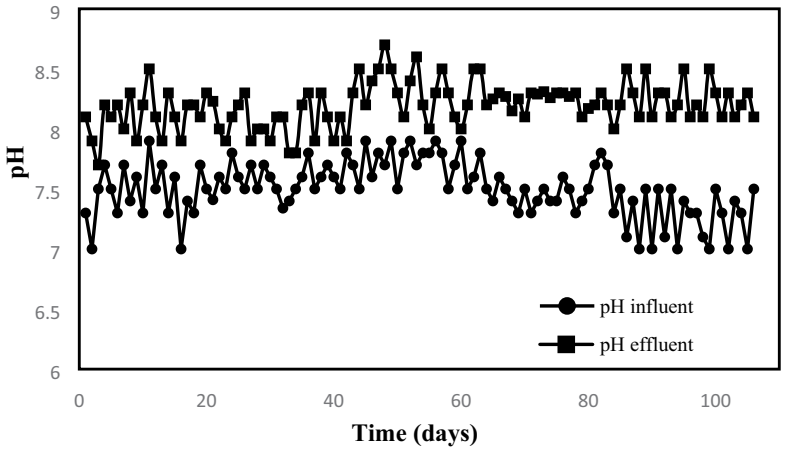

Fig. 2. Variation of pH in the reactor during the operation period.

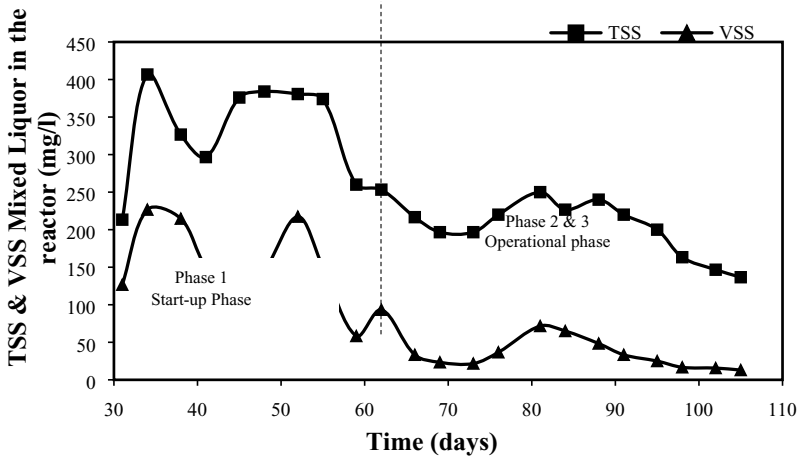

Fig. 3. Solid profile in the reactor.

of suspended and colloidal particles during filtration. Therefore, the values of filtered COD should be corresponding to the dissolved organic content present in the sample. A decrease in the filtered COD values reflects the degradation of dissolved organic matter in the sample. The COD value of the unfiltered sample decreased with time as the AFBR reached the optimum conditional parameters. The more the total COD of the effluent was reduced gradually, the more the filtered effluent was declined. The reactor was operated at several conditions in the three phases of the reactor operation to have the optimized conditions and to provide a favorable environment to microorganisms. For that purpose, the synthetic feed with nutrients was fed into the reactor daily, and the operating conditions were changed during each stage after operating sufficient time for microorganisms' growth. Thus, it made the microbes handle the increased OLR with lesser HRT and high up-flow velocity.

The BOD measurements were carried out during the second month of the start-up phase (phase two) from day 44th and week 9th. A gradual decrease in the effluent BOD during reactor operation was observed. The BOD values in the influent and effluent were in the range of 100 ± 3 and 31 ± 20 mg/L, respectively (Fig. 4b). The gradual decline in BOD values was observed due to the application of optimized operating conditions, that is, HRT and OLR. The HRT decreased from 24 to 6 h, and OLR increased from 0.50 to 1.13 g/L/d. The lower BOD indicated that the biodegradable portion of the organic content was utilized effectively by the microorganisms present in the ABFR. The efficiency of the reactor was determined based on COD and BOD removal. The reactor efficiency was assessed daily for COD removal during start-up and the operational phase. During the start-up phase, that is, from day 1 up to 44th day, the reactor efficiency for COD removal was found to be 65.4% ± 12%. During the operational phase, that is, from day 50th up to 115th day, the efficiency was gradually increased to up to 82.6% ± 1%. The change that was made in the reactor parameters over time from the start-up period to the operational period supported the improved performance of the reactor and stabilized its working performance. Hence, with the alteration made in the operational parameter from the start-up phase to the operational phase, that is, increased amount of OLR, that is, from 0.50 to 1.13 g/L/d, the flowrate from 5 to 15 L/d and shorter HRT from 24 to 6 h gradually upgraded the reactor performance based on COD removal. Also, the favorable conditions provided for microorganisms' growth in the form of nutrients fed daily, made the microbes capable of handling higher OLR with shorter HRT as compared to the start-up phase.

The reactor efficiency for BOD removal was analyzed during the operational phase from day 46th to 114th. A gradual increase in reactor efficiency has been observed during reactor operation. The efficiency of the reactor for COD removal was found to be 70.3% ± 4%. A steady increase of reactor efficiency was observed during the BOD analysis because the BOD analyses were conducted during the reactor operation period. In the operational period, the parameters of the reactor were adjusted to HRT from 24 to 6 h, and the OLR was increased from 0.50 to 1.13 g/L/d and flowrate was increased from 5 to 15 L/d. The adjustment in the parameters supported the reactor to function in a stabilized manner for five months. To aid the optimized growth of microorganisms, the synthetic feed, which was injected in the reactor every day, that is, from the start-up phase, consisted of nutrients such as glucose and sodium acetate, etc. Therefore, the reactor was able to handle the increased amount of OLR, that is, from 0.50 to 1.13 g/L/d, flowrate from 5 to 15 L/d, and shorter HRT from 24 to 6 h.

3.4. Linoleic acid removal

During the operational period, the degradation of linoleic acid was analyzed. On the 59th day of operation, linoleic acid was introduced in the reactor. The degradation period for linoleic acid continued for 1 month is depicted in (Fig. 5). During the operational period, four different concentrations of 100, 150, 200, and 250 mg/L of linoleic acid were injected gradually into the synthetic feed. The total COD of the synthetic feed during the linoleic acid concentrations was maintained 297.6 ± 6 mg/L. The reactor was operated for 26 d with various linoleic acid concentrations. The linoleic acid removal efficiency was increased from 82% to 99% during the first 5 d of the introduction of

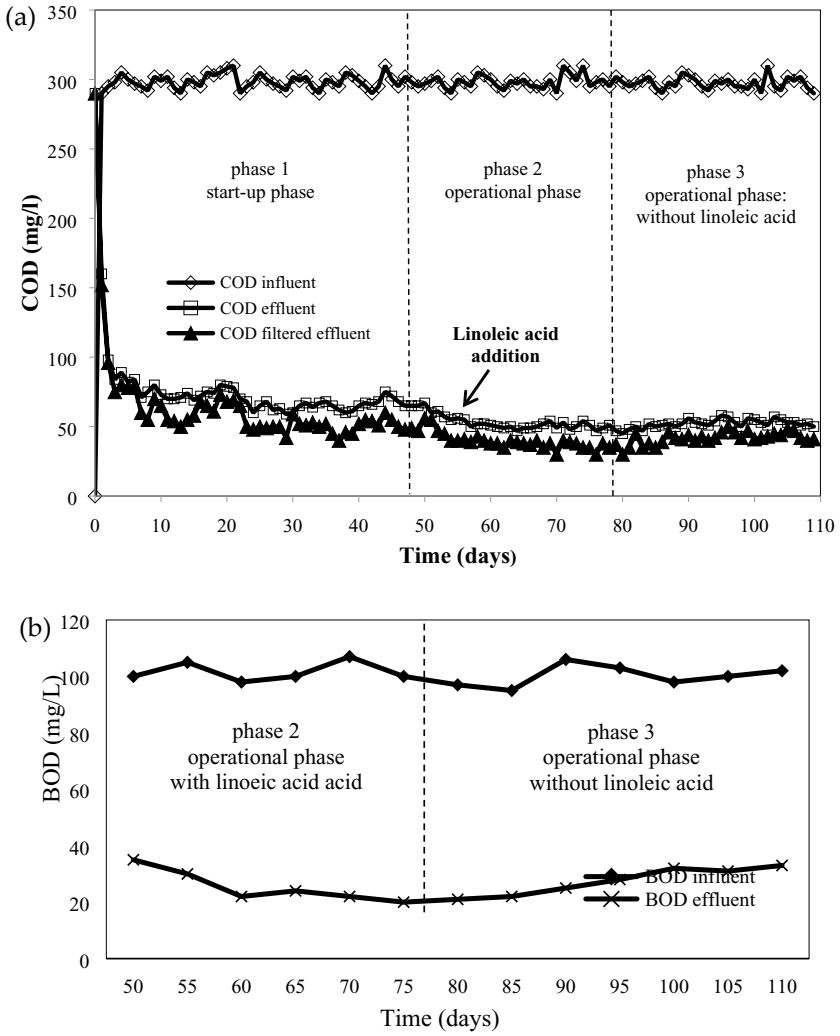

Fig. 4. (a) COD reduction during start-up and operational phases and (b) biochemical oxygen demand reduction during the operational phase.

linoleic acid because the microorganisms inside the reactor degraded linoleic acid slowly day by day. On the 6th day, the inlet concentration was increased from 100 to 150 mg/L and kept at 150 mg/L for another 5 d. The linoleic acid removal efficiency was declined to 80% because the OLR of linoleic acid was slightly increased but quickly regained up to 99% as the reactor was able to degrade linoleic acid up to 99% within 5 d. Then the inlet linoleic acid concentration was further increased to 200 mg/L, and again with the initial decline (i.e., 78%), the removal efficiency was recovered to 99% on the 18th day. A similar trend of the linoleic acid removal was observed (from 82% to 99%) when the influent concentration of linoleic acid was increased to 250 mg/L (19th–26th day of operation), as shown in Fig. 5.

The removal efficiency of linoleic acid in the reactor was decreased slightly from 92.4% ± 9.4% to 87.5% ± 9.2% when the inlet concentration was increased from 100 to 250 mg/L. The concentration of 100 mg/L was treated for 5 d, and the obtained removal was up to 93% ± 8.3%. The concentration of 150 mg/L was run for 5 d, and the removal obtained was found to be 92.4% ± 9.4%. The concentration of 200 mg/L was run for 7 d, and the removal analyzed was 87.5% ± 9.2%. The concentration of 250 mg/L was treated for eight days and removed up to 92.6% ± 6.6%. On the 1st day, the degradation obtained for 100 mg/L after the AFBR treatment was 82% and gradually decreased up to 99%. The concentration remained in the sample was found to be 3.24 mg/L and was gradually decreased up to 0.1 mg/L. From the day 6th, the concentration was increased from 100 to 150 mg/L; the degradation obtained was 80% and gradually increased up to 99.7% while the concentration of 150 mg/L remained in the sample was 1.3 mg/L and reduced gradually to 0.1 mg/L. From the 12th day, the concentration was increased from 150 to 200 mg/L; the degradation obtained was 78% and slowly increased up to 99.7% whereas, the concentration remained in the sample was 3.7 mg/L and decreased up to 0.1 mg/L. From the 19th day, the concentration was increased from 200 to 250 mg/L, the degradation obtained was 82% and gradually increased up to 99.1%. While the concentration remained in the sample was 3.8 mg/L and decreased gradually up to 0.1 mg/L. The concentration was run for more than 1 d to confirm the validity of degradation.

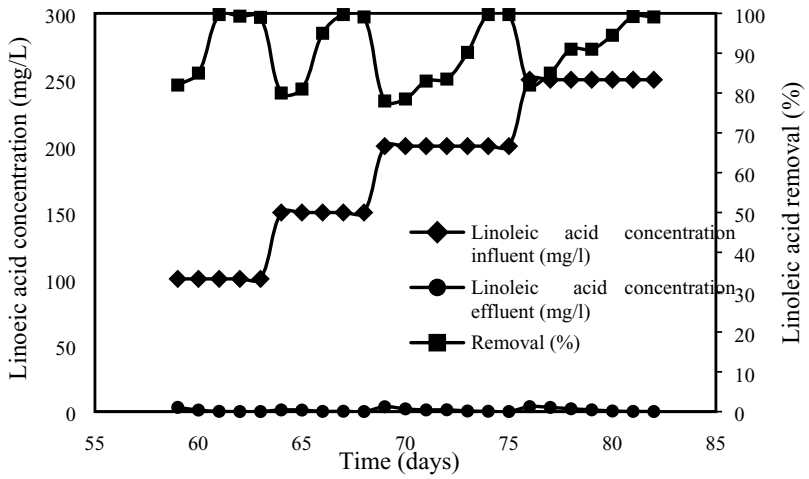

Fig. 5. Removal of linoleic acid concentration in the reactor.

The comparison of AFBR with other anaerobic reactors is given in Table 2.

It can be noted that an upflow anaerobic sludge blanket (UASB) has been used to treat edible oil wastewater with a concentration of linoleic acid 326.6 mg/L with HRT of 2.8 d at 7.8 g COD/L/d. The linoleic acid was removed up to 91% [37]. The higher efficiency observed could be explained by the recirculation of flow, which enhanced hydrodynamic mixing [38]. It is safe to operate UASB at high organic loading and short HRT [39]. The COD removal efficiency was found to be at least 60% and more than 90% [21]. UASB has been used widely on a large scale worldwide [40,41], especially for the food and edible oil industry [39]. It retains a large amount of biomass in the form of granules, the potential to treat wastewater with high suspended solid content [42,43] that cause clogging in the reactor and also produces higher methane production [44,45]. Likewise, another study used the up-flow anaerobic reactor for the treatment of edible oil wastewater used 7.6 mg/L linoleic acid at an OLR of 48 g COD/L/d with HRT of 48 d and achieved linoleic acid removal up to 99% [46]. It provided satisfactory results as low organic rate and longer HRT sufficiently degraded linoleic acid. Furthermore, it has the potential to treat high strength wastewater. It can handle high OLR and less HRT [16,17]. It has excellent mass transfer capability; therefore, it avoids clogging and short-circuiting [22]. Also, another study used a bench-scale packed bed bioreactor with a linoleic acid 25.2 mg/L with OLR 22 g COD/L/d with HRT of 2 h with linoleic acid removal of 21.7% [47]. The packed bed reactor faces clogging when operated above 20 g COD/L. As compared to the fluidized bed reactor, less efficiency may be caused due to diffusion constraints and slow biomass activity [48]. Similarly, another study used anaerobic membrane bioreactor (AnMBR) for the treatment of edible oil wastewater. The reactor treated 3.4 mg/L of linoleic acid at an organic loading road of 8 g COD/L/d with HRT of 10 d. The linoleic acid was removed up to 46% [7]. The wastewater used in the AnMBR contained a high amount of linoleic acid that accumulated on biomass, which led to slow degradation and limited mass transfer capabilities [4]. Furthermore, the problems encountered in AnMBRs were membrane fouling, high OLRs, long acclimatization periods [49].

In this study, the linoleic acid was 250 mg/L at OLR 1.13 g COD/L/d, HRT of 6 h with linoleic acid removal 92%. This performance was given due to the optimized operational parameters and acclimatization of microorganisms. From this comparison, it was evident that the AFBR used for the treatment of linoleic acid proved to be more efficient as it degraded a higher amount of linoleic acid in a fewer number of days. It was caused due to several characteristics such as large surface area due to small size carriers [22]; consequently, the availability of high surface area available for biomass attachment [18,19]. Therefore, AFBR has been widely used to treat edible oil [20,21].

In comparison with the studies mentioned above, the HRT of 6 h is the shortest along with a high concentration

Table 2
Comparison of AFBR with other anaerobic reactors for removal of linoleic acid

Reactor type	Linoleic acid concentration (mg/L)	OLR (g COD/L d)	HRT (h)	Linoleic acid removal (%)	References
UASB	326.6	7.894	67 h and 2.8 d	91%	[37]
Anaerobic membrane bio-reactor	3.4	8	10 d	46%	[7]
Packed bed reactor	25.2	22	2 h	21.7%	[47]
Upflow anaerobic reactor	7.6	48	10 d	Up to 99%	[46]
AFBR	250	1.13	6 h	Up to 99%	Present study

of linoleic acid by AFBR having a reactor efficiency of 82%. The AFBR is highly efficient due to excellent mass transfer, and the bed expansion avoids the problem of clogging and short-circuiting and large surface area due to small size carriers [22]. The AFBR has a high potential to treat wastewater generates from edible oil industries due to an available surface area for biomass attachment [18,19]. It can handle a high OLR at relatively lower HRT [16,17]. Furthermore, it avoids the problems of gas hold up or channeling issues commonly occurred in anaerobic reactors [18,19].

4. Conclusion

The AFBR designed on a laboratory scale has the potential of treating edible oil wastewater, particularly linoleic acid. It was revealed that the performance of the reactor was not stable under a certain condition, that is, HRT of 24 h at a flowrate of 5 L/d with an up-flow velocity of 9×10^{-4} m/min. However, as the flowrate was increased from 5 to 15 L/d along with HRT of 6 h, the up-flow velocity of 4.4×10^{-3} m/min and OLR of 1.13 g/L/d; the performance of the reactor observed to be improved. The COD reduced from 76 ± 3 to 51.5 ± 1 mg/L associated with the increase of reactor efficiency from 65.4% ± 12% to 82.6% ± 1%. The upgraded performance of the reactor provides the removal of linoleic acid up to 91%.

References

[1] J.A. Lalman, D.M. Bagley, Anaerobic degradation and inhibitory effects of linoleic acid, Water Res., 34 (2000) 4220–4228.
[2] A. Pereira, M. Mota, M. Alves, Degradation of oleic acid in anaerobic filters: the effect of inoculum acclimatization and biomass recirculation, Water Environ. Res., 73 (2001) 612–621.
[3] M.A. Pereira, K. Roest, A.J.M. Stams, M. Mota, M. Alves, A.D.L. Akkermans, Molecular monitoring of microbial diversity in expanded granular sludge bed (EGSB) reactors treating oleic acid, FEMS Microbiol. Ecol., 41 (2002) 95–103.
[4] M.A. Pereira, O.C. Pires, M. Mota, M.M. Alves, Anaerobic biodegradation of oleic and palmitic acids: evidence of mass transfer limitations caused by long chain fatty acid accumulation onto the anaerobic sludge, Biotechnol. Bioeng., 92 (2005) 15–23.
[5] M.A. Pereira, M. Mota, M.M. Alves, The Important Role of Mass Transfer Limitations Caused by Long Chain Fatty Acids Accumulation onto the Anaerobic Sludge, Proceedings of the 10th World Congress on Anaerobic Digestion, Braga, Portugal, 2004.
[6] J. Palatsi, J. Illa, F.X. Prenafeta-Boldú, M. Laureni, B. Fernandez, I. Angelidaki, X. Flotats, Long-chain fatty acids inhibition and adaptation process in anaerobic thermophilic digestion: batch tests, microbial community structure and mathematical modelling, Bioresour. Technol., 101 (2010) 2243–2251.
[7] R.K. Dereli, F.P. van der Zee, B. Heffernan, A. Grelot, J.B. van Lier, Effect of sludge retention time on the biological performance of anaerobic membrane bioreactors treating corn-to-ethanol thin stillage with high lipid content, Water Res., 49 (2014) 453–464.
[8] J.L. Chen, R. Ortiz, T.W.J. Steele, D.C. Stuckey, Toxicants inhibiting anaerobic digestion: a review, Biotechnol. Adv., 32 (2014) 1523–1534.
[9] V.C. Kalia, Microbial Factories: Biofuels, Waste Treatment: Vol. 1, Springer, Springer, New York, 2016, pp. 1–353.
[10] P.C. Chan, R.A. de Toledo, H. Shim, Anaerobic co-digestion of food waste and domestic wastewater – effect of intermittent feeding on short and long chain fatty acids accumulation, Renewable Energy, 124 (2018) 129–135.
[11] D.G. Cirne, X. Paloumet, L. Björnsson, M.M. Alves, B. Mattiasson, Anaerobic digestion of lipid-rich waste-effects of lipid concentration, Renewable Energy, 32 (2007) 965–975.
[12] J.H. Long, T.N. Aziz, F.L.D.L. Reyes, J.J. Ducoste, Anaerobic co-digestion of fat, oil, and grease (FOG): a review of gas production and process limitations, Process Saf. Environ. Prot., 90 (2012) 231–245.
[13] M. Canakci, The potential of restaurant waste lipids as biodiesel feedstocks, Bioresour. Technol., 98 (2007) 183–190.
[14] P. Suto, D.M.D. Gray (Gabb), E. Larsen, J. Hake, Innovative Anaerobic Digestion Investigation of Fats, Oils, and Grease, Proceedings of the Residuals and Biosolids Management Conference 2006, Nashville, Tenn., 2006, pp. 608–617.
[15] X. He, T. Yan, Impact of microbial activities and hydraulic retention time on the production and profile of long chain fatty acids in grease interceptors: a laboratory study, Environ. Sci. Water Res. Technol., 2 (2016) 474–482.
[16] D. Garcia-Calderon, P. Buffiere, R. Moletta, S. Elmaleh, Anaerobic digestion of wine distillery wastewater in down-flow fluidized bed, Water Res., 32 (1998) 3593–3600.
[17] R. Sowmeyan, G. Swaminathan, Evaluation of inverse anaerobic fluidized bed reactor for treating high strength organic wastewater, Bioresour. Technol., 99 (2008) 3877–3880.
[18] F. Toldrá, A. Flors, J.L. Lequerica, S. Vallés, Fluidized bed anaerobic biodegradation of food industry wastewaters, Biol. Wastes, 21 (1987) 55–61.
[19] R. Borja, E. González, F. Raposo, F. Millán, A. Martín, Performance evaluation of a mesophilic anaerobic fluidized-bed reactor treating wastewater derived from the production of proteins from extracted sunflower flour, Bioresour. Technol., 76 (2001) 45–52.
[20] M. Perez, R. Rodriguez-Cano, L.I. Romero, D. Sales, Performance of anaerobic thermophilic fluidized bed in the treatment of cutting-oil wastewater, Bioresour. Technol., 98 (2007) 3456–3463.
[21] P.E. Poh, M.F. Chong, Development of anaerobic digestion methods for palm oil mill effluent (POME) treatment, Bioresour. Technol., 100 (2009) 1–9.
[22] F. Ehlinger, Y. Escoffier, J.P. Couderc, J.P. Leyris, R. Moletta, Development of an automatic control system for monitoring an anaerobic fluidized bed reactor, Water Sci. Technol., 29 (1994) 289–295.
[23] R. Borja, C.J. Banks, Comparison of an anaerobic filter and an anaerobic fluidized bed reactor treating palm oil mill effluent, Process Biochem., 30 (1995) 511–521.
[24] D.W. Gao, Q. Hu, C. Yao, N.Q. Ren, W.M. Wu, Integrated anaerobic fluidized-bed membrane bioreactor for domestic wastewater treatment, Chem. Eng. J., 240 (2014) 362–368.
[25] Y. Feng, B. Lu, Y. Jiang, Y. Chen, S. Shen, Performance evaluation of anaerobic fluidized bed reactors using brick beads and porous ceramics as support materials for treating terephthalic acid wastewater, Desal. Water Treat., 53 (2015) 1814–1821.
[26] K. Chowdhury, L. Banu, S. Khan, A. Latif, Studies on the fatty acid composition of edible oil, Bangladesh J. Sci. Ind. Res., 42 (2007) 311–316.
[27] F.J. Baur, J.B. Brown, The fatty acids of corn oil, J. Am. Chem. Soc., 67 (1945) 1899–1900.
[28] J.B. Beadle, D.E. Just, R.E. Morgan, R.A. Reiners, Composition of corn oil, J. Am. Oil Chem. Soc., 42 (1965) 90–95.
[29] N.O.V. Sonntag, New developments in the fatty acid industry in America, J. Am. Oil Chem. Soc., 61 (1984) 229–232.
[30] C. Qian, Effect of long chain fatty acids on bacterial growth, Virginia Polytech. Inst. State Univ., 63 (2013).
[31] N.T. Mkhize, T.A.M. Msagati, B.B. Mamba, M. Momba, Determination of volatile fatty acids in wastewater by solvent extraction and gas chromatography, Phys. Chem. Earth, 67–69 (2014) 86–92.
[32] P. Sivakumar, P. Sivakumar, K. Anbarasu, K. Pandian, S. Renganathan, Synthesis of silver nanorods from food industrial waste and their application in improving the keeping quality of milk, Ind. Eng. Chem. Res., 52 (2013) 17676–17681.
[33] C. Qian, Effect of Long-Chain Fatty Acids on Anaerobic Digestion, Dissertation, Virginia Tech, 2013, pp. 45–78.
[34] J.I. Horiuchi, T. Shimizu, K. Tada, T. Kanno, M. Kobayashi, Selective production of organic acids in anaerobic acid reactor by pH control, Bioresour. Technol., 82 (2002) 209–213.

[35] J.J. Kabara, R. Vrable, M.S.F. Lie Ken Jie, Antimicrobial lipids: natural and synthetic fatty acids and monoglycerides, Lipids, 12 (1977) 753–759.
[36] J. Jaafari, A. Mesdaghinia, R. Nabizadeh, M. Hoseini, H. Kamani, A.H. Mahvi, Influence of upflow velocity on performance and biofilm characteristics of anaerobic fluidized bed reactor (AFBR) in treating high-strength wastewater, J. Environ. Health Sci. Eng., 12 (2014) 1–10.
[37] Y. Saatci, E.I. Arslan, V. Konar, Removal of total lipids and fatty acids from sunflower oil factory effluent by UASB reactor, Bioresour. Technol., 87 (2003) 269–272.
[38] J.B. van Lier, F.P. van der Zee, C.T.M.J. Frijters, M.E. Ersahin, Celebrating 40 years anaerobic sludge bed reactors for industrial wastewater treatment, Rev. Environ. Sci. Biotechnol., 14 (2015) 681–702.
[39] A. Gunay, D. Karadag, Recent developments in the anaerobic digestion of olive mill effluents, Process Biochem., 50 (2015) 1893–1903.
[40] C.C. Nnaji, A review of the upflow anaerobic sludge blanket reactor, Desal. Water Treat., 52 (2013) 4122–4143.
[41] S.J. Lim, T.H. Kim, Applicability and trends of anaerobic granular sludge treatment processes, Biomass Bioenergy, 60 (2014) 189–202.
[42] H.H.P. Fang, H.K. Chui, Comparison of start-up performance of four anaerobic reactors for the treatment of high-strength wastewater, Resour. Conserv. Recycl., 11 (1994) 123–138.
[43] S. Kalyuzhnyi, L. Estrada De Los Santos, J.R. Martinez, Anaerobic treatment of raw and preclarified potato-maize wastewaters in a UASB reactor, Bioresour. Technol., 66 (1998) 195–199.
[44] S.V. Kalyuzhnyi, V.I. Sklyar, M.A. Davlyatshina, S.N. Parshina, M.V. Simankova, N.A. Kostrikina, A.N. Nozhevnikova, Organic removal and microbiological features of UASB-reactor under various organic loading rates, Bioresour. Technol., 55 (1996) 47–54.
[45] S.M. Stronach, T. Rudd, J.N. Lester, Start-up of anaerobic bioreactors on high strength industrial wastes, Biomass, 13 (1987) 173–197.
[46] M.R. Gonçalves, J.C. Costa, I.P. Marques, M.M. Alves, Strategies for lipids and phenolics degradation in the anaerobic treatment of olive mill wastewater, Water Res., 46 (2012) 1684–1692.
[47] L.B. Fomuso, C.C. Akoh, Lipase-catalyzed acidolysis of olive oil and caprylic acid in a bench-scale packed bed bioreactor, Food Res. Int., 35 (2002) 15–21.
[48] M. Denac, I.J. Dunn, Packed- and fluidized-bed biofilm reactor performance for anaerobic wastewater treatment, Biotechnol. Bioeng., 32 (1988) 159–173.
[49] A.P. Trzcinski, D.C. Stuckey, Treatment of municipal solid waste leachate using a submerged anaerobic membrane bioreactor at mesophilic and psychrophilic temperatures: analysis of recalcitrants in the permeate using GC-MS, Water Res., 44 (2010) 671–680.