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Anaerobic treatment of strong sewage by a two stage system of AF and UASB reactors

Z. Sawajneh, A. Al-Omari and M. Halalsheh

ABSTRACT

An anaerobic treatment system that consists of an Anaerobic Filter (AF) and an Upflow Anaerobic Sludge Blanket (UASB) in series was built and operated to investigate its performance in treating strong domestic wastewater with high suspended solids fraction under Jordan's ambient temperatures of 25°C for summer and 18°C for winter. The system was operated from September 2003 until early April 2004. The system was operated at a Hydraulic Retention Time (HRT) of 4 hours for the first stage AF and 8 hours for the second stage UASB. Average COD_t and COD_{ss} removal efficiencies of the AF/UASB were 58% and 81% respectively for the operation period. The results showed that the first stage AF was effective in removing suspended solids. In addition, hydrolysis, acidification and methanogenesis took place in the first stage AF which was advantageous to the second stage UASB. It was concluded that the AF/UASB system is effective in treating strong domestic wastewater with high suspended solids content under Jordan's ambient temperatures.

Key words | anaerobic filter, anaerobic treatment, high rate systems, strong sewage treatment, two stage treatment systems, upflow anaerobic sludge blanket

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INTRODUCTION

Anaerobic treatment of wastewater has well known advantages which are: low sludge production, less sludge handling and treatment cost, no energy requirement for aeration, and production of methane gas which is an energy source (Rittmann & Baskin 1985). The invention of high rate reactors for which long Solids Retention Time (SRT) can be achieved at short Hydraulic Retention Time (HRT) has added significantly to these advantages, which made anaerobic treatment the choice for treating a wide range of wastewaters. The Upflow Anaerobic Sludge Blanket (UASB) reactor which is described in detail by other authors (Behling *et al.* 1997) was found by Lettinga *et al.* (1979) as "the most convenient, economical, and easily operated and controlled system that can be used for the anaerobic treatment of wastewater".

Since its invention, the UASB reactor has been successfully used to treat a wide range of wastewaters under different climatic conditions (Man *et al.* 1986; Behling *et al.* 1997; Ruiz *et al.* 1997; Blonskaja *et al.* 2003). However, under low to moderate temperatures, the UASB reactor is sensitive to the suspended solids loading. Lettinga (1992) found that the accumulation of suspended solids within the sludge bed under continuous feed leads to a drastic increase in the sludge bed height, which results in heavy washout of sludge particles from the reactor. Another problem associated with high suspended solids loading under moderate to low temperatures and high organic loading, is that suspended solids accumulation within the sludge blanket increases, (Genung *et al.* 1985; Sanz & Fdz-Polanco 1990; Zeeman & Lettinga 1999) which inhibits granule formation (Hulshoff & Lettinga 1986) and affects methanogenesis leading to reactor failure as a result of pH drop (Borja *et al.* 1996; Elmitwalli *et al.* 1999).

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To overcome these problems, several researchers investigated the use of different treatment units a head of the UASB to reduce suspended solids loading. Wang (1994) investigated the use of two UASB reactors in series for the treatment of domestic wastewater at a HRT of three hours for the first stage UASB, and two hours for the second stage UASB at 17°C and 12°C. He found that the first stage UASB reactor acted as an improved primary sedimentation tank, where high suspended solids removal was achieved in addition to some degree of hydrolysis, acidification and conversion to biogas. Total Chemical Oxygen Demand (COD_t) and Suspended Solids Chemical Oxygen Demand (COD_{ss}) removal efficiencies of 69% and 70% respectively were achieved at 17°C, while at 12°C COD_t and COD_{ss} removal efficiencies of 51% and 67% respectively were achieved. Sayed & Fergala (1995) used a two stage treatment system for the treatment of raw domestic sewage at a temperature range between 18 and 20°C, the first stage of which consisted of two identical UASB reactors seeded with flocculent sludge and operated alternately. The second stage consisted of a one UASB reactor seeded with granular sludge and operated continuously. The feeding and the stop feeding period for the first stage reactors were two days. The COD_t, of the raw wastewater ranged from 200 to 700 mg/l. At a HRT of 8 hrs for stage one and 2 hrs for stage two, COD_t removal efficiency of 75% was achieved, while at a HRT of 4 hrs for stage one and 2 hrs for stage two, COD_t removal efficiency of 84% was achieved. However, at a HRT of 8 hrs for the first stage, 41% of the COD_t stabilized was converted to methane gas, while at a HRT of 4 hrs for the first stage, only 28% of the COD_t stabilized was converted to methane gas. Elmitwalli *et al.* (1999) investigated the treatment of pre settled domestic wastewater at 13°C by an Anaerobic Hybrid (AH) reactor and by a UASB reactor. He concluded that the removal of suspended solids by pre settling resulted in an improved dissolved COD (COD_{dis}), and colloidal COD (COD_{col}) removals by the AH reactor as well as an improved COD_{col} removal efficiency by the UASB reactor. Uemura & Harada (2000) investigated the performance of a UASB reactor for the treatment of raw domestic wastewater. Reactor temperature was gradually varied from 25 to 13°C over the operation period of six months. HRT remained constant at 4.7 hrs. It was found that COD_t removal efficiency depended on the suspended solids strength of the influent rather than on the treatment temperature. However hydrolysis rate was dependent on the treatment temperature. Average COD_t and COD_{ss} removal efficiencies of 70% and 80% were achieved respectively for the operation period. Elmitwalli *et al.* (2002) investigated the performance of both Anaerobic Filter, AF, and AH for pre-treating domestic wastewater for the removal of suspended solids at a HRT of 4 hrs and a temperature of 13°C. The AF and the top of the AH were packed with vertically oriented sheets of Reticulated Polyurethane Foam (RPF) with knobs. They found that the AF reactor achieved significantly higher removal efficiencies for both COD_t and COD_{ss}. COD_t and COD_{ss} removal efficiencies of 55% and 82% respectively were achieved by the AF.

Halalsheh *et al.* (2005) investigated the treatment of strong domestic sewage generated in Jordan characterized by high COD_{ss}/COD_t ratio of (0.60–0.65) by a two stage UASB treatment system in series at 25 and 18°C which correspond to summer and winter average temperatures respectively. The first stage UASB was operated at a HRT of (8–10) hrs and the second stage UASB was operated at a HRT of (5–6) hrs. Results showed that the first stage UASB reactor removed 53% and 50% of the COD_t for summer and winter respectively, where COD_{ss} removals were 57% and 63% for summer and winter respectively. The high gas production from the first stage UASB as a result of high organic loading rate to the system caused high flow of dispersed sludge to the second stage UASB which lead to severe washout of sludge from the second stage UASB resulting ultimately in deteriorated effluent quality with high washed out sludge particles content.

The objective of the study presented in this paper is to investigate the performance of a two stage AF/UASB treatment system for treating high strength wastewater with high suspended solids content under Jordan's ambient temperatures of 25°C for summer and 18°C for winter.

MATERIALS AND METHODS

Experimental set-up

A two-stage AF/UASB pilot system was built at Abu-Nsair Wastewater Treatment Plant (WWTP), which is located

7 km north of Amman, the capital of Jordan. The two reactors are concrete cylinders. The AF has stainless steal coned bottom for regular sludge discharge. The diameters of the AF and the UASB reactor are identical of 0.60 m. The height of the AF is 2 m and the height of the UASB reactor is 4 m. The AF reactor is packed with vertically oriented sheets of RPF, the porosity of which is 97% (Huysman *et al.* 1983) with knobs at one-side. Table 1 shows the characteristics of the RPF sheets.

Seed sludge

The UASB reactor was inoculated to one third of its volume with flocculent sludge, which was brought from another pilot-scale UASB reactor treating strong sewage (average $COD_t = 1531$ mg/l). The ratio of inoculated sludge Volatile Suspended Solids (VSS) to Total Suspend Solids (TSS) was 0.54.

Set-up operation

The feed to the treatment system was pumped from the main channel of domestic wastewater that flows to Abu-Nsair WWTP after passing through screens and grit chamber. The treatment system was operated from late summer 2003 until late winter 2004 that is September 2003 until early April 2004. Average temperature for the first three months of operation was 21.7°C and for the remaining five months of operation which correspond to winter was 15.5°C. Table 2 summarizes the operational conditions for the treatment system.

Table 1 | Characteristics of the RPF used in this study (Elmitwalli *et al.* 2000)

Parameter	Value
Total sheet thickness (mm)	20
Base thickness (mm)	10
Knob thickness (mm)	10
Specific surface area (m^2/m^3)	500
Density (kg/m^3)	19–22
Number of pores (pore/inch)	7–15
Pore size (mm)	2.5

Table 2 | Operational conditions for the treatment system

Parameter	1st stage AF	2nd stage UASB
HRT (hrs)	4*	8
OLR‡ (Kg/m^3 d)	5.8–9.8	1.4–3.7
V_{up}† (m/hr)	0.5	0.5
Temperature °C	15–21	15–21
Sludge discharge frequency	Daily (50 L)	–

*Due to the high porosity of the RPF sheet of 97%, the HRT is calculated based on the total volume of the AF.
†Upflow velocity.
‡Organic loading rate.

Sampling and analysis

24-hr influent composite sample of raw domestic wastewater was taken weekly. AF and UASB effluent grab samples were taken weekly. Influent temperature and pH were measured twice a week. Samples were analyzed for COD_t, paper filtered COD (COD_{pf}), and COD_{dis} according to the Standard Methods for the Examination of Water and Wastewater (1995). COD_{ss} was calculated as the difference between COD_t and COD_{pf}. The concentration of Volatile Fatty Acids (VFA) was measured from membrane-filtered samples via the Varian Gas Chomatograph 3300 model equipped with 2 m × 1/8 inch SS porapak QS column. Helium gas was used as a carrier gas with 35 ml/min, the temperatures of the detector, injector and the column were 300°C, 220°C respectively.

RESULTS AND DISCUSSION

Influent quality

Influent characteristics for the operation period are summarized in Table 3. COD_t of the influent for the operation period ranged between 962 and 1,627 mg/l with an average of 1,349 mg/l and 1,247 mg/l for late summer and winter respectively. COD_{ss} of the influent for the operation period ranged between 573 mg/l and 1,126 mg/l with an average of 844 mg/l and 753 mg/l for late summer and winter respectively. COD_{ss}/COD_t ratio was 0.63 and 0.60 for late summer and winter respectively. According to MetCalf & Eddy (1991) the influent is classified as strong wastewater. In addition, COD_{ss}/COD_t ratio of the influent

Table 3 | Average influent characteristics for the operation period

Parameter	Unit	Late summer	Winter
Temperature	°C	21.7 (1.23)	15.5 (2.3)
pH	–	7.6 (0.15)	7.7 (0.16)
Seattlability	ml/l	6.0 (1.6)	4.7 (0.57)
TSS	mg/l	337 (100)	332 (112)
VSS	mg/l	248 (88)	251 (60)
VSS/TSS	–	0.73 (0.11)	0.78 (0.15)
COD_t	mg/l	1349 (226)	1247 (220)
COD_{ss}	mg/l	844 (183)	753 (142)
COD_{ss}/COD_t	–	0.63 (0.07)	0.60 (0.10)
COD_{col}	mg/l	162 (53)	164 (59)
COD_{dis}	mg/l	318 (66)	343 (92)
VFA	mg COD/l	219 (17)	107 (36)
Carbohydrate	mg COD/l	32 (5)	186 (20)
Lipids	mg COD/l	288 (43)	Not measured

Note: Values between parentheses are standard deviations.

was higher than that of the raw sewage reported by Sayed & Fergala (1995) of 0.45 to 0.55 and that reported by Elmitwalli *et al.* (1999) of 0.50. Average COD_{dis} of the influent was 318 mg/l for late summer and 343 mg/l for winter. Average COD_{dis}/COD_t ratio was 0.24 for late summer and 0.28 for winter which is in the range of the ratio for the raw sewage reported by Elmitwalli *et al.* (1999) of 0.25. Temperature ranged between 12 and 23°C with an average of 21.7°C for late summer and 15.5°C for winter.

Performance of the first stage AF

Percentage COD_{ss} removal by the first stage AF for the operation period is shown by Figure 1. The performance of

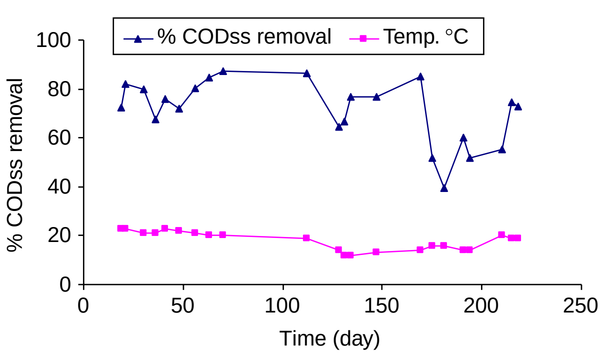

Figure 1 | % COD_{ss} removal versus time for the first stage AF.

the first stage AF oscillated with time at the beginning of the operation until day 48 when the performance started to improve steadily. After 70 days of operation, COD_{ss} removal efficiency reached its maximum of about 87%. COD_{ss} removal efficiency remained almost steady up to day 112. After that COD_{ss} removal efficiency went down corresponding to a temperature drop. During winter, there was fluctuation in the COD_{ss} removal efficiency, where a minimum removal efficiency of 39% was reached after 181 days of operation, after that COD_{ss} removal efficiency improved corresponding to a temperature rise till the end of operation period. Average COD_{ss} loading rate to the AF for late summer was 5.22 kg/m^3 d which corresponded to an average COD_{ss} removal efficiency by the first stage AF of 74%. For winter, average COD_{ss} loading rate to the AF was 4.49 kg/m^3 d which corresponded to an average COD_{ss} removal efficiency by the first stage AF of 66%. Elmittwali *et al.* (2002) obtained higher COD_{ss} removal efficiency of 82% for the AF operated at 13°C. However, the average COD_{ss} LR to the first stage AF operated in this study was about four folds of that to the AF operated by Elmittwali *et al.* (2002). Average COD_{ss} removal efficiency by the AF operated at the same HRT by Halalsheh (2002) for a similar wastewater was 71% at COD_{ss} LR of 5.13 kg/m^3 d and 25°C, which is lower than the removal efficiency obtained by the first stage AF operated in this study at an average temperature of 21.7°C and similar COD_{ss} LR of 5.22 kg/m^3 d. The improvement in COD_{ss} removal efficiency may be attributed to the lower gas production in this study due to the efficient sludge discharge from the AF. These results demonstrate that the first stage AF operated in this study is capable of removing high fraction of the influent suspended solids under average temperatures of 21.7°C and 15.5°C. In addition COD_{dis} removal by 11% was observed during late summer which is an indication that biological activity took place in the first stage AF during this period. Furthermore, VFA/COD_{dis} ratio increased from 0.69 in the influent to 0.98 in the effluent during late summer and from 0.28 in the influent to 0.54 in the effluent during winter. An increase in COD_{dis}/COD_t ratio from 0.28 in the influent to 0.44 in the effluent during winter was also observed. These numbers indicate that some degree of hydrolysis, acidification as well as methanogenesis took place in the first stage AF.

Average calculated hydrolysis, acidification and methanogenesis for the first stage AF were 42%, 46%, and 36% respectively during late summer, which decreased significantly during winter to 16%, 23%, and 12% respectively. The equations used for their estimations are mentioned in detail in Elmitwalli *et al.* (2002). SRT was found between 9 and 11 days during late summer, and between 7 and 10 days during winter. SRT was calculated assuming 15 g VSS/l attached to the filter media. Biogas production was observed in the first stage AF. COD_t balance around the first stage AF indicated that about 37% of the COD_t removed was converted into biogas during late summer which declined to 12% during winter as a result of temperature drop.

Performance of the UASB reactor

Figure 2 shows COD_t and COD_{ss} percentage removals by the second stage UASB. This figure shows considerable fluctuation in the COD_t removal efficiency over the operation period. Average COD_t removal efficiency by the second stage UASB was 26% for late summer at an average COD_t loading rate of 1.86 kg/m^3 d and an average temperature of 21.7°C. For winter, average COD_t removal efficiency was 23% at an average COD_t loading rate of 2.56 kg/m^3 d and an average temperature of 15.5°C. Figure 2 shows high fluctuation in the COD_{ss} removal efficiency by the second stage UASB. Average COD_{ss} removal efficiencies by the second stage UASB reactor were 54% and 38% for late summer and for winter respectively. The fact that the effluent VFA was higher than the influent VFA for most of the operation period as shown in Figure 3 indicates low

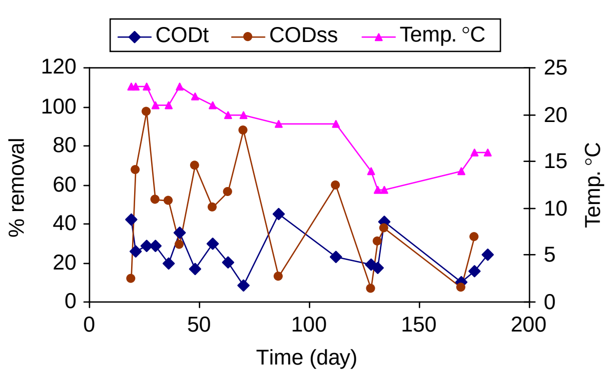

Figure 2 | % COD_t & COD_{ss} removals by the second stage UASB.

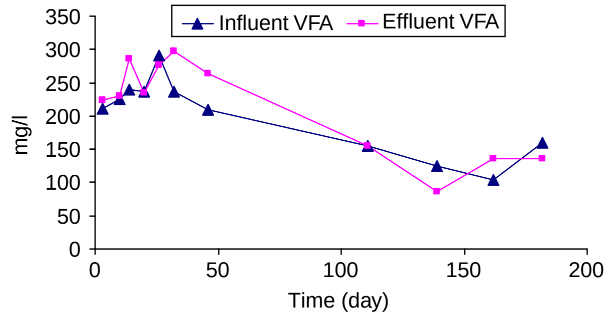

Figure 3 | Influent and effluent VFA concentrations for the second stage UASB reactor.

level of methanogenesis in the second stage UASB. Another indication of the low methanogenesis level in the second stage UASB is the low methane gas production. Based on methane gas percentage of 76% in the biogas (Kerstens 2001), average methane gas production was 5.0 l/d during the first 52 days of operation. No significant gas production was observed after that. The low level of methanogenesis in the second stage UASB means that COD_t removal in the second stage.

UASB was mainly attributed to the removal associated with the removal of SS by the physical processes of entrapment and settling in the sludge bed. The low level of methanogenesis in the second stage UASB can be explained by the fact that the system operation started late summer and continued until the end of winter. By the time the performance of the UASB peaked after about 86 days of operation, the UASB performance went down due to a temperature drop in December. After that, the UASB performance oscillated due to temperature fluctuation until the end of the operation period, early April. It is also interesting to note the high correlation between COD_t and COD_{ss} removal efficiencies in Figure 2 which suggests that COD_t and COD_{ss} are strongly related which supports the finding that COD_t removal in the second stage UASB is mainly related to the COD_{ss} reduction due to suspended solids settlement and entrapment in the sludge bed.

Performance of the AF/UASB system

Figure 4 shows the performance of the AF/UASB system for the duration of this study. This figure shows that COD_t removal efficiency of about 60% was achieved after one month of operation, COD_t removal efficiency continued to

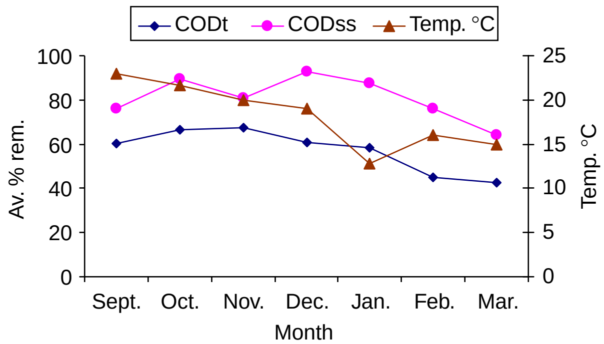

Figure 4 | AF/UASB system performance for the duration of the study.

improve until month three of operation which is November for which an average COD_t removal efficiency of 68% was achieved. After that COD_t removal efficiency dropped corresponding to a temperature drop in December which continued until March for which average COD_t removal efficiency of 42% was reached. Average COD_t removal efficiencies were 65% and 51% for late summer and winter respectively with an average of 58% for the operation period. Figure 4 also shows that average COD_{ss} removal efficiency started at 76% for September and peaked in December when the average COD_{ss} removal efficiency was 93%. After that average COD_{ss} removal started to decline corresponding to a temperature drop until March when the average COD_{ss} removal efficiency was 64%. Average COD_{ss} removal efficiency for late summer was 84% while average COD_{ss} removal efficiency for winter was 79%.

Figure 5 shows COD_t, COD_{ss} and COD_{diss} for the influent and at the different stages in the treatment process. Investigation of this figure shows that the significant portion of the COD_{ss} was removed in the first stage AF with some removal also taking place in the second stage UASB, COD_t and COD_{diss} removal took place in both the AF and the UASB at different percentages over the operation period.

Table 4 shows a summary of the performance of different treatment systems operated by other researchers as compared to the treatment system presented in this study. Table 4 shows that the performance of the AF/UASB system is better than the steady state performance of the two stage UASB treatment system operated by Halalsheh *et al.* (2005) in removing both COD_t and COD_{ss}. COD_t Removal efficiencies obtained by Wang (1994) are slightly higher than those obtained by the AF/UASB system. However COD_{ss} removal efficiencies achieved by the AF/UASB system are higher than those achieved by Wang (1994). The UASB operated by Uemura & Harada (2000) at a temperature range similar to the AF/UASB system achieved an average COD_{ss} removal efficiency of 80% over the operation period which compares well with the average COD_{ss} removal efficiency for the AF/UASB system of 81% for the operation period despite the fact that the average COD_{ss} LR to the UASB operated by Uemura & Harada (2000) was significantly lower than the average COD_{ss} LR to the AF/UASB system. However, the average COD_t removal efficiency achieved by the UASB system operated by Uemura & Harada (2000) was 70% compared to an average of 58% for the AF/UASB system which is due to the higher COD_t LR to the AF/UASB system. The two stage UASB treatment

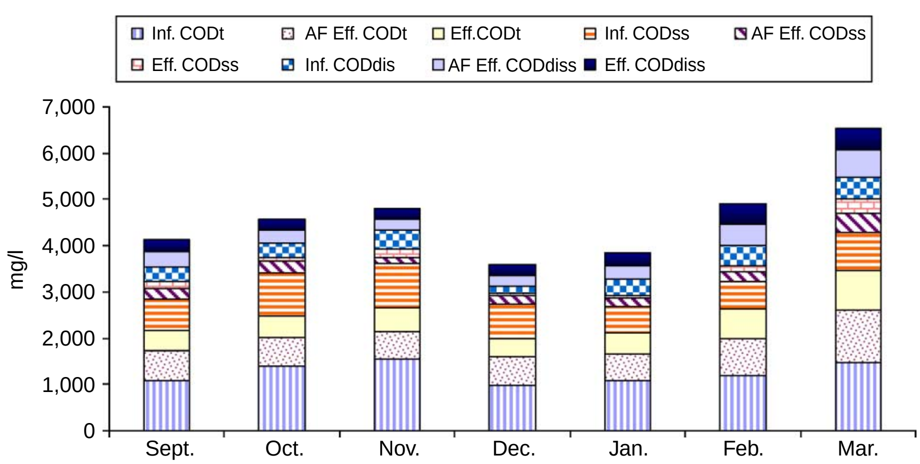

Figure 5 | COD_t, COD_{ss} and COD_{dis} at the influent and at the different stages of the treatment.

Table 4 | Summary of the performance of different treatment systems as opposed to the system presented in this study

Reactor	Seed sludge	WT	Temp. °C	Average COD_t LR ($kg/m^3 d$)	% Removal COD_t	% Removal COD_{ss}	Reference
UASB/UASB	F/G	RD	17	3.35	69	79	Wang (1994)
UASB/UASB	F/G	RD	12	2.43	51	67	Wang (1994)
UASB/UASB	F/G	RD	18–20	1.8	84	NA	Sayed & Fergala (1995)
UASB/UASB	F/G	RD	18–20	1.08	75	NA	Sayed & Fergala (1995)
UASB	G	RD	13	1.37	65	88	Elmitwalli et al. (1999)
AH	G	RD	13	1.37	66	92	Elmitwalli et al. (1999)
UASB	G	SD	13	1.03	59	79	Elmitwalli et al. (1999)
AH	G	SD	13	1.03	61	87	Elmitwalli et al. (1999)
UASB/UASB	G	RD	13–25	1.59	70	80	Uemura & Harada (2000)
UASB/UASB	None	RD	18–25	(3.6–5.0)/(2.9–4.6)	52*	60*	Halalsheh et al. (2005)
UASB†	None	RD	18–25	1.4–1.6	57*	53*	Halalsheh et al. (2005)
UASB‡	None	RD	25	1.4–1.6	58	53	Halalsheh et al. (2005)
AF/UASB	F	RD	12–23	2.61	58	81	This study

*Average for summer and winter.
†No sludge discharge.
‡Regular sludge discharge concentration in the sludge bed.
F, Flocculent; G, Granular; RD, Raw Domestic; SD, Settled Domestic; NA, Not Available.

system operated by Sayed & Fergala (1995) achieved higher COD_t removal efficiencies than the AF/UASB system which is attributed to the higher operation temperature of the first system. Further COD_t LR to the two- stage UASB operated by Sayed and Fergala was lower than COD_t LR to the AF/UASB system. COD_t Removal efficiencies by the two reactors operated by Elmitwalli *et al.* (1999) were 59% and 61% for the UASB and AH reactors respectively. Removal efficiencies for COD_{ss} were 79% and 87% for the UASB and AH reactors respectively. COD_t LR to the two reactors was 1.03 $kg/m^3 d$ and temperature was 13°C. COD_t and COD_{ss} removal efficiencies achieved by the two systems operated by Elmitwalli *et al.* (1999) compare well with the removal efficiencies achieved by the AF/UASB despite the higher COD_t and COD_{ss} Loading Rates (LRs) used in this study, however, the operation temperature for the treatment system described here was higher.

Despite the fact that the AF/UASB system in this study started operation late summer and continued through winter and despite the high COD_t and COD_{ss} loading rates, results showed that this treatment system is efficient in treating strong domestic wastewater with high suspended solids fraction. It is also justified to say that the AF/UASB treatment system is expected to perform better especially in regard to COD_t removal when operated during summer when temperatures are high.

CONCLUSIONS

A two stage anaerobic treatment system was built and operated at Abu-Nsair wastewater treatment plant to treat strong raw sewage with high suspended solids under Jordan's ambient temperatures. The first stage is an AF and the second stage is a UASB reactor. The performance of the first stage AF was found satisfactory in removing influent suspended solids. In addition hydrolysis, acidification and methanogenesis took place in the first stage AF, which was advantageous to the second stage UASB reactor. The results showed that the treatment system performance was satisfactory in treating strong domestic wastewater with high suspended solids content despite the fact that the system was operated for a short period of time most of which was during winter.

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