ANAEROBIC SEWAGE TREATMENT IN A ONE-STAGE UASB AND A COMBINED UASB-DIGESTER SYSTEM

Nidal Mahmoud[+,1], Grietje Zeeman[+], Huub Gijzen[++] and Gatze Lettinga[+]

[+] Department of Agricultural, Environmental and Systems Technology, Sub-Department of Environmental Technology, Wageningen University, P.O. Box 8129, 6700 EV, Wageningen, The Netherlands.

[++] International Institute for Infrastructural, Hydraulic and Environmental Engineering (IHE) Westvest 7, 2601 DA Delft, the Netherlands.

ABSTRACT

The potential of a novel technology consisting of a UASB complemented with a digester (UASB-Digester) for mutual sewage treatment and sludge stabilisation under low temperature conditions was investigated. The performance of the UASB-Digester system was compared with a one stage UASB. The UASB reactor was operated at a HRT of 6 hours and controlled temperature of 15°C, the average sewage temperature in the Middle East countries during wintertime, while the digester was operated at 35 °C. The UASB-Digester provided substantially better removal efficiencies and conversion than the one stage UASB reactor ($p<0.05$). The achieved removal efficiencies in the UASB-Digester and the one stage UASB for CODt, CODss, CODcol and CODdis are "66, 87, 44 and 30" and "44, 73, 3 and 5"% for both systems, respectively. The wasted sludge from the UASB-Digester is much more stabilised. The performance of the UASB digester is as good as that achieved in tropical countries. Therefore, the anaerobic sewage treatment at low temperature in a UASB-Digester system is recommended.

Keywords: Anaerobic treatment; low temperature; one stage UASB; sewage; suspended solids; UASB-Digester

---

[1] Present address: Dept. of Civil Engineering, Birzeit University, PO Box 14, Birzeit, The West Bank, Palestine; E-mail address: nmahmoud@birzeit.edu

INTRODUCTION

Anaerobic digestion has been broadly recognised as the core of sustainable waste management (Hammes *et al.* [7]). The UASB reactor is the most widely and successfully used high rate anaerobic system for sewage treatment (Lettinga [11]). It gained a lot of popularity in tropical countries where ambient temperature is rather high ranging between 20 and 30°C (Haandel and Lettinga [6]), and the sewage strength is rather low.

In the Middle East region, the ambient temperature fluctuates between winter and summer, resulting in respectively sewage temperature of 15 and 25°C. Moreover, sewage is concentrated with a high fraction of suspended solids (Mahmoud *et al.*, [13]). The performance of the one-stage UASB systems at low temperature climates (5-20°C) is highly limited by the hydrolysis of entrapped solids, which accumulate in the sludge bed when high loading rates are applied (Sanz and Fdz-Polanco [19]; Zeeman and Lettinga [23]). Consequently, the amount of excess sludge will increase leading to a lower sludge retention time (SRT) which might limit methanogens growth (Haandel and Lettinga [6]) resulting in a poor soluble COD removal and deterioration of sludge stability (Wang [22]).

The anaerobic sewage treatment is certainly not limited to regions of hot climates. Two stage systems consisting of a high loaded first stage followed by a methanogenic stage have been proposed for sewage treatment at low temperature (Wang [22]; Elmitwalli [5]). However, when applying high loaded reactors, the produced sludge is by definition not stabilised and needs further stabilisation in a separate digester. Lettinga and Hulshoff Pol [12] proposed a novel technology consisting of an integrated high loaded UASB and digester for sewage treatment under low temperature conditions. The solids, which are entrapped in the sludge bed, are conveyed to a digester operated at optimal conditions where they can be stabilised and the digested sludge is recirculated to the UASB reactor to improve its methanogenic capacity.

In the present work, the anaerobic sewage treatment using a UASB-Digester system has been investigated at a sewage temperature of 15°C. The UASB was firstly operated without incorporating the digester aiming at identifying the best location in the sludge bed for taking and re-circulating sludge and comparison of the performance of the UASB with the UASB-Digester system. The UASB-Digester was operated aiming at performance validation and demonstration in addition to formulation of criteria for good performance and further improvement.

MATERIALS AND METHODS

Experimental set-up

The experimental work has been carried out over two successive periods. Firstly, a pilot -scale of a one stage flocculent sludge UASB reactor (volume, height, diameter: 140 l, 325 cm, 23.5 cm) was operated at 15°C without incorporating a digester. Afterwards, the UASB was modified to the UASB-Digester system by incorporating a CSTR digester (working volume 106 l) operated at 35°C. A schematic diagram of the experimental set-up is illustrated in Fig. 1. The UASB reactor and the digester were constructed from Plexiglas and PVC tubes, respectively. The temperatures of the reactors content were controlled by re-circulating water in tubes wrapping the reactors through external thermostats. 5-cm thick rock wool sheets were wrapped around the UASB reactor for thermal isolation. Taps were installed over the whole UASB height at ± 25 cm for sludge discharge, re-circulation and analysis. The digester content was continuously mixed at 8 rpm.

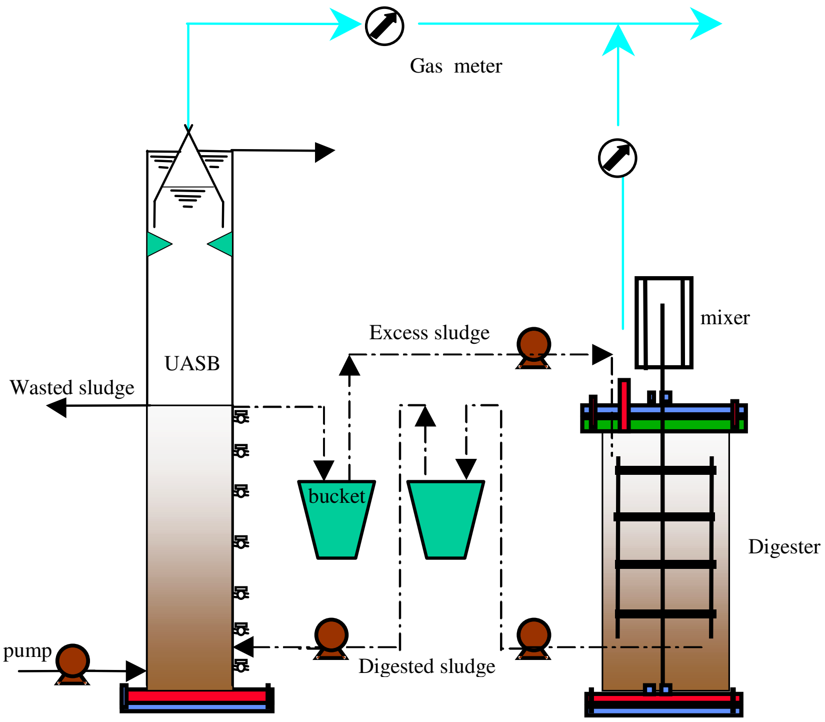

Fig. 1. Schematic diagram of the UASB-Digester pilot plant

Pilot plants operation and start up

The UASB reactor was initially inoculated with an anaerobic sludge discharged from a 6-m^3 research pilot-scale USAB reactor, located in our research hall. This reactor is operated at ambient temperature, treating domestic sewage originating from the village of Bennekom - The Netherlands. The digester was inoculated with digested primary sludge from the wastewater treatment plant of Ede-The Netherlands. During the operation of the one stage UASB system, the excess sludge was fed to the digester to accelerate the digester start up, without sludge re-circulation.

The sludge bed was kept below tap 9, *ca*. 190 cm from the UASB bottom, by once daily opening this tap for discharging the sludge accumulated above. The discharged sludge was collected in 10 litre buckets, from which the sludge was immediately fed to the digester by a peristaltic pump. At the same time, the digester effluent was pumped out to another bucket, while a third pump was re-circulating it to tap 1 of the UASB, *ca*. 15-cm from the bottom. Sludge was wasted from the UASB at tap 9 after a settling period of half an hour after finishing the recirculation process. The one stage UASB and the UASB-Digester were operated for 81 and 83 days, respectively of which the first 35 and 33 days were (arbitrarily) considered as start-up periods. The reactors behaviour during the steady state period met the criteria for steady state set by Noyola *et al.* [15] and Polprasert *et al.* [16]. Noyola *et al.* [15]) considered 'steady state' of an anaerobic reactor treating domestic sewage to be achieved after an operation period of 10 times the new HRT with a minimum of 2 weeks. Polprasert *et al.* [16] considered 'steady state' to be achieved once the effluent COD concentrations varied within ±10%. Elmitwalli [5] considered these criteria satisfactory for achieving steady state conditions.

Sewage

The used sewage of the village of Bennekom-The Netherlands comes from a combined sewer system and is continuously pumped to our experimental hall. The concentration of this sewage was slightly (about 9%) increased by being continuously pumped to a 350 l settler at a flow rate of 55 l/hr of which 12 l/h was overflowed to the sewer system and 43 l/h was pumped during 8:00 am - 21:00 p.m. to a buffer tank, from which the UASB was continuously fed. The content of the buffer tank was continuously mixed at 60 rpm. Composite samples for 48, 48 and 72 hours of the buffer tank and the UASB effluent were collected in containers stored in a refrigerator at 4°C.

Analytical methods

COD analysis was carried out using the micro-method, described by Jirka and Carter [8]. Raw samples were used for COD total (CODt); filtered samples through 4.4 μm folded paper-filters (Schleicher & Schuell 5951/2, Germany) for COD filtrate (CODpf) and through 0.45 μm membrane filters (Schleicher and Schuell ME 25, Germany) for dissolved COD (CODdis). The COD suspended (CODss) and COD colloidal (CODcol) were calculated by the difference between "CODt and CODpf" and "CODpf and CODdis", respectively. Volatile fatty acids (VFA) were measured from membrane-filtered samples with a gas chromatograph, as described by Elmitwalli [5]. The biogas composition (CH_4, CO_2, N_2, O_2) was determined using a gas chromatograph, as described by Elmitwalli [5]. The Kjeldahl nitrogen (Nkj), sludge volume index (SVI), capillary suction time (CST), total solids (TS), volatile solids (VS) were measured according to the *Dutch Standard Normalised Methods* [4]. Total ammonium (NH_4^+- N) was determined with an automatic analyser (Skalar 1520).

Total lipids, carbohydrates and dewaterability were determined as described by Elmitwalli [5]. The analysed sludge samples for total COD, total carbohydrates and Nkj were previously homogenised by ultra – Turrax (Heidolph, DIAX 900). Sludge stability was measured in serum bottles (500 ml) incubated at 30 ºC as described by Elmitwalli [5]. Methane in the headspace was determined by the gas displacement method using 5% NaOH solution.

Calculations

The equations which have been used for describing the conversion processes and solids retention times (SRT) are presented below.

One stage UASB

$$Hcarb\,(\%) = 100\,\frac{(Ccarb_{(inf)} - Ccarb_{(eff)})\ x\ Q_{(inf)} - Ccarb_{(w)}\ x\ Q_{(w)}}{Ccarb_{(inf)}\ x\ Q_{(inf)}} \tag{1}$$

$$Am\,(\%) = 100\,\frac{NH4(eff)\ x\ Q(eff) + Q(w)\ x\ NH4(w) - Q(inf)\ x\ NH4(inf)}{Nkj(inf)\ x\ Q(inf)} \tag{2}$$

$$H(\%) = 100\left(\frac{CH_4\text{-}COD + CODdis_{(eff)} - CODdis_{(inf)}}{CODt_{(inf)} - CODdis_{(inf)}}\right) \tag{3}$$

$$A(\%) = 100\left(\frac{CH4\text{ -}COD + VFA\text{ -}COD_{\,(eff)} - VFA\text{ -}COD_{\,(inf)}}{CODt_{\,(inf)} - COD\text{ -}VFA_{\,(inf)}}\right) \tag{4}$$

$$M(\%) = 100\left(\frac{CH4\text{ -}COD}{CODt_{\,(inf)}}\right) \tag{5}$$

$$SRT = \frac{M_{SB}}{Q_{(w)}\ x\ X_{(w)}} \tag{6}$$

UASB-Digester

$$Hcarb_{\,(U\ -\ dig)}\,(\%) = 100\,\frac{(Ccarb_{\,(inf)} - Ccarb_{\,(eff)})\ x\ Q_{(inf)} - Q_{(w)} * Ccarb_{\,(w)}}{Qinf\ \ x\ Ccarb_{\,(inf)}} \tag{7}$$

$$Hcarb_{\,(dig)}\,(\%) = 100\,\frac{Q_{(exc)}\ x\ Ccarb_{\,(exc)} - Q_{(dig)}\ x\ Ccarb_{\,(dig)}}{Q_{(inf)}\,(Ccarb_{\,(inf)} - Ccarb_{\,(eff)})} \tag{8}$$

$$Hcarb_{\,(UASB)}\,(\%) = Hcarb_{\,(U\ -\ dig)} - Hcarb_{\,(dig)} \tag{9}$$

$$Hcarb_{(digester)}(\%) = 100 \frac{Ccarb_{(exc)} - Ccarb_{(dig)}}{Ccarb_{(exc)}} \quad (10)$$

$$Hnitrog.(digester)(\%) = 100 \frac{(Nkj(exc) - NH4(exc)) - (Nkj(dig) - NH4(dig))}{(Nkj(exc) - NH4(exc))} \quad (11)$$

$$Hlipids_{(digester)}(\%) = 100 \frac{Clipids_{(exc)} - Clipids_{(dig)}}{Clipids_{(exc)}} \quad (12)$$

$$Am(\%) = 100 \frac{Q(inf)\ x\ NH4(eff) - Q(inf)\ x\ NH4(inf) - Q(dig)\ x\ NH4(dig) + Q(exc)\ x\ NH4(exc) + Q(w)\ x\ NH4(w)}{Q(inf)\ x\ Tkj(inf)} \quad (13)$$

$$SRT_{(UASB)} = \frac{M_{SB}}{Q_{(exc)}\ x\ X_{(exc)}} \quad (14)$$

$$SRT_{(dig)} = HRT = \frac{V_{(dig)}}{Q_{(dig)}} \quad (15)$$

Where: *H*, percentage hydrolysis; *A*, percentage acidification; *M*, percentage methanogenesis; *Am*, percentage ammmonification (ammonia production in the UASB reactors due to particulate-N hydrolysis and acidification as a percentage of the influent Nkj-N); Ccarb, total carbohydrates; w, wasted sludge from the UASB; *inf*, influent; *eff*, effluent; *exc*, excess sludge (sludge conveyed from the UASB to the digester); dig, digested sludge (digester effluent); M_{SB}, total sludge mass (g VS/l) in the sludge bed (average of 5 measurements); *Q*, flow rate (l/d); equations 2, 3 and 4 are also valid for the UASB and digester of the UASB-Digester system; CH_4 as COD = CH_4 as $COD_{(liquid\ form)}$+ CH_4 as $COD_{(gas\ form)}$

RESULTS AND DISCUSSION

Removal of various COD fractions

The main characteristics of the sewage used in this research are presented in Table 1. The reduction of the influent COD during the performance of the UASB-Digester run in comparison with the one stage UASB is due to dilution with rainwater.

Table 1. Characteristics of the influent sewage (Bennekom - The Netherlands)

+parameter	UASB		UASB-Digester	
	++n =16	n = 6	n = 20	n = 6
CODt	721 (171)		460 (122)	
CODss	398 (167)		251 (100)	
CODcol	151 (46)		124 (24)	
CODdis	172 (42)		86 (37)	
COD-VFA	76 (38)		34 (25)	
Total carbohydrates		68 (22)		99 (29)
Suspended carbohydrates		41 (3)		76 (27)
Colloidal carbohydrates		15 (9)		11 (2)
Dissolved carbohydrates		12 (4)		12 (2)
Nkj-N		72 (12)		50 (13)
NH_4^+-N		57 (14)		43 (8)
PH	7.4 (0.1)		7.3 (0.2)	

+ All parameters are in mg/L except pH; ++ number of measurement except pH (daily)

The mean values of effluent CODt and fractions and the removal efficiencies of the UASB and the UASB-digester systems are depicted in Table 2. The results clearly reveal that the UASB-Digester system achieved substantially better physical removal efficiencies of all COD fractions as compared to the one stage UASB system ($p<0.05$) and a more stable performance as can be seen by the low standard deviations.

Although, the removal of VFA-COD in the UASB of the UASB-digester was very high, the removal of CODdis was limited (30%) (Table 1). The achieved effluent soluble COD of almost 50 mg COD/l is obviously the lowest achievable soluble COD value in anaerobic sewage treatment of the village of Bennekom (Last *et al.* [9]; Elmitwalli [5]). Apparently, the soluble fraction of the effluent COD (partly) consisted of soluble microbial products (SMP), which are resistant to anaerobic degradation (Aquino and Stuckey [1]).

The substantial improvement of CODcol removal achieved in the combined system over the one-step UASB reactor might be due to the creation of better digestion conditions in the combined system. Elmitwalli [5] found that the colloidal particles in the sewage are highly biodegradable and attributed the reported poor colloidal removal during anaerobic sewage treatment at low temperature to poor physical removal. Similarly, the improvement of CODss removal might result from the better digestion conditions, which can also justify the enhancement of CODcol removal, since colloids may be generated from the suspended solids (Elmitwalli [5]). Accordingly, our results suggest the existence of a capturing - de-capturing mechanism for solids removal in the sludge bed. Consequently, the solids physical removal might not only be affected by the characteristics of the influent particles and the sludge but also by the digestion conditions.

Hydrolysis, acidification and methanogenesis

The percentage hydrolysis, acidification and methanogenesis are depicted in Table 3. In the one stage UASB reactor, not hydrolysis, but methanogenesis was limiting the overall conversion of organic matter to methane. The effluent contained a high amount of soluble COD amounting to 162(47) mg COD/l of which 80(40) mg COD/l was in the form of VFA. Differently, in the UASB of the UASB- Digester system, hydrolysis was the limiting step of the overall digestion processes. Moreover, the results clearly reveal that the conversion in the UASB of the UASB-Digester system is substantially higher than in the one stage UASB. On one hand, this can be attributed to the existence of better methanogenic conditions in the UASB of the UASB-Digester system, which might have enhanced the hydrolysis step through, e.g. improving the contact between the substrate and the hydrolytic enzymes due to biogas production (Sanders [18]). On the other hand, the reduction of the OLR from 2.88 (0.69) g COD/l.d in the one stage UASB run to 1.84 (0.49) g COD/l.d in the UASB-Digester run, due to the lower influent COD, is also a factor that might have enhanced the conversion in the UASB-digester run. The COD mass balance presented in Fig. 2 shows that the main COD conversion takes place in the UASB reactor.

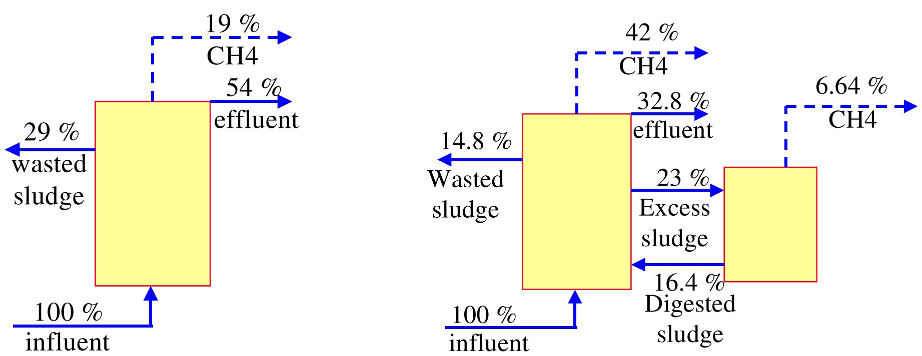

Fig. 2. COD mass balance of a one stage UASB (left) and a UASB-digester system (right) over a period of respectively 47 and 45 days. Both UASB reactors were operated at HRT=6 hours; T = 15 °C and the digester at SRT = 21 days and T = 35 °C.

Sludge characteristics

The characteristics of the excess, digested and wasted sludges are presented in Table 4. The results show a substantially higher VS/TS ratio of the excess sludge of the UASB reactor in comparison with that from the UASB of the UASB-Digester system, which indicates better stability of the latter. This was confirmed by the results of the stability test. The sludge digested in the digester has substantially higher stability than the excess sludge from the UASB of the UASB-Digester system due to dilution of the sludge bed with the influent solids. The relatively low SVI of the UASB, UASB of the UASB-Digester system and the digester sludges reveals high settleability with no influence of the digestion conditions.

The high filterability constant of the wasted sludge of the UASB of the UASB-Digester system as compared to that of the UASB reactor demonstrates that the first sludge is better dewaterable ($P<0.05$) but the digested sludge is not ($P<0.05$). This can be explained by production of small particles during digestion and hence increase of particles specific surface area (Lawler *et al.* [10]).

The TS measured along the sludge bed height showed a decline trend in concentration from 33 to 13 g TS/L at the bottom and top of the sludge bed, respectively, with clear stratification at the border of 40% height of the bottom of the reactor. The VS/TS ratio was almost constant over the sludge bed height, which indicates that the sludge is equally stabilised over the bed.

The results presented in Table 5 reveal that the carbohydrates in sewage are efficiently removed in the UASB systems, as a result of high removal of the suspended part. The results show insignificant ($p<0.05$) difference in carbohydrate conversion between the UASB and the UASB-Digester system.

The Nkj-N was partly removed in the UASB reactors due to particulate N removal, but NH_4^+- N was released as a result of protein hydrolysis (Table 5). The hydrolysis of particulate N in the studied systems could not accurately be calculated as the difference between Nkj- N and NH_4^+- N was very low and within the marginal error of the used measuring instruments. Instead, the hydrolysis of particulate N was based on ammonia production (eq. 2 and 12). The results show no ammonia production in the UASB, while it was significant ($p<0.05$) in the UASB of the UASB-Digester.

In the digester, the percentage conversion of the particulate N, carbohydrates and lipids based on the digester influent were 29 (5), 25 (16) and 52 (3), respectively. Nkj removal of 6 (1.5)% occurred in the digester ($p<0.05$) which might be due to ammonia precipitation through complex formation, e.g. precipitation of ammonium as struvite ($MgNH_4PO_4.6H_2O$) (Mamals *et al.* [14]). The low carbohydrate degradation in the digester is due to the relatively high carbohydrate conversion in the UASB; the same could also stand for the lipids as much more lipid hydrolysis at the applied digestion conditions was found (Mahmoud *et al.* [13]) when digesting primary sludge in a CSTR.

Table 4. Characteristics of the retained and wasted sludge in the UASB system and the retained, excess and wasted sludge in the UASB-Digester system. Standard deviations are presented between brackets

Parameter	Unit	UASB	UASB-Digester	
			UASB	Digester
Retained sludge				
Concentration	g $VS.l^{-1}$sludge bed	16.81 (1.15)	13.63 (0.93)	5.34 (0.77)
+SRT	days	24.27 ± 5.19	29.7 ± 9.36	21.16 ± 1.52
Excess sludge				
VS/TS	%		67 (2)	
SVI	$ml.g^{-1}.SS$		37.35 (6.23)	
Stability	g CH_4-$COD.g^{-1}COD$			
COD/VS	gCOD/gVS		1.73 (0.01)	
$\chi x10^6$	$kg^2.m^4.s^{-2}$		62.45 (17.66)	
Wasted sludge				
VS/TS	%	71 (1.13)	67.5 (2)	
SVI	$ml.g^{-1}.SS$	31.4 (1.7)	32.98 (1.40)	
Stability	g CH_4-$COD.g^{-1}COD$	45.6(0.5)	36.2(4.9)	
COD/VS	gCOD/gVS	1.87 (0.12)	1.74 (0.07)	
$\chi x10^6$	$kg^2.m^4.s^{-2}$	29.26 (5)	59.09 (29.45)	
Digested sludge				
VS/TS	%			63.5 (0.6)
SVI	$ml.g^{-1}.SS$			30.09 (1.20)
Stability	g CH_4-$COD.g^{-1}COD$		19.9(6.6)	
COD/VS	gCOD/gVS			1.77 (0.13)
$\chi x10^6$	$kg^2.m^4.s^{-2}$			26.14 (4.48)

+SRT with 95% confidence interval

Sludge production

The daily wasted sludge from the UASB (0.17(0.04) g VS/g COD_{inf}) is significantly lower than from the UASB-Digester system (0.0.08(0.01) g VS/g COD_{inf}). The sludge production in the UASB-Digester system is similar to that reported by Cavalacanti *et al.* [2] (0.08 and 0.07 g VSS/ g CODin) during anaerobic sewage treatment at 4 - 8 hours HRT and 25 - 28 °C.

General discussion

The results clearly reveal the high potential of the UASB-Digester system for sewage treatment at low temperature of 15 ºC as it couples wastewater treatment and sludge stabilisation. The system solves the problem of solids accumulation in the sludge bed at low temperature conditions. Consequently it can be successfully applied for sewage treatment in almost all countries with low or fluctuating temperature climates like the Middle East. Ruiz *et al.* [17] reported during anaerobic treatment of domestic sewage at 20 ºC in a bench scale UASB (2 l), an increase of the COD and SS removal efficiencies by about 5% when incorporating a digester.

The system is not only superior to the one stage UASB system for sewage treatment at low temperature climates but also to other so far proposed systems, e.g. the two stage Hydrolysis Upflow Sludge Bed (HUSB) + Expanded Granular Sludge Bed (EGSB) system (Wang [22]) and Anaerobic filter (AF) - Anaerobic hybrid (AH) (Elmitwalli [5]). Worth mentioning that both researches of (Wang [22]) and (Elmitwalli [5]) were carried out in our experimental hall, using the same sewage source we used in this research. The effluent CODt of the UASB-Digester (151 mg COD/L) is lower than that of the HUSB-EGSB system (200-250 mg COD/L) and the AF+AH when operated at 2+4 hours (211 mg COD/L) and 3+6 hours (195 mg COD/L) and differs only in 15 mg COD/l from the AF-AH system when operated at 4+8 hours. Nonetheless, the excess sludge from the UASB-Digester is well stabilised, while that from both the HUSB+EGSB and AF+AH systems was poorly stabilised and consequently would need further digestion in a separate digester. Since the digester should be incorporated to the HUSB+EGSB and AF+AH systems, it is rational to compare the volume of those systems with only the volume of the UASB without including the volume of the digester. As the UASB of the UASB-Digester system, HUSB+EGSB and AF+AH were operated at 6, 5 and 12 hours, the UASB -Digester system is more compact in comparison to the AF+AH but not the HUSB+EGSB. Nonetheless, the UASB-Digester system is less complex and achieved better effluent quality. Moreover, the HUSB+EGSB system is not expected to be an attractive technology for the treatment of high strength sewage at low temperature like the case in the Middle East (CODss: ± 1000 mg COD/l) (Mahmoud *et al.* [13]). The reduction of suspended solids removal in the HUSB with decreasing temperature will certainly lead to deterioration of granular sludge in the EGSB system (Lettinga and Hulshoff Pol [12]).

The removal efficiency of total COD in the UASB-Digester system is as high as those reported for tropical countries like Sao Paulo-Brazil by Vieira [21] (70%), Bucaramanga - Columbia by Schellinkhout *et al.* [20] (66 %) and Kanpur - India by Draaijer *et al.* [3] (62 - 70 %).

The volume of the digester can be greatly reduced. Our previous work (Mahmoud *et al.* [13]) showed hardly any improvement in the digester performance at increasing the SRT above 10 days at 35 °C or 15 days at 25 °C. Moreover, due to solids content stratification in the sludge bed while maintaining a uniform stability, sludge with a high concentration can be conveyed from the UASB to the digester. This will lead to substantial reduction in the digester volume. Similarly, the volume of the UASB in the UASB-Digester can also be reduced as the results clearly show that it was under loaded.

CONCLUSIONS

- The here presented UASB-Digester system represents an efficient technology for anaerobic sewage (pre) treatment at low temperature conditions, i.e. it provides average removal efficiencies for CODt, CODss, CODcol and CODdis of 66, 87, 44 and 30%, respectively.
- The sludge re-circulation improved both the solids physical removal and the conversion as it increased the methanogenesis from 20 % in the one stage UASB reactor to 47 % in the UASB-Digester system.
- The sludge production from the UASB-Digester system is very low, the sludge is very well dewaterable and stabilised.

RECOMMENDATIONS

- The sludge to be re-circulated from the UASB to the digester is recommended to be taken from the first 40% height of the sludge bed.
- The sludge wastage is recommended to be from the digester not the UASB.
- The produced biogas should be reused for heating the digester content.

REFERENCES

[1] Aquino, S. F. and Stuckey, D. C. (2001) Characterization of soluble microbial products (SMP) in effluents from anaerobic reactors. *Proc. 9th. Int. Symp. on Anaerobic Digestion*. Antwerpen, Belgium. 109 - 116.

[2] Cavalacanti, P. F. F., Medeiros, E. J. S., Silva, J. K. M. and Haandel, A. van. (1999) Excess sludge discharge frequency for UASB reactors. *Water Sci. Technol.* **40**(8), 211-220.

[3] Draaijer, H., Maas J. A. W., Schaapman, J. E. and Khan, A. (1992) Performance of the 5 mild UASB reactors for sewage treatment at Kanpur, India. *Water Sci. Technol.* **25**(7), 123-133.

[4] Dutch Standard Normalized Methods (1969) The Netherlands Normalisation Institute, Delft, The Netherlands.

[5] Elmitwalli, T. A. (2000) Anaerobic treatment of domestic sewage at low temperature. Ph.D. Thesis, Department of Environmental Technology, Wageningen University, Wageningen, The Netherlands.

[6] Haandel, A. C. van and Lettinga, G. (1994) *Anaerobic Sewage Treatment. A Practical Guide for Regions with a Hot Climate*. John Wiley and Sons, New York.

[7] Hammes, F., Kalogo, Y. and Verstraete, W. (2000) Anaerobic digestion technologies for closing the domestic water, carbon and nutrient cycles. *Water Sci. Technol.* **41**(3), 203-211.

[8] Jirka, A. and Carter, M. J. (1975) Micro semi-automated analysis of surface and waste waters for chemical oxygen demand. *Analytical chem.* **47**, 1397 - 1401.

[9] Last, A. R. M. van der and Lettinga, G. (1992) Anaerobic treatment of domestic sewage under moderate climatic (Dutch) conditions using upflow reactors at in creased superficial velocities. *Water Sci. Technol.* **25**(7), 167-178.

[10] Lawler, D. F., Chung, Y. J., Hwang, S. J. and Hull, B. A. (1986) Anaerobic digestion: effect on particle size and dewaterability. *J. Water Pollut. Control Fed*. **58**(12), 1107-1117.

[11] Lettinga, G. (2001) Digestion and degradation, air for life. *Water Sci. Technol.* **44**(8), 157-176.

[12] Lettinga, G. and Hulshoff Pol, L.W. (1991) UASB process design for various types of wastewater. *Wat. Sci. Tech.*, **24**(8), 87-107.

[13] Mahmoud, N., Zeeman, G., Al-Sa'ed, R. and Lettinga, G. (2001) Digestion optimisation and performance prediction of the integrated UASB-Digester system for sewage treatment in the Middle East. *Proc. 9th. Int. Symp. On Anaerobic Digestion* (poster papers). Antwerpen, Belgium. 583 - 586.

[14] Mamals, D., Pitt, P. A., Cheng, Y. W., Loianco, J. and Jenkins, D. (1994) Determination of ferric chloride dose to control struvite precipitation in anaerobic sludge digesters. *Water Environ. Res*. **66**, 912-918.

[15] Noyola, A., Capdeville, B. and Roques (1988) Anaerobic treatment of domestic wastewater with a rotating-stationary fixed-fil reactor. *Water Res.*, **22**(12), 1585-1592.

[16] Polprasert, C., Kemmadamnrong, P. and Tran, F. T. (1992) Anaerobic baffle reactor (ABR) process for treating slaughterhouse wastewater. *Environm. Technol.*, **13**, 857-865.

[17] Ruiz, I., Soto M., Veiga, MC, Ligero, P., Vega, A. and Blazquez R. (1998) Performance of and biomass characterisation in a UASB reactor treating domestic waste waster at ambient temperature. *Water SA* **24**(3), 215-222

[18] Sanders, W. T. M (2001) Anaerobic hydrolysis during digestion of complex substrate. Ph.D. Thesis, Department of Environmental Technology, Wageningen University, Wageningen, The Netherlands.

[19] Sanz, I. and Fdz-Polanco, F. (1990) Low temperature treatment of municipal sewage in anaerobic fluidized bed reactors. *Water Res.* **24**(4), 463 - 469.

[20] Schellinkhout, A., Jakma, F. F. G. M. and Forero, G. E. (1988) Sewage treatment: the anaerobic way is advancing in Columbia. *Proc. 5th. Int. Symp. On Anaerobic Digestion*. Bologna, Italy. 767-770.

[21] Vieira, S. (1988) Anaerobic treatment of domestic sewage in Brazil. Research results and full scale experience. *Proc. 5th. Int. Symp. on Anaerobic Digestion*. Bologna, Italy. 185-196.

[22] Wang Kaijun (1994) Integrated anaerobic and aerobic treatment of sewage. PhD thesis, Department of Environmental Technology, Wageningen University, Wageningen, The Netherlands.

[23] Zeeman, G. and Lettinga, G. (1999) The role of anaerobic digestion in closing the water and nutrient cycle at community level. *Water Sci. Technol.* **39**(5), 187-194.

Table 2. Effluent COD and VFA concentrations and removal efficiencies (%) during anaerobic sewage treatment in a UASB and a UASB-digester system. Standard deviations are presented between brackets

Reactor	Effluent concentration (mg/L)					Removal efficiency (%)				
	CODt	CODss	CODcol	CODdis	VFA-COD	CODt	CODss	CODcol	CODdis	VFA-COD
UASB	390	100	128	162	80	44	73	3	5	-8
	(62)	(36)	(19)	(47)	(40)	(9)	(14)	(46)	(17)	(42)
UASB-Digester	151	32	68	50	3	66	87	44	30	95
	(34)	(24)	(17)	(10)	(3)	(6)	(5)	(15)	(36)	(8)

Table 3. Percentage of hydrolysis, acidification and methanogenesis during the treatment of domestic sewage in a one stage UASB and a UASB-digester systems. Standard deviations are presented between brackets

	⊕UASB-Digester			One stage UASB
	UASB	+Digester	Overall system	
H	44	19.99		25
	(15)	(38.2)		(7)
A	41	19.68		24
	(12)	(40.83)		(8)
M	44	19.62	47	21
	(11)	(34.23)	(15)	(5)

+ calculations are based on the digester influent and effluent

⊕ calculations are based on total methane production including dissolved fraction

Table 5. Carbohydrates, Nkj and NH_4^+ removal efficiencies (% of the influent), carbohydrates hydrolysis (% of the influent carbohydrates) and ammonification (ammonia production in the UASB and the UASB of the UASB-digester systems, % of the influent *Nkj*-N) during anaerobic sewage treatment in a UASB and a UASB-digester systems. Standard deviations are presented between brackets

		UASB	UASB-digester		
Removal efficiency			UASB	Digester	UASB-Digester
Carbohydrates	Total	64.27 (11)	83 (4.98)		
	Suspended	93.66 (7.34)	98.26(2.13)		
	Colloidal	20.4(45.39)	33.88(29.43)		
	Dissolved	26.6 (14.85)	34.95(16.92)		
Nkj-N		4.26(6.21)	4.82(6.19)		
NH_4^+-N		-1.8(7.63)	-17.95(5.76)		
Carbohydrates hydrolysis		23.11 (15.25)	29.57 (20.26)	16.12 (11.78)	44.47 (9.79)
Ammonification		0.21(0.62)	14.93(2.95)		