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Pilot-scale anaerobic treatment of domestic wastewater in upflow anaerobic sludge bed and anaerobic baffled reactors at ambient temperatures

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ABSTRACT

The efficiencies of an upflow anaerobic sludge bed (UASB) reactor and an anaerobic baffled reactor (ABR) were compared for the treatment of domestic wastewater at ambient temperatures. Two pilot-scale anaerobic biological reactors were operated for about two years at ambient conditions at psychrophilic and/or sub-mesophilic temperatures. The average total chemical oxygen demand removal was 56 and 58% in the UASB reactor, whereas it was 41 and 50% in ABR, respectively, in summer and winter periods. The amount of methane gas production was between 0.05 and 0.18 m^3 CH_4/kg $COD_{removed}$ in the UASB reactor, although no methane production was observed in the ABR. Temperature was not a limiting factor in anaerobic reactors that were operated at ambient conditions. Because of its higher efficiency, the UASB reactor was recommended over the ABR for the anaerobic treatment of domestic wastewater of the small community investigated within the scope of the study. However, anaerobic treatment of domestic wastewater is considered only as a pretreatment step, since it requires further removal of nutrients.

Keywords: Anaerobic treatment; Ambient temperature; Domestic wastewater; UASB reactor; Anaerobic baffled reactor; Organic matter removal

1. Introduction

Anaerobic processes have been applied successfully for the treatment of medium and high strength wastewaters for many years. Anaerobic treatment has recently begun to be applied with satisfactory removal efficiencies for low-strength wastewaters such as domestic wastewater. The benefit of anaerobic treatment is very significant in terms of energy particularly in the treatment of concentrated domestic wastewater [1]. Anaerobic process is efficient for the removal of both organic matter and suspended solids from domestic wastewater. Total Chemical Oxygen Demand (TCOD) removals up to 80–90% were possible and average TCOD removal of 70% could be expected at temperatures above 20°C [2].

Psychrophilic (10–20°C) and/or sub-mesophilic anaerobic treatment has become a feasible option for the wastewaters discharged at moderate to low temperatures. Many recent studies have shown that tem-

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perature is not a limiting factor in anaerobic treatment applications if the appropriate process design is chosen and adaptation of micro-organisms can be achieved [3,4]. The most widely used anaerobic system for treating domestic wastewater has been the upflow anaerobic sludge bed (UASB) reactor because of low investment and operation costs [5,6]. The application of anaerobic baffled reactor (ABR), which can be considered as a series of UASB reactors, has also improved in recent years. In ABR, baffles divide the reactor into compartments and force the liquid flow up and down from one compartment to next. ABR has a higher tolerance to hydraulic and organic shock loads compared to many other high rate anaerobic reactors [2].

The main disadvantage in the anaerobic treatment of domestic wastewater is the restricted biogas production. Low influent COD results in low substrate levels inside the reactor, which eventually results in very low biogas production in anaerobic systems when treating such dilute streams [7]. Another disadvantage of anaerobic systems is the high concentrations of ammonium, phosphate, and sulfur in the effluent. Domestic effluents are known to comprise high amounts of organic nitrogen and phosphorus. High nutrient contents after anaerobic treatment should be removed in order to meet the discharge standards. Therefore, treatment of domestic wastewaters by anaerobic systems should be considered as a pretreatment alternative [8].

The main objective of this study was to investigate the anaerobic treatability of domestic wastewater at two pilot-scale anaerobic systems (UASB and ABR) that were operated at ambient temperatures without any additional heating. Thus, it may be considered as an alternative treatment system to be applied for the small residential areas in temperate climate regions of Turkey.

2. Materials and methods

The pilot-scale anaerobic reactor system constructed at the campus of TUBITAK-MRC (Marmara Research Center) was formed of a UASB and an ABR operated in parallel for comparison purposes (Fig. 1). The system acted as a pretreatment step for the removal of organic matter and suspended solids upstream of a constructed wetland system. Pilot-scale studies were performed for the treatment of domestic wastewater of about 30 people in order to show the applicability of these systems. The experimental period covered about two years in order to be able to monitor the seasonal variations. The start-up period of reactors lasted about two months before the first steady-state results were picked up.

Both reactors (UASB and ABR) were operated at ambient temperatures without external heating of reactors. However, the reactors were covered with insulation material in order to prevent the adverse

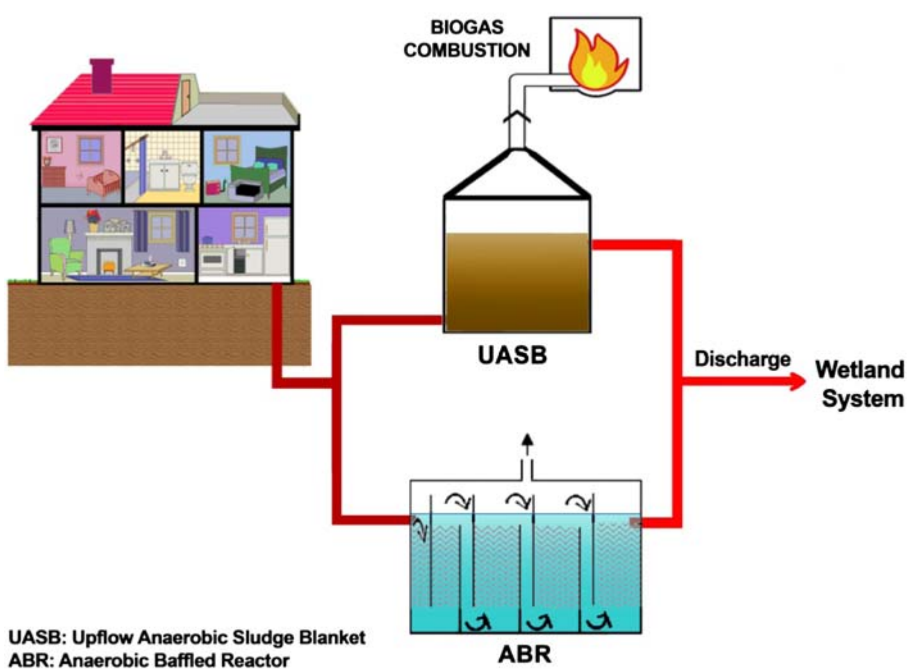

Fig. 1. Schematic diagram of pilot-scale UASB and ABR operated in parallel.

effects of sharp temperature changes. The temperature of water in the reactor is considered to be an important parameter in anaerobic treatment. The ambient temperature determines the temperature of water when there is no external heating. The temperature of wastewater in the effluent of the reactor was observed in the range of 12–28°C (psychrophilic and/or sub-mesophilic) during the whole study period. Volume of UASB reactor was approximately 0.5 m^3 with a 0.5 m diameter and 2.5 m height. Volume of the ABR was approximately 1 m^3 with dimensions of 2.1 m length, 0.6 m width and 0.8 m height. ABR was divided into three equal compartments separated by baffles.

Both reactors were seeded with a flocculent anaerobic sludge. Sludge samples taken from the UASB reactor during the operation had mixed liquor suspended solids (MLSS) concentrations between 26,400 and 79,000 mg/L and mixed liquor volatile suspended solids (MLVSS) concentrations between 18,600 and 62,000 mg/L with an MLVSS/MLSS ratio ranging between 0.70 and 0.78. Sludge samples taken from three different zones of ABR during the operation had MLSS between 1,544 and 17,300 mg/L and MLVSS between 1,160 and 12,300 mg/L with an MLVSS/MLSS ratio ranging between 0.71 and 0.85. Biomass concentrations could not be kept constant throughout the compartments. Accumulation of biomass was observed in the last compartment of ABR. Biomass growth was apparently less in the ABR compared to the UASB reactor. Both reactors were operated at a hydraulic loading rate of 12.1 h. Organic loading rates were in the range of 0.33–0.77 kg COD/m^3 day and 0.30–0.72 kg COD/m^3 day, respectively in the UASB reactor and ABR reactors. Flow rate to both reactors was between 2 and 3 m^3/day. The characteristics of domestic wastewater is shown in Table 1.

In order to investigate the performances of anaerobic reactors, total (TCOD) and soluble chemical oxygen demand (SCOD), biochemical oxygen demand (BOD_5), and total (TSS) and volatile suspended solids (VSS) analyses were performed in the influent and effluent. All these analyses were performed according to the Standard Methods for the Examination of Water and Wastewater [9]. The samples were filtered through 0.45 μ filters prior to SCOD analyses. The amount of total gas produced in the reactors was measured by the method of water displacement. The percentage of methane gas was measured periodically by ABB AO 2000 series gas analysis instrument.

Table 1
The characteristics of domestic wastewater used in the experiments

Parameter	
TCOD (mg/L)	230–850
SCOD (mg/L)	160–360
TSS (mg/L)	90–450
VSS (mg/L)	80–380
TKN (mg/L)	39.8–85
NH_4-N (mg/L)	28.8–70
PO_4-P (mg/L)	3.6–15
pH	7.2–8.1
Alkalinity (mg $CaCO_3$/L)	232–504

3. Results and discussion

3.1. Treatment performance in the UASB reactor

In the UASB reactor, TCOD removal ranged between 20 and 85% and SCOD removal between 25 and 67%. The effluent TCOD and SCOD ranged between 96–369 mg/L and 29–187 mg/L, respectively. Some of TCOD removal is supposed to occur via physical means; i.e. some particulate organic matter is retained in the sludge bed. In a literature study, it was proposed that SCOD/TCOD ratio ranges between 0.2 and 0.5 in a typical domestic wastewater and the removal efficiency for SCOD is expected to be about 40% [10]. These results were consistent with the findings of the present study. Influent and effluent concentrations of TCOD and SCOD and their removal efficiencies are shown in Fig. 2.

In anaerobic reactors, pH and alkalinity are two important factors showing the stability of the process. The alkalinity levels reveal a potential anaerobic process performance. A low value of effluent alkalinity is an indication of a possible reactor failure [11]. Therefore, alkalinity as well as pH of influent and effluent was monitored regularly. The influent pH ranging between 7.2 and 8.3 decreased to between 7.1 and 8, and the influent alkalinity of 215–511 mg $CaCO_3$/L increased to 285–527 mg $CaCO_3$/L in the effluent of UASB reactor. These values were sufficient for a stable anaerobic process.

The influent concentrations of total suspended solids ranging between 74–450 mg/L decreased to 20–180 mg/L in the effluent of UASB reactor (Fig. 2c), whereas volatile suspended solids decreased from 33–380 mg/L to 16–142 mg/L. High removal of suspended solids also had a considerable impact on the removal of TCOD from the system via sedimentation within the anaerobic sludge. The change in differences between TCOD and SCOD concentrations in Table 2 indicates the removal of particulate organic matter via physical means.

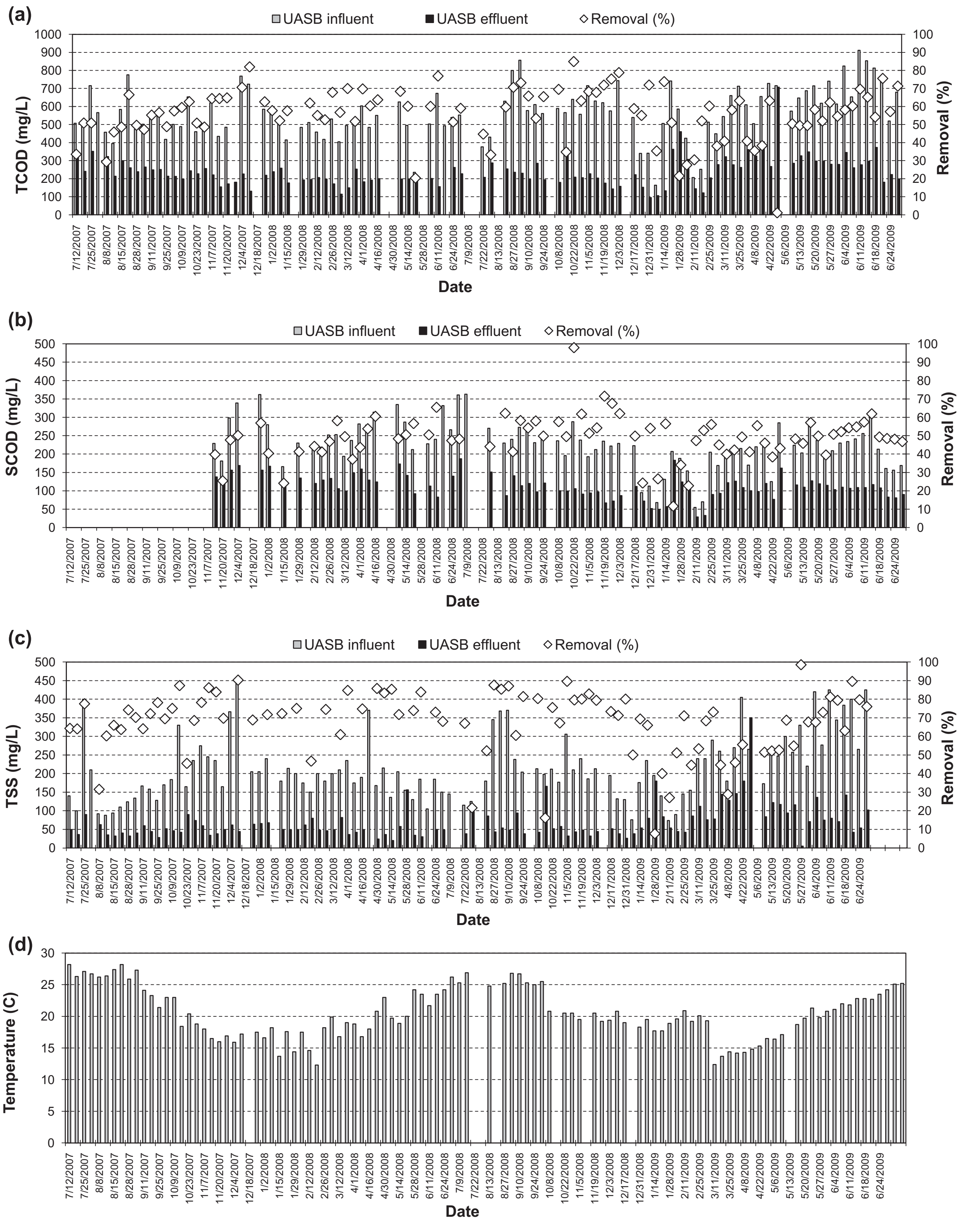

Fig. 2. (a) TCOD, (b) SCOD, and (c) TSS concentrations and removal efficiencies in the UASB reactor and (d) temperature of the influent wastewater.

Table 2
Performances of anaerobic reactors during summer and winter periods

	TCOD	SCOD	BOD_5	TSS	VSS
Summer					
Influent (mg/L)	591 ± 132	251 ± 50	162 ± 46	219 ± 88	186 ± 78
UASB effluent (mg/L)	259 ± 84	120 ± 25	56 ± 22	73 ± 55	67 ± 47
UASB removal (%)	56 ± 12	51 ± 8	64 ± 14	67 ± 19	66 ± 21
ABR effluent (mg/L)	315 ± 59	185 ± 39	91 ± 26	67 ± 29	62 ± 28
ABR removal (%)	41 ± 13	28 ± 11	40 ± 15	64 ± 13	60 ± 15
Winter					
Influent (mg/L)	517 ± 150	198 ± 69	152 ± 55	199 ± 75	165 ± 64
UASB effluent (mg/L)	205 ± 79	105 ± 39	60 ± 19	60 ± 29	48 ± 23
UASB Removal (%)	58 ± 15	46 ± 13	58 ± 14	67 ± 17	67 ± 17
ABR effluent (mg/L)	249 ± 75	147 ± 42	78 ± 32	57 ± 21	48 ± 19
ABR removal (%)	50 ± 14	11 ± 7	50 ± 16	71 ± 11	69 ± 12

3.2. Treatment performance in the ABR

In the ABR, TCOD removal ranged between 15 and 80% and SCOD removal was between 10 and 55%. The effluent TCOD and SCOD ranged between 141–472 mg/L and 47–264 mg/L, respectively. Influent and effluent concentrations of TCOD and SCOD and their removal efficiencies are shown in Fig. 3.

In the ABR, influent pH ranging between 7.2 and 8.3 was observed to decrease slightly to between 7.0 and 8.0 in the effluent. Alkalinity was not at critical values for the reactor. Influent alkalinity ranged between 215 and 511 mg $CaCO_3$/L and effluent values were between 284 and 500 mg $CaCO_3$/L. These values were also sufficient for a stable anaerobic process.

The influent concentrations of total suspended solids ranging between 74–450 mg/L decreased to 20–176 mg/L in the effluent of ABR (Fig. 3c). Volatile suspended solids decreased from 33–380 to 14–146 mg/L. Removal of suspended solids and suspended organic matter was also an important mechanism in the ABR similar to the UASB reactor.

3.3. Performance evaluation of anaerobic reactors

A comparison of the UASB reactor and ABR is shown in Table 2 considering mainly two seasons: summer and winter when extreme climatic conditions occur. Both, in summer and winter periods the UASB reactor performed much better than the ABR in terms of both organic matter and suspended solids (Table 2). The differences were statistically significant at a confidence interval of 95% as obtained by paired *t*-test. This can be mainly attributed to much higher biomass concentrations in the UASB reactor. Another reason may be the uneven distribution of sludge within the compartments of ABR and accumulation of sludge at the last baffle of the ABR. The accumulation of sludge in one compartment led to insufficient use of total reactor volume and negatively affected the biological activity in the other zones of the reactor.

In summer, the temperature of influent domestic wastewater ranged between 23.0 and 28.2˚C, whereas in winter the temperature was between 12.3 and 20.9˚C (Figs. 2d and 3d). High temperatures did not result in improved organic matter decomposition in the summer period. Mesophilic conditions are normally expected to give better yield compared to psychrophilic and sub-mesophilic conditions. However, micro-organisms can acclimate to low temperatures [2]. Wastewater temperatures determined to be above 12˚C throughout the study did not have a notable influence on the performance of the reactor. It can be suggested that the gradual temperature changes between seasons enabled an efficient acclimation of the microbial culture eliminating a loss of efficiency or reactor failure at low temperatures. Previous studies also showed that temperature is not a limiting factor in anaerobic treatment of domestic wastewaters [3,4]. However, it is important to note that the pilot-scale system used in the study was in a temperate climate region. The wastewater temperature was never below psychrophilic temperatures. Hence, the results obtained in this study are not expected to apply to very cold regions where wastewater temperatures could be usually below 10˚C during winter.

Higher TCOD removal efficiencies (Table 2) observed in the winter period were related to lower initial concentrations in the winter period. This eventually resulted in lower OLRs which led to increased

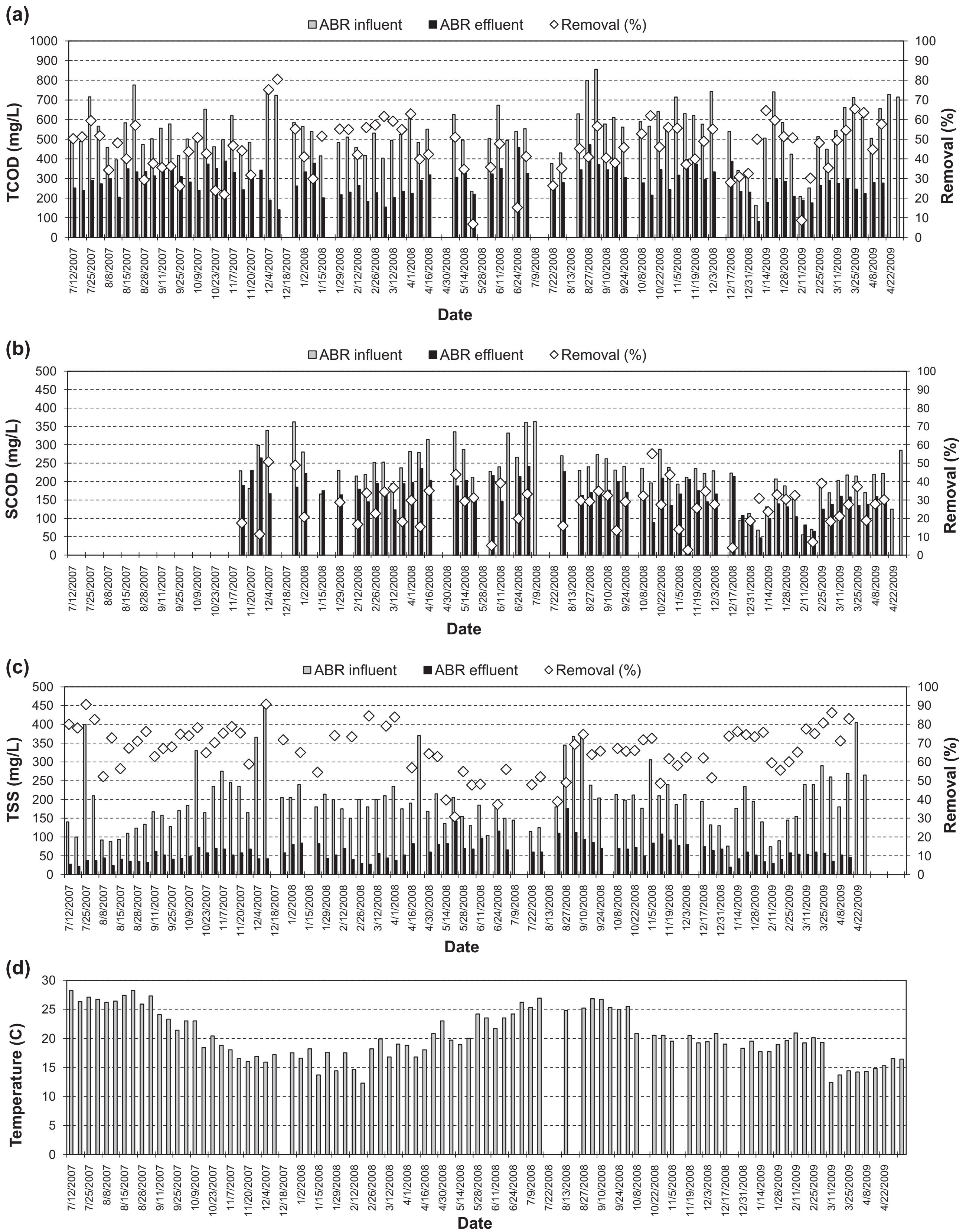

Fig. 3. (a) TCOD, (b) SCOD, and (c) TSS concentrations and removal efficiencies in the ABR and (d) temperature of the influent wastewater.

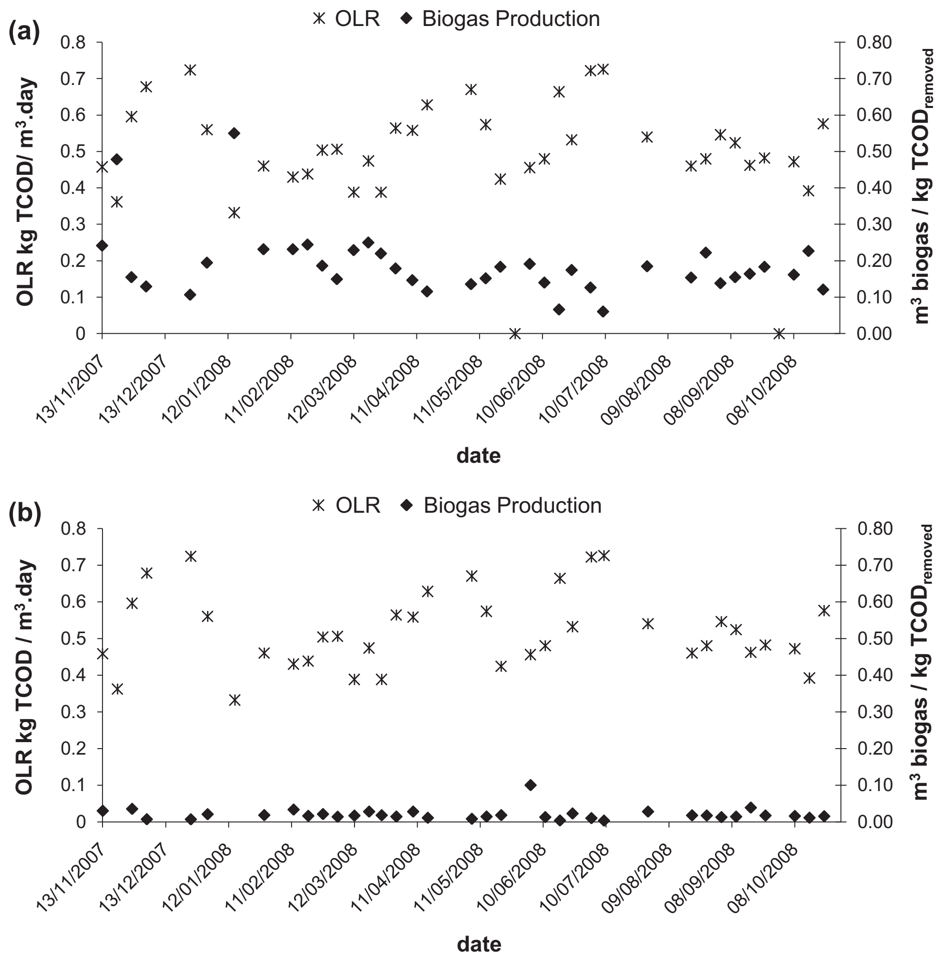

Fig. 4. Biogas production and organic loading rates in (a) UASB reactor and (b) ABR.

reactor performances. The higher removal of TCOD in the winter period may also be due to a higher removal of suspended solids in the case of ABR. This was related to poor solid separation in summer rather than low biological activity.

Throughout the experimental period, concentrations of nitrogen and phosphorus were also monitored both in the influent and effluent of the reactors. The removal of these nutrients was not sufficient in both anaerobic reactors as expected. Therefore, further treatment of the effluent is required to obtain nitrogen and phosphorus concentrations stipulated by the regulations.

3.4. Biogas production

Biogas production was in the range of 0.08–0.28 $m^3/kg\ COD_{removed}$ in the UASB reactor (Fig. 4a). This was in accordance with typical biogas production as reported in the literature in the range of 0.1–0.3 $m^3/kg\ COD_{removed}$ [12]. Low influent COD resulted in low substrate levels inside the reactor which eventually resulted in a low biogas production rate as also reported in a previous study [4]. The efficiency of UASB reactors drops significantly particularly at COD concentrations less than 300 mg/L [13]. Some biogas loss through dissolution is also expected [14] particularly at the reduced temperatures of psychrophilic and sub-mesophilic conditions because of increased gas solubility compared to mesophilic conditions. The amount of methane gas production was between 0.05 and 0.18 $m^3\ CH_4/kg\ COD_{removed}$ with an average methane/biogas ratio of 56%. The relationship between biogas production and organic loading rate is seen in Fig. 4a. It was observed that biogas production decreased slightly when organic loading rates increased in the UASB reactor. Biogas production in the ABR (Fig. 4b) was only 0.01–0.05 $m^3/kg\ COD_{removed}$, which was much lower compared to the UASB reactor. The measurement of low biogas production in the ABR may be due to possible loss of biogas with the effluent.

Biomass production in the UASB reactor was better compared to the previous lab-scale studies performed at the campus of Istanbul Technical University [15], since the organic content of the domestic wastewater was higher and daily fluctuations were lower in the present study. On the other hand, in terms of organic matter removal, performance of the pilot-scale reactors in this study was not better than the previous lab-scale studies [15] where total COD removal was more than 65%. Considering both organic matter removal and biogas production, the results of the pilot-scale study showed that UASB reactors can be successfully used as a pretreatment step. A previous study also recommended the use of UASB reactors in the treatment of domestic wastewaters to be followed by posttreatment in constructed wetlands [16].

4. Conclusions

A comparison of an UASB reactor with an ABR showed that the UASB reactor performed better in terms of organic matter removal and methane production. The efficiency of total COD removal ranging between 41 and 50% in the ABR increased to 56–58% in the UASB reactor. Therefore, the UASB reactor is recommended for the treatment of domestic wastewater of the small community in the present pilot-scale study because of its better performance.

The results of the study showed that temperature was not a limiting factor in anaerobic treatment of domestic wastewaters under the temperate climate conditions of the study region. However, anaerobic treatment at ambient temperatures is not recommended for cold climate regions. It was shown that anaerobic treatment of domestic wastewaters without the requirement of heating may be considered as an appropriate alternative. However, the anaerobic treatment alternative can only act as a pretreatment step and requires further removal of nutrients such as nitrogen and phosphorus in order to achieve the discharge standards.

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