Optimization of a Combined UASB and Continuous-flow SBR System for Sludge Reduction and Biogas Production

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Abstract
An integrated system that combines an up-flow anaerobic sludge blanket (UASB) and a continuous-flow sequencing batch reactor (CSBR) was tested for treating medium-strength domestic wastewater. CSBR requires less control and is simple compared to conventional SBR, which is an important advantage in small and decentralized areas. After the start-up, the system was operated for 115 days at a retention time of 5.7 h in the UASB reactor and a cycle time of 8 h in the CSBR. The average chemical oxygen demand (COD) and total suspended solids (TSS) removal efficiencies in the UASB reactor were 48% and 46% respectively. The overall average removal efficiencies for COD, TSS and ammonia in the system were 85%, 87%, and 82%, respectively. Then, the system optimized for excess sludge production. For that reason, the system was tested for about 120 days for sludge recycling to the inlet of the UASB. By implementing this strategy, a 75% reduction in sludge production and a 35% increase in biogas production were achieved. There was no effect on the removal efficiencies of COD, TSS, and NH_4 during the sludge recycling process that was performed for over 4 months. The findings indicate that the proposed scheme in this study could be a promising and cost-effective option for decentralized wastewater treatment and wastewater generation in small communities.

Keywords
Continuous-flow SBR; UASB; Wastewater; Reuse.

INTRODUCTION

An emerging alternative for additional water resources is wastewater recycling and reuse. In particular, anaerobic treatment methods for the treatment of wastewater are becoming increasingly popular. The possibility of using an up-flow anaerobic sludge blanket (UASB) reactor for sewage treatment is an attractive alternative, especially in developing countries, as they have a need for a low-cost, reliable method for wastewater treatment (McCarty and Smith, 1986). With the UASB system, the benefits of anaerobic systems over aerobic systems are retained, that is, energy production, low excess sludge production, and low volume requirement. Among the high-rate anaerobic reactors, the UASB reactor has gained popularity over the last 30 years (Seghezzo et al., 1998). With the UASB reactor, a chemical oxygen demand (COD) removal rate of 70% to 80% can be achieved. The COD removal rate in the UASB reactor depends on the influent strength, especially the solid COD concentration, rather than the operational temperature (Uemura and Harada, 2000).

In UASB reactors, removal of ammonia is difficult. Therefore, using a UASB reactor alone may not meet the desired effluent standards, and secondary treatment of the effluent from the UASB reactor may be required. A variety of post-treatment methods based on diverse combinations of UASB treatments have been investigated in the literature, including the sequencing batch reactor (SBR), trickling filter, submerged aerated bio-filter, and aerated fixed bed reactor. Combined UASB-aerobic systems can lead to high reduction in sludge production and energy consumption (Kassab et al., 2010). Based on an extensive review of the literature, it seems that the SBR is the most promising solution among these systems (Kassab et al., 2010; Khan et al., 2011; Chong et al., 2013). In recent years, SBR has become the subject of great interest for decentralized wastewater treatment because of its simple configuration (all the necessary processes take place in a time-sequenced manner in a single basin). Further, due to its operational flexibility, it is quite simple to increase its efficiency in treating wastewater by changing the duration of each phase rather than adding or removing tanks in continuous flow systems (Mahvi et al., 2004). Several studies have examined the efficiency of SBR with regard to the removal of residual COD, NH_4 and total suspended solids (TSS) from the UASB effluent, and these studies have reported a removal efficiency of more than 90% (Moawad et al., 2009; Khan et al., 2011; Khan et al., 2013).

While the famous conventional SBR system has many advantages and superior removal efficiency, it does have some shortcomings (Mahvi et al., 2004). These disadvantages can be overcome by adding a continuous-flow Sequencing Batch Reactor (CSBR), which is believed to be superior to the conventional SBR (Lin and Cheng, 2001; Mahvi et al., 2004; Khan et al., 2013). The system allows for continuous inflow of wastewater to the basin. Further, influent flow to the basin is not interrupted during the settle and decant phases or at any point of time during the operating cycle. In conventional SBRs, there are five phases: fill, react, settle, draw, and idle. In contrast, in the CSBR, there are only three phases: react, settle, and draw. Continuous inflow allows the process to be controlled based on time, rather than flow, and ensures equal loading and flow to all basins. The use of a time-based control system facilitates simple changes that can be made to the process control program. The duration of each cycle and segment of each operating cycle are the same among all basins in a time-based system. Therefore, changes to the process are made simply by changing the duration of individual segments (Mahvi et al., 2004). CSBR requires less control and has a simple configuration compared to a conventional SBR (Lin and Cheng, 2001). This is an important advantage in a developing country such as Egypt. Moreover, better denitrification can be achieved in a CSBR due to the continuous supply of substrate during non-aeration periods (Khan et al., 2013).

During operation of biological wastewater facilities, a large quantities of excess sludge should be disposed in order to maintain the required MLSS in the aeration basin. Handling and treatment of sludge represents more than 50% of the operational cost of any wastewater facility. Hence, reduction of sludge production is one of the serious challenges in wastewater facilities. Some studies in the literature have investigated the use UASB for the anaerobic pretreatment and waste activated sludge digestion step (La Motta et al., 2007 and Pontes et al., 2003). In these studies, sludge from aerobic step was pumped to the inlet UASB unit. Such scheme was not studied before in either a combined UASB-SBR or UASB CSBR systems. Therefore, the objective of this study is to optimize an integrated UASB-CSBR system with regard to decreasing sludge production and increasing biogas production by recycling excess sludge through the inlet of the UASB. The proposed scheme could be a promising and cost-effective option for treating wastewater in decentralized areas.

MATERIALS AND METHODS

A pilot plant was constructed and operated at the El-Berka wastewater treatment plant (WWTP) in Cairo, Egypt. The pilot plant consists of a 500-l storage tank, a 50-l UASB reactor, and a CSBR with a capacity of 180 l (Figure 1). Raw domestic wastewater from the grit removal chamber is collected and processed before it flows into the primary sedimentation tanks. The storage tank is filled daily with the raw wastewater, which feeds the pilot plant continuously over 24 h. The average influent water characteristics are shown in Table 1. The WWTP receives medium-strength wastewater from different rural areas around Cairo.

The start-up of the system took about 3 months to reach the steady state. Then, the system was optimized for the best hydraulic retention time (HRT) in the UASB reactor and the best cycle period in the CSBR (data not shown). The UASB reactor was intended for use as a pre-treatment unit for removing 50%–60% of the organic load in raw water. Therefore, the UASB process was optimized at an HRT of 5.7 h, which is close to the 6 h typical HRT for UASB reactors (van Lier et al. 2008). The UASB reactor had eight ports along its height for sludge sampling (Figure 1). The UASB was provided by a conical gas solids separator at the top of the tank. The biogas production rate was measured using the water displacement method. The sludge blanket level was maintained at sampling port 5, which represents about 60% of the height of UASB reactor, by opening this sampling port once a week for discharging the sludge accumulated above.

The CSBR reactor was separated into two zones (pre-react [15%] and main react [85%]) by a baffle wall (Figure 1). The pre-react zone acts as a biological selector that enhances the proliferation rate of the most desirable organisms and limits the growth of filamentous bacteria. The total cycle time, aeration period, settling period, and decanting period in the SBR was maintained at 8, 6.75, 1.1, and 0.15 h respectively. The fill percentage of the CSBR was adjusted at 40% along the experimental period. The time of the sequencing aeration-decanting system was controlled by a timer. The DO in the CSBR was maintained in the range 2.0-4.0 mg/l.

The excess sludge was withdrawn manually on a daily basis as mixed liquor during the reaction period. The concentration of dissolved oxygen in the SBR during the aeration period was maintained above 2 mg/l. The system was operated for about 115 days under these conditions. Then, the system was tested for excess sludge recycling to the inlet of the UASB for a little over 120 days in order to minimize sludge production. Thus, the excess sludge that was withdrawn manually on a daily basis from the SBR was mixed with raw wastewater in the storage tank (Figure 1). Excess sludge was removed from the UASB on a weekly basis in order to prevent clogging. The system was operated at almost the same HRT and CSBR cycle time of 8 h as the first stage. The removal efficiency and gas production of the two operational stages were compared.

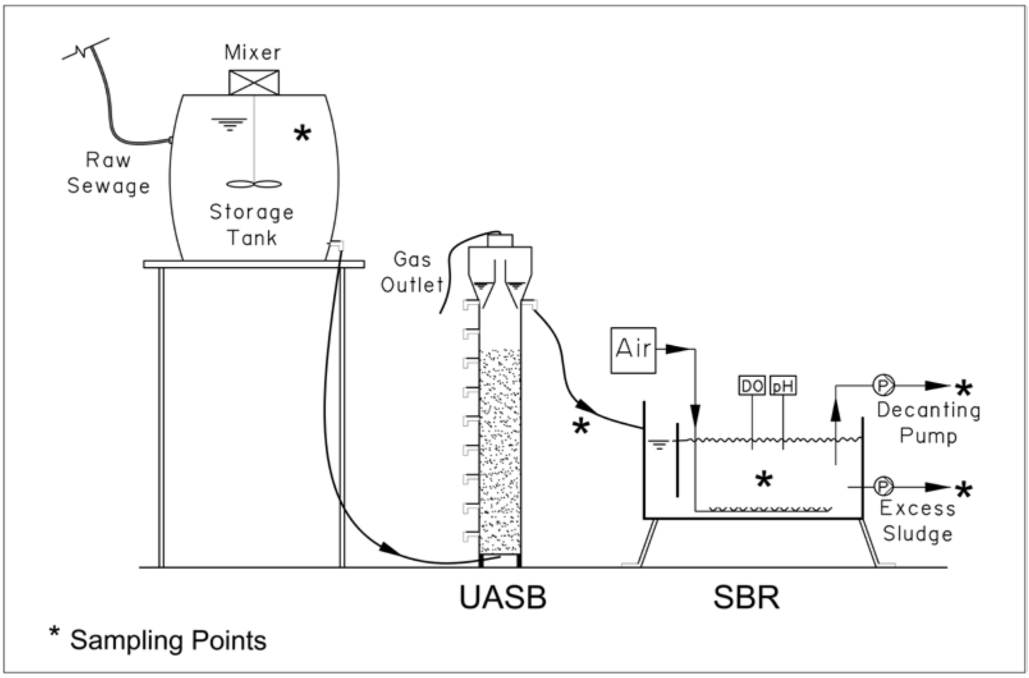

Figure 1. Schematic diagram of the combined UASB and CSBR system

The performance of the treatments was evaluated by monitoring the quality of the raw wastewater and effluents at each treatment step. The following parameters were measured: COD, biochemical oxygen demand (BOD_5), TSS, volatile suspended solids (VSS), temperature, ammonia-nitrogen (NH_3-N), nitrite-nitrogen (NO_3-N), nitrate-nitrogen (NO_2-N), total Kjeldahl nitrogen (TKN), total phosphorus (TP), mixed liquor suspended solids (MLSS), sludge volume index (SVI), pH, and alkalinity. All the analyses were carried out in accordance with standard methods (APHA, 2005).

Table 1. Influent water parameters (the average values are shown in mg/l, except for the pH values)

Parameters	**Range**	**Avg.**
pH-value	6.66 - 8.40	7.45
Chemical oxygen demand(COD)	301 - 671	452.4
Biological oxygen demand(BOD)	156 - 423	288
Total suspended solids (TSS)	145 -353	232.7
Total Kjeldahl nitrogen (TKN)	34.8– 62.7	49.2
Ammonia (NH_4–N)	14 - 41.6	28.1
Nitrate (NO_3–N)	2.5 - 11.5	4.8
Nitrite (NO_2–N)	0.2 – 0.9	0.5

Table 2. Operating conditions throughout the study

Parameters	**without Sludge Recycling 115 days**		**with Sludge Recycling 120 days**	
	Range	Avg.	**Range**	**Avg.**
Temp °C	19 - 28	22.7	20 - 29	24.3
Flow rate (l/d)	187 - 223	212	191 - 218	204
HRT in UASB (hr)	5.38-6.42	5.66	5.50-6.28	5.88
OLR in UASB (kg COD/m^3/d)	1.27-2.85	2.06	1.22-2.39	1.72
DO in SBR	1.9 – 2.75	2.2	2.1 – 2.65	2.35
SVI in SBR (ml/g)	78 - 177	116	62 - 173	105

RESULTS AND DISCUSSION

Organic and nitrogen removal efficiencies

The COD, TSS and TKN values for the raw wastewater, after UASB, and after SBR are shown in Figures 2, 3 and 4 respectively throughout the whole study period. For the first part of this study without excess sludge recycle, the results indicated that the average COD and TSS removal efficiencies in UASB were 48% and 46% respectively. The overall average removal efficiencies after CSBR for COD, TSS and ammonia were 85%, 87%, and 82%, respectively. The effluent efficiency in this study was comparable to that of other combined UASB-aerobic systems in the literature. Khan et al., 2013 achieved BOD, TSS and ammonia removal efficiencies of 83%, 90% and 74%, respectively in a combined UASB-CSBR system. Torres and Foresti, 2001 achieved high removal efficiency for COD, TSS and TKN of 91%, 84%, and 90%, respectively in a combined UASB-SBR system. Cao et al., 2009 achieved removal efficiency for COD, TSS and TKN of 86.4%, 94.5%, and 92.2%, respectively in a combined UASB-SBR system.

The average COD, BOD_5, TSS and ammonia nitrogen in the effluent were 70, 42, 36 and 9 mg/l, respectively. Although, the effluent quality in this study is in accordance with the Egyptian standards (law 48, 1982). However, it was noticed that effluent quality from combined UASB-CSRB system is slightly less than that of UASB-SBR in the literature (Khan et al., 2013). This could be because of a decrease in the efficiency of the settling process due to dilution caused by the continuous wastewater influent flow. However, this effect could be minimal in a large full-scale reactors and higher effluent quality might be achieved.

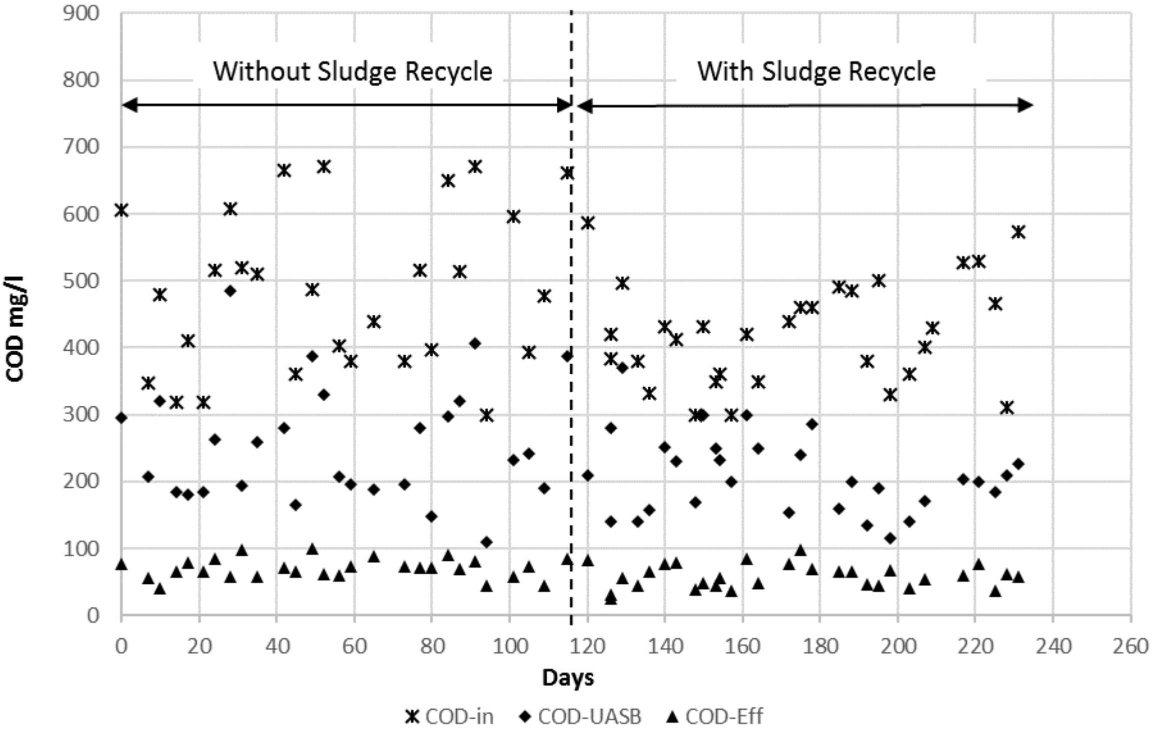

Figure 2. COD values of raw wastewater before UASB, after UASB and after SBR treatment

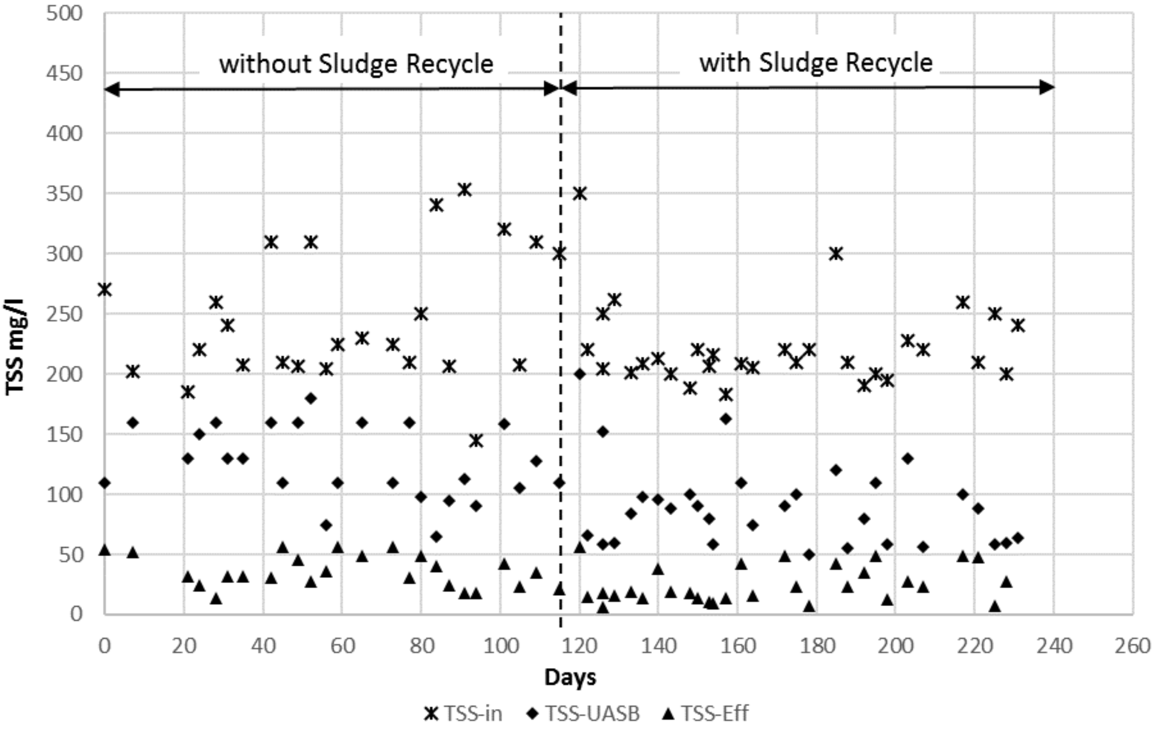

Figure 3. TSS values of raw wastewater before UASB, after UASB and after SBR treatment

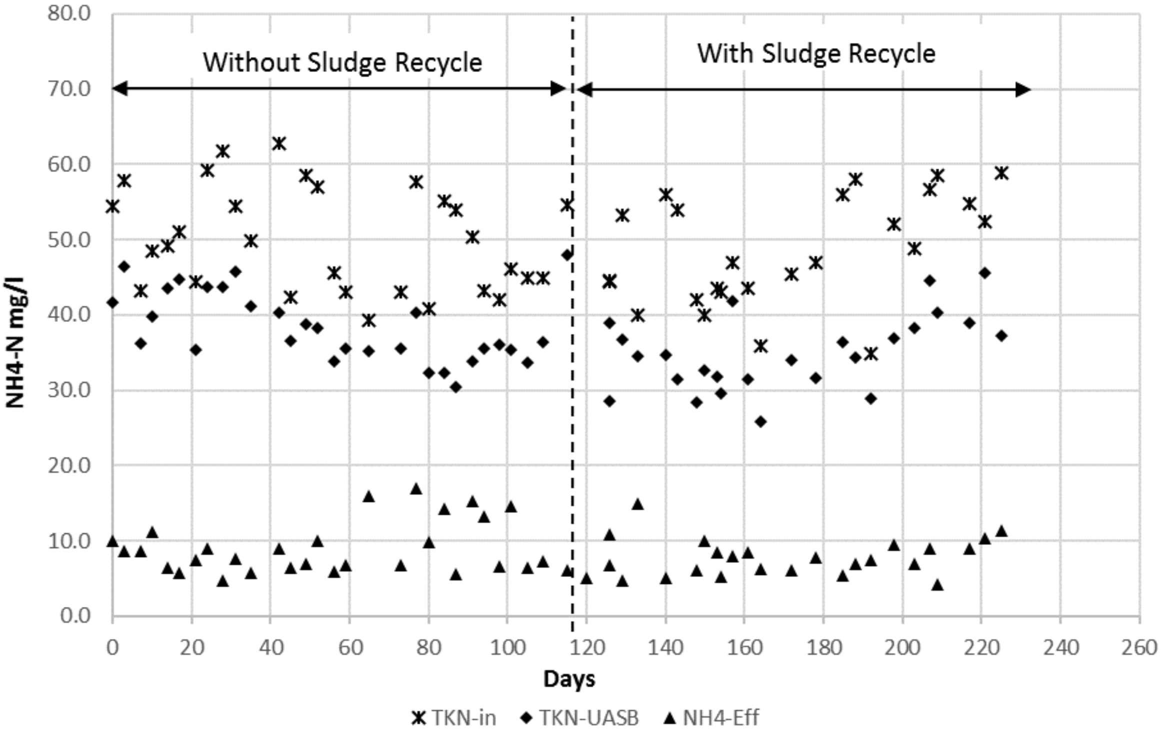

Figure 4. TKN and NH_4-N values of raw wastewater before UASB, after UASB and after SBR treatment

For the second part of this study, the sludge was recycled to the inlet of UASB reactor over 120 days. In this stage, the results indicated that the average COD and TSS removal efficiencies in UASB were 49% and 54% respectively. The overall average removal efficiencies after CSBR for COD, TSS and ammonia were 86%, 89%, and 84%, respectively. The average COD, BOD_5, TSS and ammonia nitrogen in the effluent were 58, 31, 25 and 7.7 mg/l, respectively. The effluent quality during sludge recycle operational strategy was slightly better than the normal operation. This means that UASB process in integrated UASB-aerobic systems could be successfully work as anaerobic pretreatment and waste activated sludge digestion at the same time without affecting the treatment efficiency. These findings are in accordance with literature (La Motta et al., 2007 and Pontes et al., 2003).

The alkalinity in the influent wastewater was sufficient and in the range of 210 – 420 mg/l with an average of 285 mg/l. The pH in the raw water, UASB-effluent, and SBR-effluent were 7.45±0.23, 7.51±0.25, and 7.34±0.23 respectively. This range of alkalinity was successful in operation of the UASB over experimental period with no significant pH change with is in agreement with literature (Seghezzo et al. 1998). The system denitrification rates were not monitored during this study.

Excess sludge production

For the first part of this study (115 days), the excess sludge in UASB was withdrawn weekly by opening this sampling port no.5 for discharging the sludge accumulated above. For this purpose, in average 8.3 l of sludge have been withdrawn every week from sampling port no. 5 (Figure 1). For the CSBR, the MLSS concentrations were maintained in the range 2000 – 3000 mg/l. This was done by withdrawing an average 21.8 l/d of as a mixed liquor during the aeration period in CSBR. Sludge retention time (SRT) in CSBR corresponding to this operational strategy was 8.6 days in average.

In stage 2, the 21.8 l/d mixed liquor was withdrawn on a daily basis from CSBR and then was mixed with raw wastewater in the influent storage tank (Figure 1). It was noticed that the UASB removal efficiency was decreased for the first 10 days. Therefore, it was decided to increase the sludge withdrawal from UASB. Thus, 7.5 l of the digested sludge was withdrawn twice weekly (total of 15 l weekly) from sampling port no. 5. Based on the suspended solids measurements for the sludge samples, more than 75% of sludge dry solids production can be reduced using the suggested sludge recycle approach.

The sludge volume index (SVI) values of the mixed liquor in CSBR are presented in Table 2. The SVI was reduced from an average value of 116 to 105 ml/g, which indicates excellent settleability. The sludge recycle approach enhanced the settleability in CSBR. For the digested sludge from UASB, VSS/TSS ratio was in the range 0.55–0.63 which indicates that the wasted sludge from the UASB reactor is well stabilized.

Biogas production

For UASB process, the influent average organic loading rate (OLR) in stage 1 was slightly higher than OLR in stage 2 (Table 2). The organic loading rate due to sludge recycle should be added to the applied OLR from raw wastewater. The measured biogas production rate through the whole study ranged between 60 and 280 m/g COD removed. The rate of biogas production was lower than the theoretical value of 350 ml/g COD removed (Metcalf and Eddy, 2003). The biogas production during sludge recycle process was 35% higher than without sludge recycle. This can be attributed to the additional biogas production from the digestion of the recycled sludge.

CONCLUSIONS

A combined UASB-CSBR system is promising for decentralized wastewater treatment and reuse in semi-arid areas such as Egypt. High removal efficiencies for COD, TSS and ammonia in the system were of 85%, 87%, and 82%, respectively were achieved. The water quality of the treated wastewater complies with Egyptian standards for regulating wastewater discharge into agriculture drains. The sludge recycling approach proposed in this study was helpful in reducing sludge production and increasing gas production. Moreover, this approach did not have a significant impact on the removal of organic content and nitrogen. Further investigations on the effect of sludge recycling on sludge characteristics and dewaterability are required.

REFERENCES

APHA, A WWA and WEF. 2005 Standard Methods for the Examination of Water and Wastewater, twenty-first ed., *American Public Health Association, Washington, DC.*

Cao, Y.S., Ang, C.M. 2009 Coupled UASB-activated sludge process for COD and nitrogen removals in municipal sewage treatment in warm climate, *Water Science and Technology*, 60(11), 2829-2839.

Chong, S., Sen, T.K., Kayaalp, A., Ang, H.M. 2012 The performance enhancements of upflow anaerobic sludge blanket (UASB) reactors for domestic sludge treatment - A State-of-the-art review. *Water Research* 46, 3434-3470.

Kassab, G., Halalsheh, M., Klapwijk, A., Fayyad, M., van Lier, J.B. 2010 Sequential anaerobic–aerobic treatment for domestic wastewater – A review. *Bioresource Technology* 101, 3299–3310.

Khan, A.A., Gaur, R.Z., Tyagi, V.K., Khursheed, A., Lew, B., Mehrotra, I., Kazmi, A.A. 2011 Sustainable options of post treatment of UASB effluent treating sewage - a review, *Resource Conserve Recycle* 55(12),1232-1251.

Khan, A.A., Gaur, R.Z., Diamantis, V., Lew, B., Kazmi, A.A., Mehrotra I. 2013 Continuous fill intermittent decant type sequencing batch reactor application to upgrade the UASB treated sewage, Bioprocess Biosystems Engineering, 36,627-634.

La Motta, E.J., Silva, E., Bustillos. A., Padrón, H., Luque, J. 2007 Combined anaerobic/aerobic secondary municipal wastewater treatment: Pilot-plant demonstration of the UASB/aerobic solids contact system. *Journal of Environmental Engineering*, 133(4), 397-403.

Lin, S., and Cheng, K. 2001. A new sequencing batch reactor for treatment of municipal sewage wastewater for agricultural reuse, Desalination 133, 41–51.

Mahvi, A.H., Brown, P., Vaezi, F., and Karakani, F. 2005 Feasibility of Continuous Flow Sequencing Batch Reactor in Synthetic Wastewater Treatment. *Journal of Applied Sciences* 5(1), 172-176.

McCarty, P., Smith, D. 1986 Anaerobic wastewater treatment. *Environmental Science and Technology* 20 (12), 1200-1206.

Metcalf and Eddy, Inc. 2003. Wastewater Engineering: Treatment and Reuse, *McGraw-Hill*, *New York*.

Moawad, A., Mahmoud, U., El-Khateeb, M., El-Molla, E. 2009. Coupling of sequencing batch reactor and UASB reactor for domestic wastewater treatment, *Desalination* 242, 325-335.

Pontes, P., Chernicharo, C., Frade, E., and Porto, M. 2003 Performance evaluation of a UASB reactor used for combined treatment of domestic sewage and excess aerobic sludge from a trickling filter. *Water Science Technology*, 48(6), 227–234.

Seghezzo, L., Zeeman, G., Lier, J.B., Hamelersm, H.V.M., Lettinga, G.A. 1998 A review: the anaerobic treatment of swage in UASB and EGSB reactors, *Bioresource Technology* 65(3), 175-190.

Torres, P., Foresti, E. 2001 Domestic sewage treatment in a pilot system composed of UASB and SBR reactors. *Water Science and Technology*, 44 (4), 247-253.

Uemura, S., Harada, H. 2000 Treatment sewage by a UASB reactor under moderate to low temperature conditions, *Bioresource Technol*ogy, 72(3) ,275-282.

van Lier, J. B., Mahmoud, N. & Zeeman, G. 2008 Anaerobic wastewater treatment. In: Henze, M., et al. (eds), Biological Wastewater Treatment Principles, Modeling and Design. IWA Publishing, London.