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Minimization of sludge production in an integrated UASB–continuous flow sequencing batch reactor system

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ABSTRACT

A pilot plant consisting of a combined up-flow anaerobic sludge blanket (UASB) and a continuous flow sequencing batch reactor (cSBR) was tested for treating domestic wastewater. After the start-up, the system was operated for 115 d at a retention time of 5.7 h in the UASB reactor and a cycle time of 8 h in the cSBR. The efficiency of the removal of the average chemical oxygen demand (COD) and the total suspended solids (TSS) in the UASB reactor were 48% and 46%, respectively. The overall average removal efficiencies for the COD, TSS, and ammonia in the system were 85%, 87%, and 82%, respectively. The system was optimized for sludge production and tested for approximately 120 d for sludge cycling between the cSBR and the inlet of the UASB. In comparison with sludge production at a solids retention time of 8.6 d, the implementation of this strategy resulted in an average 89% reduction in sludge production and a 32% increase in biogas production. No effect on the removal efficiencies of COD, TSS, and ammonia was seen during the sludge cycling process, which ran for more than 4 months. The findings indicate that the scheme proposed in this study could be a promising, cost-effective option for wastewater treatment in small communities and decentralized systems.

Keywords: Up-flow anaerobic sludge blanket; Continuous flow sequencing batch reactor; Sludge reduction; Domestic wastewater treatment

1. Introduction

Aerobic biological wastewater treatment is the system that is most widely used to treat domestic wastewater, and it has a high organic and nutrient removal efficiency. However, during the operation of aerobic biological wastewater facilities, large quantities of excess sludge must be disposed of to maintain the required levels of mixed liquor suspended solids (MLSS) in the aeration basin [1]. Sludge must be treated before disposal to prevent negative environmental and public health impacts. The handling and treatment of the sludge represent more than 50% of the operational costs for a wastewater facility. Hence, minimization of sludge production is a serious challenge for wastewater facilities [2].

Anaerobic systems are becoming increasingly popular biological wastewater treatment systems, especially in developing countries that need a reliable and low-cost method for treating wastewater. The up-flow anaerobic sludge blanket (UASB) reactor is high-rate anaerobic reactor that has become more popular beginning in the mid-1990s. In a UASB system, the benefits of anaerobic systems over aerobic systems are retained, including a low volume requirement, low sludge production, and energy recovery [3–5]. In a UASB reactor, the removal of the chemical oxygen demand (COD) depends on many factors, including the temperature, hydraulic retention time (HRT), wastewater composition, alkalinity, and organic loading rate (OLR). A long HRT results in the starvation of the biomass, while a very short HRT results in a washout of the sludge and a shorter contact time between the substrate

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and the biomass. In a UASB reactor, COD removal rates between 65% and 80% can be achieved for an HRT between 4 and 9 h [4]. Higher removal efficiencies of up to 90% have been reported in the literature at higher HRTs [6].

Ammonia removal is difficult in a UASB reactor. Therefore, using a UASB reactor alone may not meet the desired effluent standards, and secondary treatment of the effluent from a UASB reactor may be required. The literature contains reports concerning different post-treatment systems for UASB effluent, including activated sludge (AS), the sequencing batch reactor (SBR), the submerged aerated biofilter, the trickling filter, and the aerated fixed bed reactor. Combined UASB–aerobic systems can lead to a high reduction in sludge production and energy consumption [7]. An extensive literature review indicated that SBR seems to be the most promising solution. An integrated UASB and SBR system eliminates the need for primary and final settlers [5,7–9]. Nevertheless, Guimaraes et al. [8] reported start-up difficulties due to the formation of foam and a low initial nitrification rate.

In recent years, SBR systems have been recommended for decentralized and small wastewater treatment systems because of their simple configuration. Compared with conventional AS systems, SBR systems allow both biological processes and settling occurs in a single reactor. Furthermore, the efficiency of an SBR system can be increased simply by modifying the duration of each step rather than by removing or adding tanks, as is required in a conventional AS system [10]. Several studies have examined the efficiency of an SBR system for the removal of residual COD, ammonium (NH_4^+), phosphate (PO_4^{3-}) and total suspended solids (TSS) from the UASB effluent, and have reported a removal efficiency >90% [5,9,11,12].

While the well-known conventional SBR system has many advantages and a superior removal efficiency, it has some shortcomings as well, such as a complex control system and the need for equalization and intermittent wastewater flow to the reactors so that at least two reactors are required; moreover, the organic and hydraulic loading are variable over time [10]. Due to these disadvantages, an SBR might not be preferred for small wastewater systems, especially in developing countries such as Egypt. Some of these disadvantages can be overcome by adding a continuous flow sequencing batch reactor (cSBR) [10,12,13]. A cSBR allows for continuous flow to the tank, and this flow is not interrupted during the settling and decanting stages.

cSBR systems have only three operational stages: aeration, settling, and decanting. In contrast, a conventional SBR system has four operational stages: filling, aeration, settling, and decanting. In a cSBR system, the control of the process is time-based rather than flow-based. This ensures equal flow and loading to all of the cSBR tanks because the cycle and operational stage periods are the same for all the tanks. The use of a time-based system simplifies the process control system. Changes to the process can be made easily by changing the duration of each operational stage [10]. A cSBR requires less control and has a simple configuration compared with a conventional SBR [13], which is an important advantage in a developing country such as Egypt. Moreover, better denitrification can be achieved in a cSBR due to a continuous supply of organic substrate during non-aeration periods [12]. However, less overall nitrogen removal is expected in a cSBR compared with that in an SBR because the soluble constituents that enter during the settling and decanting periods can escape in the effluent due to the continuous flow. However, a cSBR still has an advantage over an SBR for small wastewater systems and developing countries because no high restriction on nitrogen removal is usually present in a cSBR [14].

Very few studies in the literature have investigated the use of UASB for the anaerobic pretreatment and waste sludge digestion step to minimize sludge production [8,15,16]. In these studies, sludge from the aerobic step was pumped to the inlet UASB unit. Although these previous studies have reported that this strategy is feasible for decreasing excess sludge production, most of the studies were based on laboratory experiments in a controlled environment. Moreover, this strategy has not yet been studied in a combined UASB–cSBR system. Therefore, the present study aimed to optimize an integrated UASB–cSBR system to minimize sludge production by recycling the excess sludge through the inlet of the UASB in a pilot plant operated at ambient temperature and under variable organic and nutrient loads. The proposed scheme could be a promising and cost-effective option for treating wastewater for small communities.

2. Materials and methods

A pilot plant was constructed and operated at the El-Berka wastewater treatment plant (WWTP) in Cairo, Egypt. The pilot plant consisted of a storage tank (500 L), a UASB reactor (50 L), and a cSBR with a capacity of 180 L (Fig. 1). Raw domestic wastewater from the grit removal chamber was collected and processed before it flowed into the primary sedimentation tanks. The raw wastewater was screened with a 2-mm fine mesh screen to avoid clogging. The storage tank was filled once daily with raw wastewater, which fed the pilot plant continuously over 24 h. A mixer was installed in the storage tank to ensure homogeneous influent throughout the same day. The average influent water characteristics are shown in Table 1. The WWTP received medium-strength wastewater from different rural areas around Cairo.

The UASB reactor was initially seeded with 25 L of digested sludge, and the cSBR was seeded with 50 L of AS mixed liquor from the aeration tanks of the same WWTP. The seeded, digested sludge and the activated mixed liquor had suspended solids of 8.4 and 2.45 mg/L, respectively. It took approximately 3 months for the start-up of the system to reach the steady state. Then, the system was optimized for the best 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 pretreatment unit to remove 50%–60% of the organic load in the raw water. Therefore, the UASB process was optimized at an HRT of 5.7 h, which is longer than the recommended minimum HRT of 4 h for a UASB reactor [4]. The UASB reactor had eight ports along its height for sludge sampling (Fig. 1). The UASB was provided via 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 represented approximately 60% of the height of UASB reactor, by opening this sampling port once a week to discharge the accumulated sludge.

The cSBR consisted of two compartments (prereaction [15%] and the main reactor [85%]) (Fig. 1). The prereaction compartment served as a biological selector that enhanced the production rate of desirable bacteria, while limiting the growth of filamentous bacteria [1]. The total cycle time, aeration period, settling period, and decanting period in the SBR were maintained at 8, 6.75, 1.1, and 0.15 h, respectively. The filling percentage of the cSBR was adjusted to 40% throughout the experimental duration. The time for the sequencing aeration–decanting system was controlled by a timer. The air flow was supplied from the bottom of the reactor through fine diffusers. The dissolved oxygen (DO) concentration in the cSBR was measured using a portable DO meter (YSI ProODO, VT, USA), and maintained in a range of 2.0–3.0 mg/L throughout the entire experimental duration. The pH and temperature were measured regularly in the influent and effluent of the UASB and cSBR using a pH meter (YSI Proplus, VT, USA). During the experimental duration, the temperature varied between 19°C and 29°C (Table 2).

The experiment consisted of two runs. In the first run, the excess sludge was manually withdrawn from the cSBR daily as a mixed liquor during the reaction. The system was operated for approximately 115 d under these conditions. In the second run, the system was tested for excess sludge cycling to the inlet of the UASB for 120 d to minimize sludge production. Thus, the excess sludge that was withdrawn from the cSBR was mixed with raw wastewater in the storage tank daily (Fig. 1). Excess sludge was removed from the UASB weekly to prevent clogging. The system was operated at almost the same HRT and the same cSBR cycle time of 8 h as in the first experimental run. Table 2 summarizes the operational conditions for the two experimental runs. The removal efficiency and gas production of the two experimental runs are compared in the results section.

The treatment efficiency was evaluated by monitoring the wastewater quality at the influent and effluent of the UASB and the cSBR. Grab samples were taken from the influent and

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

Parameters	Range	Average
pH value	6.66–8.40	7.45 ± 0.4
Chemical oxygen demand (COD)	301–671	452 ± 105
Biological oxygen demand (BOD)	156–423	288 ± 75
Total suspended solids (TSS)	145–353	233 ± 45
Total Kjeldahl nitrogen (TKN)	34.8–62.7	49.2 ± 7
Ammonia (NH_4–N)	14–41.6	28.1 ± 6
Nitrate (NO_3–N)	2.5–11.5	4.8 ± 1.1
Nitrite (NO_2–N)	0.2–0.9	0.5 ± 0.3

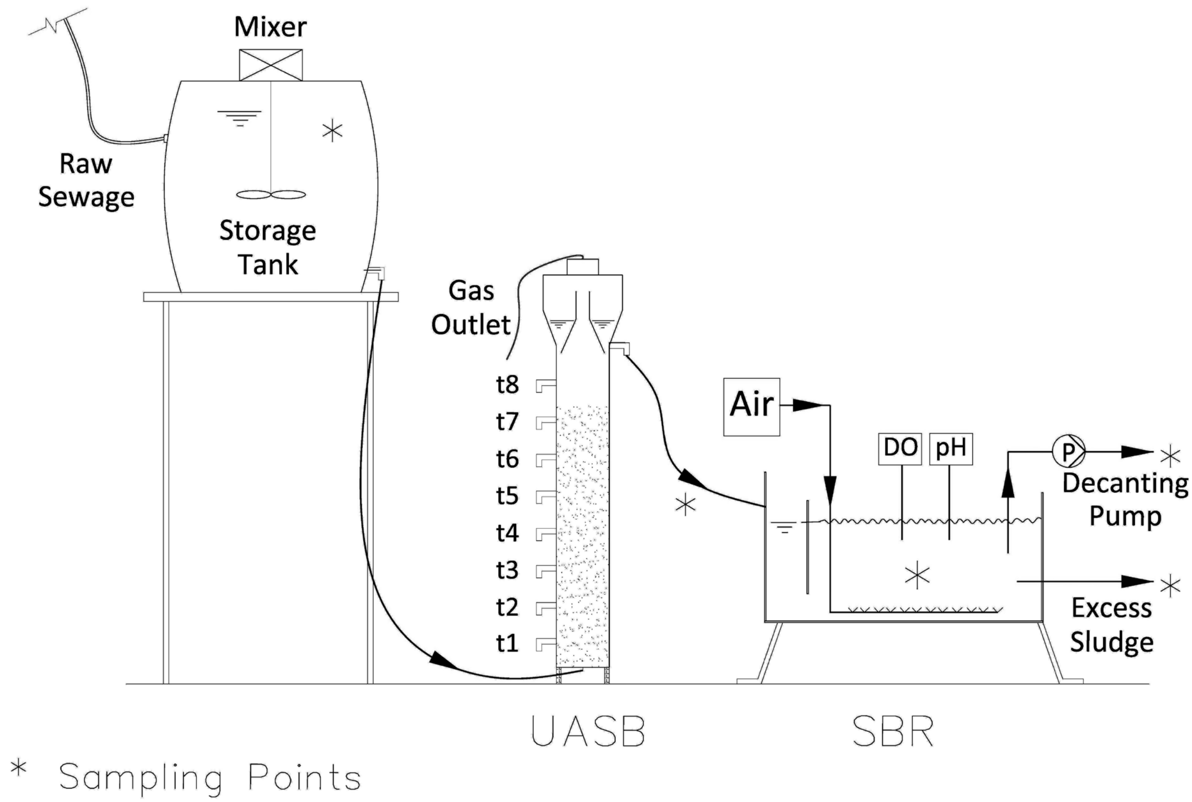

Fig. 1. Schematic of the combined UASB and cSBR system.

effluent of the UASB and cSBR three times per week. Effluent samples from the cSBR were taken after the aeration period directly before the reactor was decanted. The inlet storage tank was helpful in reducing the load variation over the same day; therefore, the grab samples from the influent are representative and lowered the sampling cost.

The COD, biochemical oxygen demand (BOD_5), TSS, volatile suspended solids (VSS), temperature, ammonia–nitrogen (NH_4–N), nitrite–nitrogen (NO_3–N), nitrate–nitrogen (NO_2–N), total Kjeldahl nitrogen (TKN), MLSS, sludge volume index (SVI), pH, and alkalinity were measured. All the analyses were conducted according to the standard methods [17].

3. Results and discussion

3.1. Organic and nitrogen removal efficiencies

The COD, TSS, and TKN values for the raw wastewater after the UASB and after the SBR for the entire experimental duration are shown in Figs. 2–4, respectively. For the first experimental run, without excess sludge recycling, the results indicated that the average COD and TSS removal efficiencies in the UASB were 48% ± 11% and 46% ± 15%, respectively. The overall average removal efficiencies after the cSBR for the COD, TSS, and ammonia were 85% ± 4%, 87% ± 6%, and 82% ± 7%, respectively. The average COD, BOD_5, TSS, and NH_4–N in the effluent were 70 ± 12, 42 ± 9, 36 ± 11, and 9 ± 3 mg/L, respectively.

In the present study, the effluent efficiency was comparable with that of other combined UASB–aerobic systems reported in the literature. Table 3 compares the performance of the integrated UASB–cSBR system used in this study with other integrated UASB-suspended growth aerobic systems from the literature without sludge cycling. Khan et al. [12] achieved BOD, TSS, and ammonia removal efficiencies of 83%, 90%, and 74%, respectively, in a combined UASB–cSBR system. Torres and Foresti [18] achieved a higher removal efficiency for COD, TSS, and TKN of 91%, 84%, and 90%, respectively, in a combined UASB–SBR system. Cao and Ang [19] achieved a removal efficiency for COD, TSS, and TKN of 86.4%, 94.5%, and 92.2%, respectively, in a combined UASB–SBR system. Although the effluent quality in the present study was in accordance with the Egyptian standards (Egyptian law no. 48, 1982), the effluent quality from the combined UASB–CSRB system

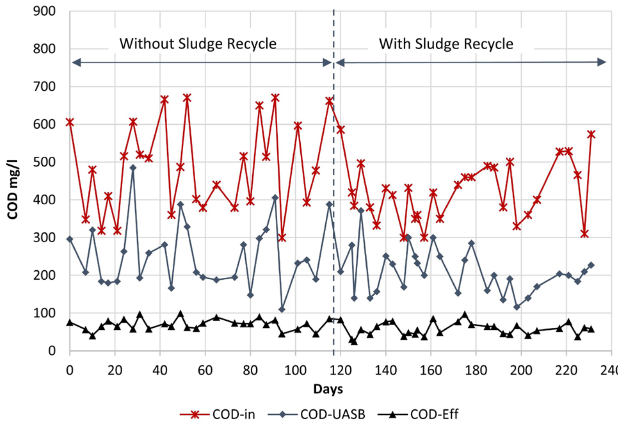

Fig. 2. COD values of raw wastewater, UASB effluent, and SBR effluent.

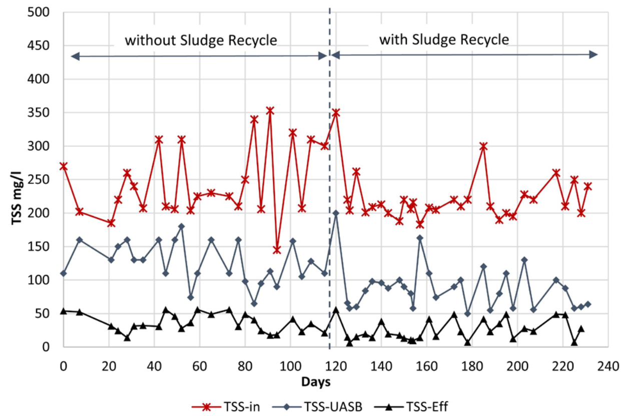

Fig. 3. TSS values of raw wastewater, UASB effluent, and SBR effluent.

Table 2
Operating conditions for the two experimental runs

Parameters	Run 1: without sludge cycling (115 d)		Run 2: with sludge cycling (120 d)	
	Range	Average	Range	Average
Temperature (°C)	19–27	22.7 ± 2.3	20–29	24.3 ± 3.7
Flow rate (L/d)	187–223	212 ± 18	191–218	204 ± 12
HRT in UASB (h)	5.4–6.4	5.7 ± 0.5	5.5–6.3	5.9 ± 0.35
Influent OLR in UASB (kg COD/m³/d)	1.27–2.85	2.1 ± 0.5	1.22–2.39	1.7 ± 0.3
Total OLR in UASB including sludge recycling (kg COD/m³/d)	–	2.1	–	2.57
Biogas production (mL/g COD removed)	60–240	174 ± 61	78–280	230 ± 67
DO in SBR	1.9–2.75	2.2	2.1–2.65	2.35
MLSS in SBR (mg/L)	1,639–2,835	2,023 ± 594	1,508–2,579	1,890 ± 650
SVI in SBR (mL/g)	78–177	116 ± 14	62–173	105 ± 21

was found to be slightly less than that of the UASB–SBR system reported in the literature. This could be because of a decrease in the efficiency of the settling process due to dilution caused by the continuous wastewater influent flow [12]. However, this effect could be minimal in a large full-scale reactor in which a higher effluent quality might be achieved.

For the second experimental run, the sludge was recycled to the inlet of the UASB reactor for 120 d. The results indicated that the average COD and TSS removal efficiencies in the UASB reactor were 49% ± 14% and 54% ± 14%, respectively. The overall average removal efficiencies after the cSBR for COD, TSS, and ammonia were 86% ± 4%, 89% ± 6%, and 84% ± 7%, respectively. The average COD, BOD_5, TSS, and NH_4–N in the effluent were 58 ± 16, 31 ± 17, 25 ± 12, and 7.7 ± 2 mg/L, respectively. The effluent quality using the sludge recycle operational strategy was slightly better than normal operation. This means that, in an integrated UASB–aerobic system, the UASB process could successfully work as an anaerobic pretreatment and enhance waste AS digestion simultaneously without affecting the treatment efficiency. This study's findings are in accordance with the results reported by the few previous researchers who tested sludge cycling in a UASB-suspended growth aerobic system [8,15,16]. Table 4 compares the performance of the integrated UASB–cSBR system used in this study with the systems used in previous studies.

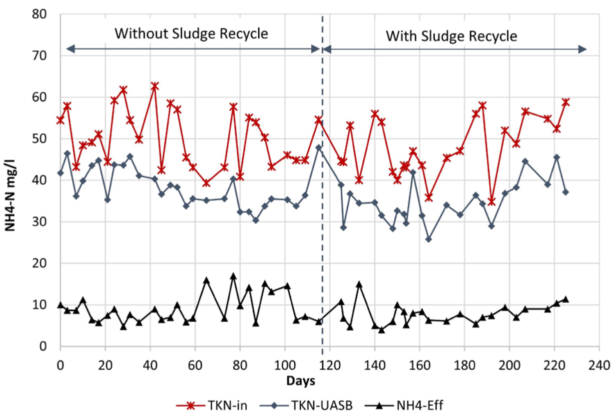

Fig. 4. TKN and NH_4–N values of raw wastewater raw wastewater, UASB effluent, and SBR effluent.

Sludge cycling in a combined UASB and SBR system was studied by Sousa and Foresti [16]. The integrated system was used for treating synthetic wastewater that had a COD of 422 mg/L, and the system was operated at 30°C. The UASB reactor had a volume of 4 L and an HRT of 4 h, while the SBR had a volume of 3.6 L and a cycle time of 4 h. Sludge cycling did not affect system performance, and Sousa and Foresti [16] achieved a very good COD and ammonia removal of up to 95% and 85%, respectively. However, approximately 91% of the COD removal was achieved in the UASB reactor. Guimaraes et al. [8] also tested sludge cycling in a UASB–SBR system. The system was used to treat domestic sewage with an average COD of 587 mg/L, and it was operated at an average temperature of 25°C. In that study, the UASB reactor had a volume of 10 L and an HRT of 4 h, while the SBR had a volume of 7 L and a short aeration time of 1 h. At different solids retention times (SRTs) of 9, 11, and 15 d, the system had good COD removal (up to 92%), regardless of the SRT. Approximately, 82% of the organic load was removed by the anaerobic step. Complete nitrification was achieved at SRTs of 11 and 15 d. La Motta et al. [15] investigated excess sludge cycling in a UASB–AS system. The system was used for

Table 3
Comparison with other integrated UASB-suspended growth aerobic systems without sludge cycling

System	Temperature (°C)	UASB				Aerobic unit		Overall removal efficiency %		Reference
		Volume (L)	HRT (h)	OLR (kg COD /m^3/d)	COD removal %	Volume (L)	Conditions	COD	Ammonia	
UASB–cSBR	19–27	50	5.4–6.4	2.1	48	180	Cycle time: 8 h SRT: 8.6 d	85	82	This study
UASB–cSBR	32	45	8	0.18	60–65	34–47	Cycle time: 4, 6, and 8 h F/M: 0.05–0.32	70–85	74	Khan et al. [12]
UASB–SBR	21	150	6	2.1	72	90	Cycle time: 4, 6, 12, and 24 h SRT: 30 d	91–92	69–100	Torres and Foresti [18]
UASB–SBR	14–28	47	4	1.3–5.3		31	Cycle time: 6, 8, and 12 h	84–89	60–100	Moawad et al. [11]
UASB–AS	30	416	4	2.3–4.4	81–94	23	HRT: 2.8 h F/M: 0.6–0.9	85–93	–	Von Sperling et al. [28]
UASB–AS	30	6.3	6	1.5		6.6	HRT: 6.3 h SRT: 10 d	86	92	Cao and Ang [19]

Table 4
Comparison with other integrated UASB-suspended growth aerobic systems with sludge cycling strategy

System	Temperature (°C)	UASB				Aerobic unit		Overall removal efficiency %		Reference
		Volume (L)	HRT (h)	OLR (kg COD/m³/d)	COD %	Volume (L)	Conditions	COD	Ammonia	
UASB–cSBR	20–29	50	5.5–6.3	2.57	49	180	Cycle time: 8 h	86	84	This study
UASB–SBR	30	4	4	2.5	91	3.6	Cycle time: 4 h	95	–	Sousa and Foresti [16]
UASB–SBR	25	10	4	3.8	82	7	HRT: 2.6 h SRT 9, 11, and 15 d	92–93	–	Guimaraes et al. [8]
UASB–AS	15–30	396	3.2	2.6	34	240, 360	HRT: 2.3 h F/M: 1.5, 0.9	87	–	La Motta et al. [15]

treating domestic sewage with an average COD of 341 mg/L, and it was operated at moderate temperatures ranging between 15°C and 30°C. The UASB reactor had a volume of 396 L and an HRT of 3.2 h, while the aeration tank had HRTs of 2 and 3 h. The system successfully removed up to 87% of the COD regardless of the HRT. Although the UASB reactor only removed 34% of the COD, the overall performance of the system was satisfactory. Other researchers have also reported no significant impact on the treatment performance in UASB-attached growth aerobic systems when excess sludge was recirculated [20,21].

The alkalinity in the influent wastewater was sufficient, in a range of 210–420 mg/L with an average of 285 mg/L. The pH of the raw water, the UASB effluent, and the SBR effluent were 7.45 ± 0.23, 7.51 ± 0.25, and 7.34 ± 0.23, respectively. This alkalinity range allowed successful operation of the UASB during the experimental duration with no significant pH change, which is in agreement with the alkalinity reported in the literature [3]. The system denitrification rates were not evaluated in the present study.

3.2. Excess sludge production

In the present study, during experimental run 1 (115 d), the excess sludge in the UASB was withdrawn weekly by opening sampling port no. 5 and discharging the accumulated sludge. An average of 8.0 L of sludge was withdrawn weekly from sampling port no. 5 (Fig. 1). The sludge was mixed and homogenized to measure the suspended solids. The concentrations of dry solids in the UASB sludge ranged from 795 to 1,860 mg/L, with an average concentration of 1,447 mg/L. It is important to note that the sludge was withdrawn weekly in this study to prevent the small effluent tubes in the UASB from clogging. In practice, sludge is withdrawn from a UASB less often. For the cSBR system in experimental run 1, an average 21.8 L/d of waste sludge was withdrawn as mixed liquor during the aeration period in the cSBR. The dry solids concentrations in the wasted sludge ranged from 1,639 to 2,835 mg/L, with an average of 2,023 mg/L (Table 2). The SRT in the cSBR corresponding to this operational strategy was 8.6 d on average.

In experimental run 2, excess sludge withdrawal from the cSBR was continued using the same regime and quantity as in experimental run 1. The dry solids concentrations ranged from 1,508 to 2,579 mg/L, with an average of 1,890 mg/L (Table 2). The excess sludge was mixed with the raw wastewater in the influent storage tank (Fig. 1). The UASB removal efficiency decreased for the first 10 d. Therefore, we decided to increase the sludge withdrawal from the UASB. On average, 7.5 L of the digested sludge was withdrawn twice weekly from sampling port no. 5. The concentrations of the dry solids in the UASB sludge ranged from 1,274 to 2,830 mg/L, with an average concentration of 2,260 mg/L. Based on the measurements of the suspended solids in the sludge samples, on average, the production of more than 89% of the sludge dry solids can be reduced using the suggested sludge cycling strategy.

Sousa and Foresti [16] reported a low sludge production of only 4% of the influent COD when the sludge was cycled in a UASB–SBR system. La Motta et al. [15] studied sludge cycling in a UASB–AS system with no sludge withdrawal for 106 d to investigate the sludge accumulation in a UASB. We conducted a literature review to evaluate sludge cycling techniques in an integrated UASB–aerobic system and compared it with other techniques. Several other techniques for sludge production minimization have been reported in the literature and covered in a recent review [2,22]. A simple technique used to minimize sludge production is to control the operating parameters by increasing the SRT and DO concentration in the bioreactor. This technique significantly increases the plant operation costs due to excessive aeration. Other significant techniques include the disintegration of the returned AS using physical, thermal, chemical, or thermochemical processes, all of which have been extensively studied in the literature. However, this technique requires a high capital investment and ongoing maintenance [2].

Sludge cycling under different conditions of the oxidation–reduction potential is another strategy in the literature that has been used to minimize sludge yield. The concept is to pass the return sludge line on an anaerobic tank, which could reduce the sludge yield by 55% [23]. However, the disadvantages of this method are that anaerobic conditions for the entire biomass could affect the biomass growth and a large tank is required to handle the return sludge quantities. This approach was recently improved by recirculating the excess sludge only between an anaerobic sidestream reactor (ASSR) and then back to the main reactor in an SBR system [24]. This strategy resulted in a lower capital cost and was successful in reducing excess sludge by up to 77% [25].

The concept of integrating an SBR with an ASSR has been studied frequently in the literature. In this combined system, biomass hydrolysis is done through various means, including biomass hydrolysis, the destruction of extracellular polymeric substances, and cell lysis. Then, the biomass is recirculated to the main reactor and allowed to decay further [24,26]. While the ASSR technique seems attractive, the only use for the anaerobic tank is floc destruction and cell lysis without energy recovery. The sludge cycling approach recommended in this study in a UASB–aerobic system is similar to the ASSR approach. However, the technique used in the present study and discussed in this paper is completely different from the ASSR technique.

In our strategy, the sludge is recirculated and mixed with the influent flow at the UASB inlet. The solids in the excess sludge are trapped in the sludge blanket and subsequently digested. Hydrolysis of excess sludge increases the organic load on the UASB, thereby enhancing its performance and biogas production. Solids are reduced directly via the transformation of solids to low molecular weight compounds and gasses by acid- and methane-forming bacteria. Biogas production is increased, and the UASB works as anaerobic pretreatment and waste sludge digestion step. This strategy does not require an additional anaerobic tank as does the ASSR technique because the UASB replaces the function of the anaerobic tank. Moreover, the HRTs required for UASB, which are in the range of 4–8 h, are much shorter than the HRTs for the anaerobic tank in the ASSR technique, which could be longer than 10 d [24,26]. Thus, the 95% sludge minimization reported in this study is competitive with the sludge minimization realized using the ASSR technique, especially in small and decentralized areas. However, the strategy proposed in this paper was only studied for 4 months. The effect of a longer operation period and different conditions should be investigated in the future.

One limitation of this study is that the impact of sludge cycling on phosphorus removal was not investigated. However, because sludge production was reduced, it could lead to the accumulation of phosphorous in the reactor. Thus, phosphorus removal in experimental run 2, when the sludge cycling strategy is implemented, is expected to be less than in experimental run 1, when no sludge cycling occurs. Still, additional investigations are required to clarify the effect of sludge cycling on phosphorus removal and to improve the proposed system for phosphorus removal.

3.3. Sludge settleability

The SVI values of the mixed liquor in the cSBR are presented in Table 2. The SVI was reduced from an average value of 116–105 mL/g, which indicates excellent settleability. The excess sludge cycle strategy enhanced the settleability in the cSBR. For the digested sludge from the UASB, the VSS/TSS ratio was in a range of 0.55–0.63, which indicates that the sludge generated from the UASB reactor was well stabilized. The results showed that sludge settleability was enhanced after sludge recycling. These findings are in accordance with those of Guimaraes et al. [8], who reported SVI values <80 mL/g in a UASB–SBR system operated with an excess sludge cycling strategy. Good settleability of sludge in an aeration tank could mean that the system can be operated at a higher MLSS [7]. However, further studies are required to investigate the effect of sludge cycling on sludge characteristics and dewaterability.

3.4. Biogas production

For the UASB process, the influent average OLR in experimental run 1 was higher than in run 2 (Table 2). However, when the OLR due to sludge recycling is added to the influent OLR, it will be higher. The estimated OLR from sludge recycling is 0.87 kg COD/m^3/d on average which makes the total OLR in experimental run 2 approximately 2.57 kg COD/m^3/d (Table 2). The measured biogas production rate throughout the entire study ranged between 60 and 240 mL/g, with an average of 174 mL/g COD removed at an average OLR of 2.1 kg COD/m^3/d. The rate of biogas production is lower than the theoretical value of 350 mL/g COD removed [1]. Biogas production depends on different operational parameters, such as the temperature and the OLR [6]. Mahadevaswamy et al. [27] reported biogas production of 150 mL/g COD removed at an OLR of 1 kg COD/m^3/d and 400 mL/g COD removed at an OLR of 2.1 kg COD/m^3/d. The biogas production during experimental run 2, with sludge recycling, ranged between 78 and 280, with an average of 230 mL/g COD removed at an average OLR of 1.7 kg COD/m^3/d. Biogas production in experimental run 2 was, on average, approximately 32% higher than it was in experimental run 1. This can be attributed to the higher OLR in experimental run 2 that resulted from the recycled sludge. It is important to note that the excess sludge in this study was not cycled directly to the UASB; instead, it was cycled to the storage tank once a day and then to the UASB throughout the day. This scheme could help start earlier starvation and hydrolysis of the sludge under anaerobic conditions in the storage tank.

4. Conclusions

A combined UASB–cSBR system proved promising for decentralized wastewater treatment and reuse in semi-arid areas such as Egypt. The proposed system achieved a high removal efficiency for COD, TSS, and ammonia (85%, 87%, and 82%, respectively). The quality of the treated wastewater met Egyptian standards for regulating wastewater discharged into agriculture drains. The sludge cycling strategy proposed in this study is a promising approach that minimized the production of sludge dry solids by up to 89% and increased gas production by 32% in comparison with the values measured when the sludge was 8.6 d old. Moreover, this proposed approach did not have a significant impact on the removal of the organic content or nitrogen. Sludge reduction that results from sludge cycling in a UASB–cSBR system is comparable with other sludge minimization techniques reported in the literature. The capital and operating costs for this proposed technique are expected to be lower than other physical- and chemical-based sludge minimization techniques. The results of this study indicate that the proposed sludge recycling technique results in improved sludge settleability. However, further studies are needed to investigate the effect of sludge cycling on the sludge characteristics and its dewaterability.

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