Desalination and Water Treatment
www.deswater.com
doi: 10.1080/19443994.2013.775669

51 (2013) 7490–7498
December

Taylor & Francis
Taylor & Francis Group

Innovative sustainable anaerobic treatment for wastewater

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Received 19 September 2012; Accepted 9 February 2013

ABSTRACT

The main objective of this study is to demonstrate and implement a cost-effective system for low-strength municipal wastewater treatment in rural areas. An integrated compact anaerobic treatment pilot plant unit was designed, constructed and operated for almost two years. The pilot plant consists of three successive compartments mainly: primary sedimentation (PS), packed bed upflow anaerobic sludge blanket (P-UASB) and inclined plate settler. The pilot plant was operated continuously at a hydraulic loading rate of 6 m^3/day, average organic loading rate of 2.03 kg COD/m^3/day and average retention time of 4 h at the P-UASB and a total retention time 6 h for the integrated treatment unit. The performance of the treatment train was monitored via physicochemical as well as bacteriological and parasitological analysis. The average removal rates of chemical oxygen demand, biological oxygen demand and total suspended solids were 78, 79 and 91%, respectively, with corresponding average residual values of 71 mgO_2/L, 39 mgO_2/L and 18 mg/L. Bacterial analysis indicated that great majorities were removed but still some residuals exist. The treated wastewater, after disinfection, was complying with the Egyptian Code for wastewater reuse in restricted irrigation. The results indicated that the total life cost of the pilot plant, during the research period, proved to be a cost-effective process for treating low-strength wastewater.

Keywords: Low-strength wastewater; Anaerobic treatment; Packed upflow anaerobic sludge blanket; Inclined plate settler

1. Introduction

Wastewater is one of the challenging environmental problems in Egypt. Wastewater treatment in rural areas and small communities lags far behind potable water supply; this practice causes serious environmental and hygienic problems. The high construction, operation and maintenance costs for a centralized conventional wastewater collection and treatment system represent an obstacle for the Egyptian government in the installation of such a system in rural areas. All that made the on-site low-cost options or decentralized sanitation systems are all become interesting solution for application and testing [1]. This alternative can meet a sustainable wastewater management requirement and has a promising future, especially for developing countries [2]. From the

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perspective, one technology that could deliver similar effluent quality compared to the centralized conventional wastewater treatment is the anaerobic technology [3].

Nowadays, intensive research works have been conducted on the treatment of dilute sewage wastewater at ambient temperatures using anaerobic reactors such as upflow anaerobic sludge blanket (UASB), expanded granular bed and anaerobic baffled reactors (ABRs). Feng et al. [4] studied the performance of bamboo carrier ABR for treatment of dilute domestic sewage from rural areas of china, total chemical oxygen demand (TCOD) removal efficiency varied from 79% at 48 h hydraulic residence time (HRT) to 69% at 18 h HRT. Manariotis and Grigoropoulos [5] conducted experiments on ABR to evaluate the treatment of low-strength synthetic wastewater (chemical oxygen demand [COD] of 300–400 mgO_2/L) at 26˚C and HRTs of 24 and 12 h and observed that COD removal efficiencies ranged from 87 to 91%. Sabry [6] used upflow septic tank/baffled reactor system which produced an average removal values of COD, biological oxygen demand (BOD) and total suspended solids (TSS) of 84, 81 and 89%, respectively, at a retention time of 20 h. Also, Gopala et al. [7] studied the performance of 10 L laboratory scale ABR operated for almost 600 days at a temperature ranging from 20 to 32˚C for treating low-strength complex wastewater of COD 500 mgO_2/L at HRTs of 20, 15, 10, 8 and 6 h with corresponding organic rates of 0.8, 1.2, 1.5 and 2 kg $COD/m^3/day$. The removal efficiencies of COD and BOD exceeded 88%. Furthermore, the use of packing material in upflow anaerobic sludge blanket plays an important role in increasing the surface area for faster biofilm development and improved methanogenesis. Many carrier materials have been investigated regarding their stability as support for biofilm, including cheap, readily available materials like, sand, clay, glass, quartz and a number of plastics [8]. Picanco et al. [9] reported that the efficiency of removing organic matters in fixed-bed reactors is directly related to the characteristics of the support material used for immobilization of anaerobes.

It is widely accepted that organic support material has a higher affinity than inorganic material [10]. It is worth noting that most of the studies using anaerobic reactors for low-strength wastewater were carried out at high retention times and with or without packing materials. Therefore, the main objective of this study is to investigate and evaluate the performance and capability of a compact anaerobic packed bed reactor with lamella, operated at a very low retention time (4 h), for sustainable treatment and reuse in agricultural purposes.

2. Material and methods

2.1. Description of the pilot plant

The integrated combined anaerobic treatment unit consists of three successive compartments namely primary sedimentation (PS) (option), upflow anaerobic sludge blanket packed with lamella sheets (P-UASB) and inclined plate settler (IPS). The unit is located at a nearby wastewater treatment plant. The pilot plant unit is made of PVC of 8 mm thickness. The packing material is a lamella corrugated plastic sheets (Fig. 1) with a specific surface area of 150 m^2/m^3. The treatment train and the schematic diagram of the pilot unit are shown in Figs. 2 and 3. Full description of the treatment unit is given in Table 1.

2.2. Operating conditions

The pilot plant was operated continuously for almost two years at a hydraulic loading rate of 6.0–6.5 m^3/day, average organic loading rate of 2.5 kg COD/m^3/day and at ambient temperature ranged from 12 to 42˚C for almost two years. The system was fed with domestic sewage after coarse screening to prevent clogging and damage caused by rough suspended solids of influent wastewater. During the start-up period, the flow rate was gradually increased from 2.0 m^3/day up to 6.0 m^3/day until it reached the steady-state conditions. In order to evaluate the function of packing material, non-packed UASB experiment was also conducted. The non-packed reactor was operated at

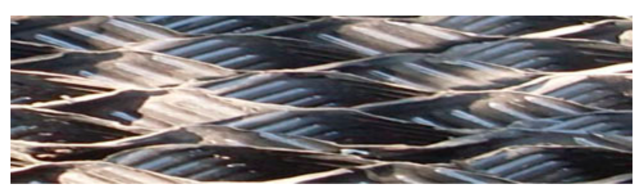

Fig. 1. Photo for the packing material (lamella sheets).

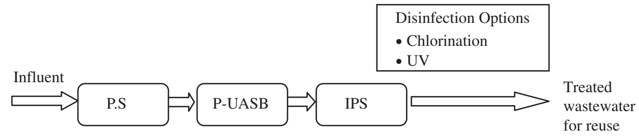

Fig. 2. Schematic diagram of the pilot plant.

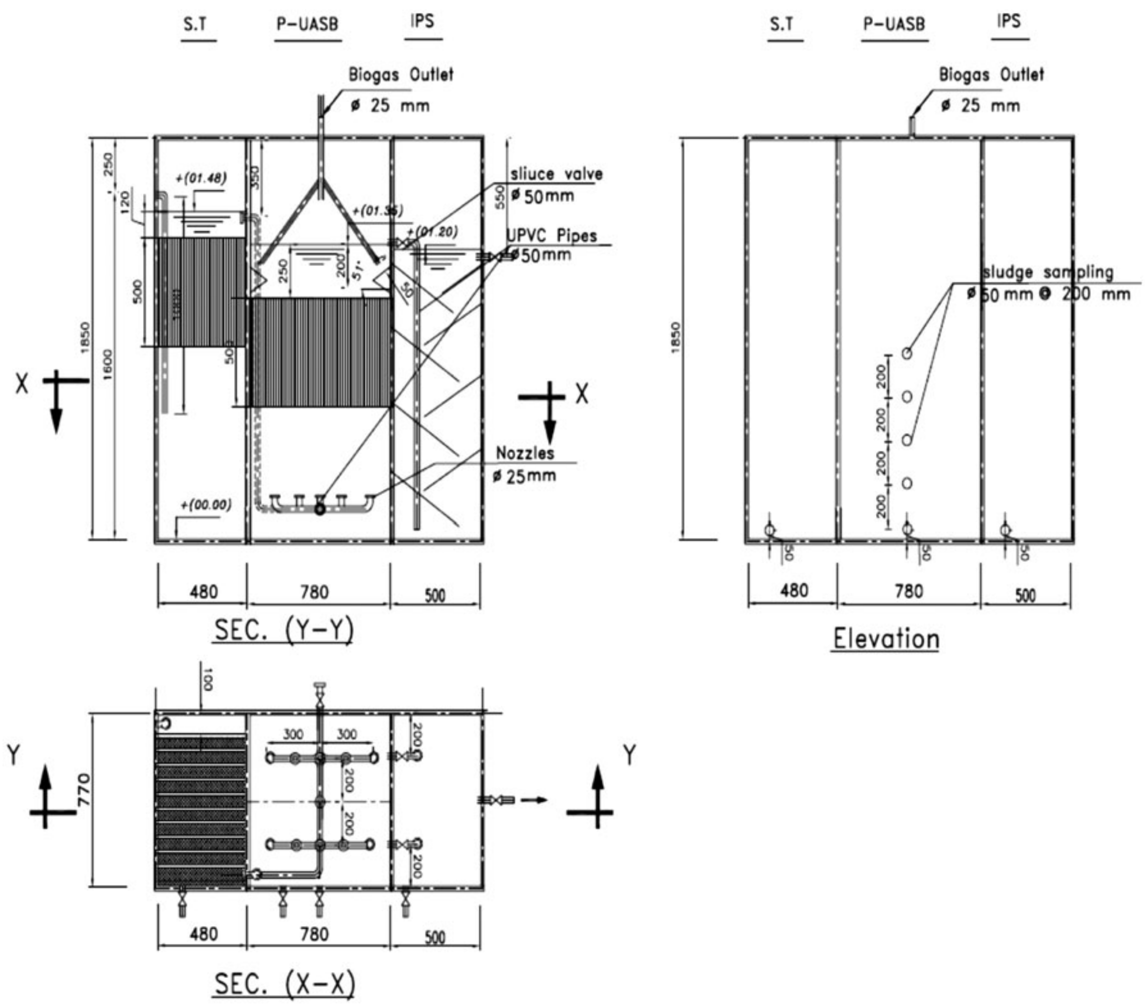

Fig. 3. Engineering design of the pilot plant.

Table 1
Full description of the treatment unit

Parameters	PS	UASB*	IPS
Designed retention time (h)	1	4	1
Sizing (L)	250	1,080	250
Flow rate (m^3/day)	1	4.32	1
Upflow velocity (m/h)	–	0.42	–
Remarks	Option if needed	Packing material is corrugated plastic sheets with specific surface area ca. 150 m^2/m^3	Provide by plastic inclined sheets (60° inclination)

[a]Packed as well as classical UASB reactors.

the same organic and hydraulic loading rates. The duration of this experiment extended for three weeks only after finishing P-UASB operation. The total number of collected samples for waste quality analyses was three.

2.3. Acclimatization and sludge inoculation

The acclimatization period of the treatment unit took about four months from the first inoculation to the P-UASB reactor. It was seeded with primary digested sludge obtained from a secondary wastewater treatment plant. The sludge was kept in anaerobic condition before feeding to the P-UASB. The seeded sludge has a concentration of 63.4 g/L for TSS and 27.3 g/L for volatile suspended solids (VSS). The volume of the sludge represents almost 40% from the total volume of the P-UASB reactor. During the steady-state operation phase, the excess sludge was discharged every two months. Before sludge withdrawal, several sludge samples were collected from the different points along the reactor height at 10, 28, 41, 54 and 69 cm from the reactor bottom. These samples were analysed for total solids (TS) and volatile solids (VS). Accordingly, the composite sludge concentration inside the reactor was calculated and compared to that of the start initial value of the seeded sludge as a potential to determine the excess sludge concentration. In each wasting case, the volume of the excess sludge was observed. Furthermore, the performance of the integrated anaerobic treatment unit was monitored by intermittent measurements of COD and TSS until it reached the steady state.

2.4. Analysis

The investigated physicochemical analyses were pH, temperature, turbidity, TCOD, soluble chemical oxygen demand (SCOD), BOD_5, TSS, VSS, total kjeldahl nitrogen (TKN), ammonia (NH_3), total phosphorous (TP), oil and grease and all extractable matters by chloroform, hydrogen sulphide and volatile fatty acids (VFA). The gas produced was detected using portable ambient air analyzer (MIRAN SapphlRe, 205A series), while its flow was measured using gas flow metre. The pathogenic analysis include faecal coliform (FC) and helminthes (Nematodes, cestodes and trematodes). All the analyses, unless otherwise specified, were carried out according to the American Public Health Association for Examination of Water and Wastewater [11].

3. Results and discussion

3.1. Start-up of the pilot plant treatment unit

To reach the steady-state conditions, the system was operated at 2.88 m^3/day then gradually increased to 4.33 m^3/day, then to 6.0 m^3/day. The system reached the steady state after almost four months as indicated by constant measurements of total COD and turbidity which reached 158 mgO_2/L and 70 NTU, respectively.

3.2. Wastewater characterization

From the results depicted in Table 2 and Fig. 4, it is obvious that the wastewater fed to the treatment unit is classified as a low-strength wastewater [12]. The average values for total COD, soluble COD and particulate COD were 320.5, 108 and 211.5 mgO_2/L, respectively. The average BOD and TSS were 190 mgO_2/L and 200 mg/L, respectively.

Table 2
Physicochemical characterization of raw wastewater

Parameters		Unit	N^a	Min.	Max.	Average
pH-value		–	25	6.78	7.54	–
Turbidity		NTU	25	89	208	135.5
COD_{tot}		mgO_2/L	25	292	398	320.5
COD_{sol}		mgO_2/L	25	77	180	108
COD_{part}		mgO_2/L	25	215	218	211.6
BOD_{5tot}		mgO_2/L	25	140	240	190.8
Settleable solids	10 min	mL/L	25	0.5	2.5	1.38
	30 min	mL/L	25	0.8	3.0	1.7
TSS		mg/L	25	110	289	200
VSS		mg/L	25	94	243	150.9
TKN		mgN/L	25	24.9	66.8	40.0
NH_4–N		mgN/L	25	14.0	30.0	22.6
TP		mg/L	25	2.8	6.6	3.8
Oil and grease		mg/L	25	23.4	88.0	46.1
H_2S		mg/L	25	1.8	9.5	5.0

[a] *N*: number of samples.

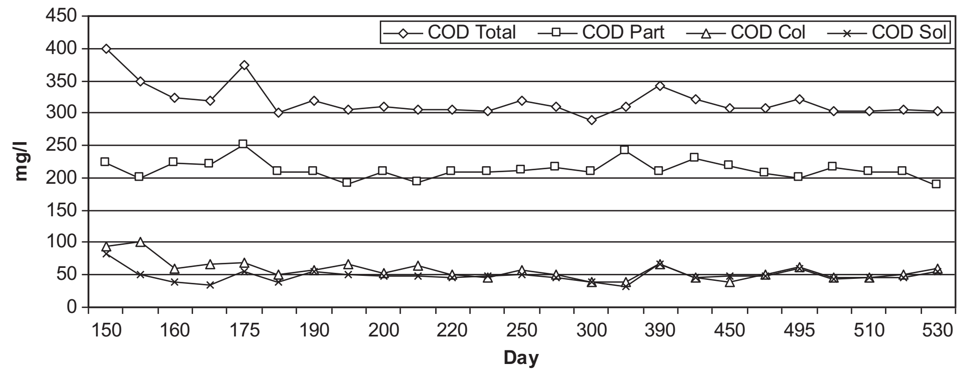

Fig. 4. COD fractions for raw wastewater.

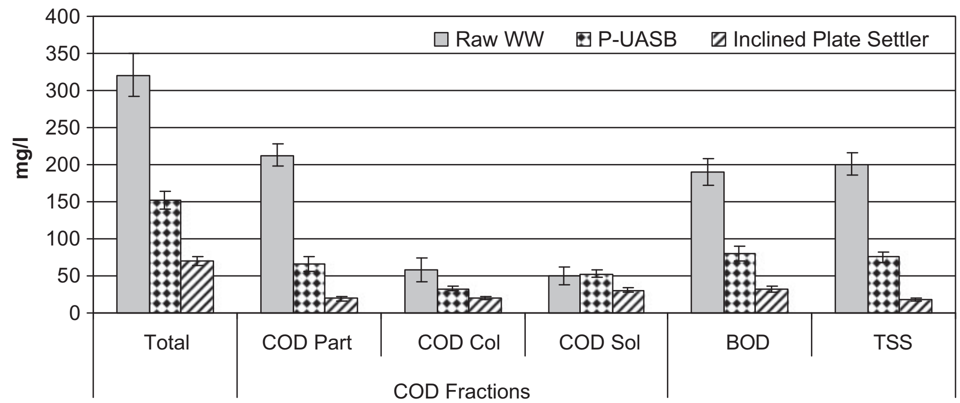

Fig. 5. Efficiency of the treatment system.

3.3. Performance of the integrated anaerobic treatment unit

3.3.1. COD fractions, BOD and TSS removal

The overall efficiency of the integrated anaerobic treatment unit is shown in Fig. 5. The average removal rates of TCOD, BOD and TSS were 78, 79 and 91%, respectively, with corresponding residual values of 71 mgO_2/L, 39.7 mgO_2/L and 18 mg/L. It is obvious from the values depicted in the figure that the use of packing material in the UASB, with high surface area, aids in the accumulation of suspended solids at the bottom of the reactor so increasing the average removal efficiency of TSS to 62%. Also, it was found that the use of IPS, which is provided by plastic inclined sheets at 60 inclination, improves the settleability of suspended solids (up to 91% removal of TSS) which is then accumulated and discharged with the sludge. Also, it can be explained that suspended solids settle, agglomerate and flow down the sloped plate surfaces, while the treated effluent is conducted upwards. Moreover, a biofilm is developed on the surface of IPS where biocatalysts such as micro-organisms, particulate matters and extracellular polymers exist on the surface of an inert media or adhere with other micro-organisms [13]. Similar results were obtained [14]. They found that clean vertical sheets of reticular polyurethane foam could effectively remove suspended solids from domestic sewage mainly because of their high specific surface area and porosity; moreover, the presence of a biofilm improved the bisorption of suspended and colloidal particles. Although the discharge of the accumulated sludge from the system reduces the total amount of biomass in the reactor, it prevents clogging of the filter media. The results in Fig. 5 also showed that the TCOD improved by 53.4% in the IPS compared to P-UASB, while the SCOD was limited to (60%). This may be explained that SCOD (partly) consisted of soluble microbial products which are resistant to anaerobic degradation. These are in agreement with Aquino and Stuckey [15].

The packing material was removed and the system was evaluated. Fig. 6 shows the performance of the conventional (non-packed) UASB compared with packed UASB.

The P-UASB reactor was found to be efficient for removal of COD and TSS (52 and 62%) than the conventional UASB reactor (45 and 57%), respectively.

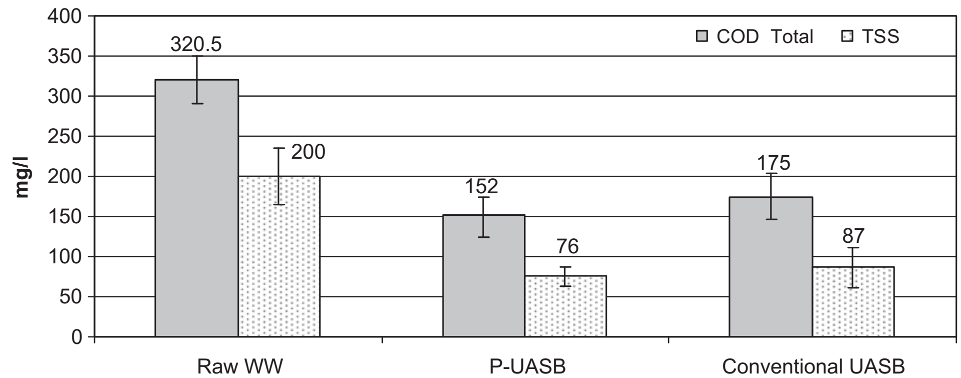

Fig. 6. Comparison between P-UASB and classical UASB reactor.

These results are in a good agreement with that obtained by El-Gohary et al. [16].

3.3.2. VFA removal

The average VFA concentration in the P-UASB increased from 35.6 mg/L in the influent wastewater to 73.2 mg/L and consequently slightly lowered the pH value from 7.2 to 6.9. This demonstrates that hydrolysis and acidogenesis were the main biochemical activities taking place in the P-UASB [17]. However, degradation of VFA took place in the final effluent and it was reduced to 28.7 mg/L resulting in the increase of the pH value of the final effluent to 7.14. This indicated that the organic content in wastewater such as COD and VFA is consumed by the biofilm passing through the reactor P-UASB and IPS.

3.3.3. Nutrient removal

The integrated anaerobic treatment unit displayed nutrient removal efficiency of 68.5% for total organic nitrogen, 66.8% for ammonia and 65% for TP at a HRT in P-UASB of 4 h. These results are close to that obtained by Tawfik et al. [18], although they used multi-stage treatment unit (UASB – down flow hanging sponge) at a total HRT of 10.7 h.

3.3.4. Sludge bioactivity

Fig. 7 shows the sludge sampling including the average sludge concentrations along different height levels of the reactor. This figure shows the initial concentration of the sludge when it was measured in the laboratory without any expansion (TS = 84.4 g/L; VS = 38.9 g/L). The initial concentration after expansion (sludge blanket at 10 cm above reactor's bottom) due to the upflow inside the reactor was (TS = 63.4 g/L; VS = 27.3 g/L). Although there is reduction in the biomass concentration of the sludge, the reactor still worked with acceptable performance and sludge activity. The sludge methanogenic activity was determined along the operation time at different temperature ranges and compared to the actual sludge loading rate according to the fluctuated concentrations of the influent wastewater. It was found that the sludge loading rates were fluctuated within range of 0.13–0.17 g COD/g VS d with an average value of 0.15 g COD/g VS d along the different experimental runs and temperatures. The average values of total methanogenic sludge bioactivity were 0.11 g COD_{rem}/g VS d along the different experimental runs. This means that the sludge has a very good response and interaction with the increasing of sludge loading rate without any risk of overloading inhibition. It is also confirmed the ability of sludge activity to overcome the obstructions due to change of operating conditions.

3.3.5. Biogas production

The quantity and quality of biogas produced were measured frequently. The methane content was ranged between 72 and 77% of the total biogas. Also, the biogas included some other gases such as nitrogen, NH_3, CO_2, CO and N_2O. The specific methane gas production was determined according to the removed COD and influent COD as well as the influent wastewater discharge. The removed COD-specific CH_4-gas production ranged between 180 and 220 L CH_4/kg $COD_{removed}$ with an average value 200 L CH_4/kg $COD_{removed}$. The influent COD-specific CH_4-gas production ranged between 80 and 160 L/kg COD_{in} with an average value of 120 L/kg

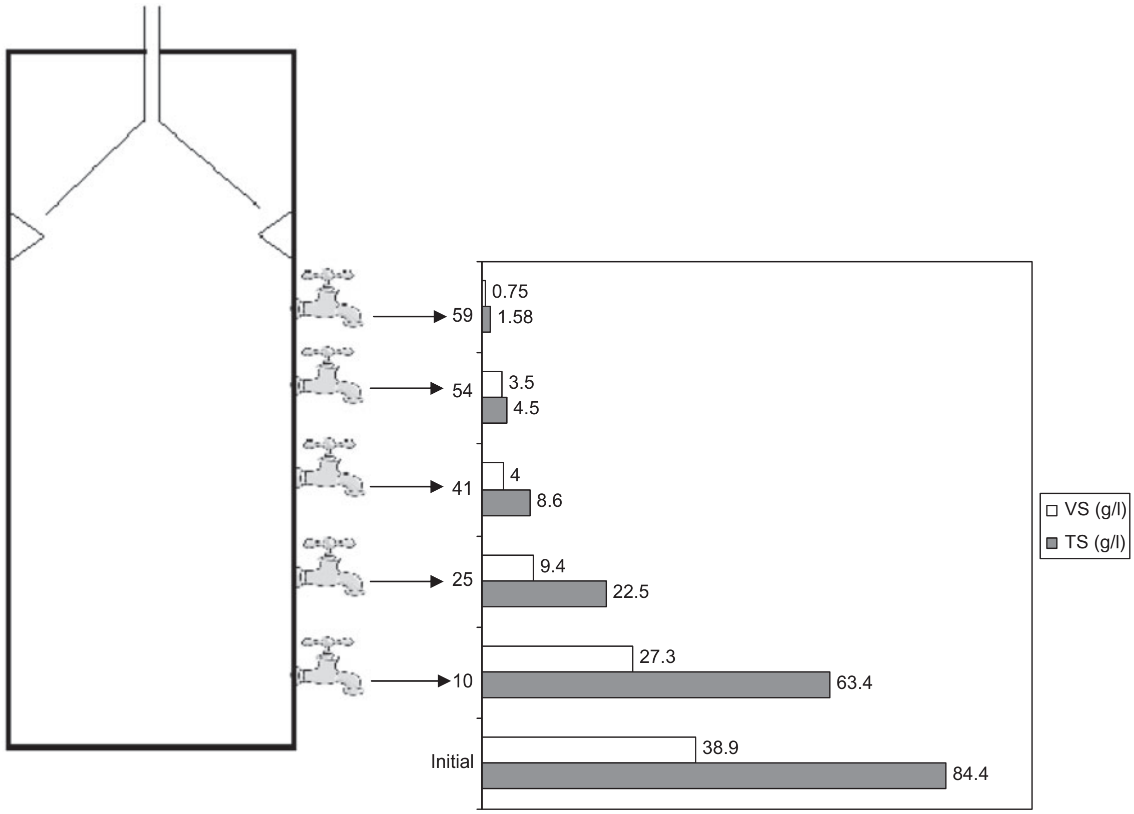

Fig. 7. Sludge concentration in the P-UASB reactor.

COD_{in} along the whole runs. In comparison to the previous studies, it is proved that the obtained values are considered in a normal range of methane production for anaerobic treatment of municipal wastewater [13,19].

Table 3
Efficiency of overall treatment scheme for FC removal

Samples	FC-MPN-index/100 mL	
	Influent	Effluent
1	1.5×10^7	1.5×10^3
2	1.5×10^6	9.0×10^2
3	1.4×10^7	7.0×10^2
4	7.0×10^6	4.8×10^2
5	9.0×10^5	9.3×10^2
6	7.0×10^6	2.8×10^2
7	1.5×10^7	1.5×10^3
8	2.0×10^7	2.8×10^2
Min	9.0×10^5	2.8×10^2
Max	2.0×10^7	1.5×10^3
Average	1.0×10^7	8.2×10^2

3.3.6. Pathogens removal

The results shown in Table 3 indicated that the average removal rate of FC reached 99.92% with average residual value of 8.2×10^2. Also, total helminthes (nematodes, cestodes and trematodes) could not be completely removed due to the short HRT and the high upflow velocity in the P-UASB. The mean values of nematodes, cestodes and trematodes indicated that the total helminthes reached 0.3 ova/L. Feng et al. [4] reported that anaerobic process had certain effect on the removal of pathogenic species such as FC and *Ascaris* eggs, but it is necessary to take further appropriate post-disinfection process to guarantee the effluent safety. However, FC and helminthes ova in our study are in compliance with the Egyptian Code for Wastewater Reuse in Restricted Irrigation (FC = 1,000 and helminthes ova = 1).

4. Economic analysis

To calculate the economic analysis of the proposed treatment system, a simulation of upscaling module was designed for 500 m^3/d using the integrated anaerobic wastewater treatment plant (5,000 PE) with low-strength wastewater (average 320 mgO_2/L COD). The designed sizing was done based on the results of optimum total HRT of 6 h and required removal efficiencies stated in the Egyptian Code for wastewater reuse in restricted irrigation (COD = 80 mgO_2/L, BOD = 40 mgO_2/L and TSS = 20 mg/L). The investment cost was calculated according to the current construction market in Egypt. The investment cost of the plant was about $112,000, including land ($0.1 million). The per capita investment cost is $20. The annual operation costs are about $0.45 per capita ($0.012/m^3). It is obvious that the investment cost of such integrated system is reduced by 40% from the conventional activated sludge process.

4.1. Economic benefits of biogas utilization

$$\text{Produced methane gas} = 19{,}200\ \text{L/d}(19.2\ \text{m}^3/\text{d}) \quad (1)$$

$$\text{Equivalent produced energy} = 213.12\ \text{KWh/d} \quad (2)$$

$$\text{Energy demand for UASB reactor [20]} = 0.08\ \text{KWh/kg}\,\text{COD}_{\text{removed}} = 12.8\ \text{KWh/d} \quad (3)$$

$$\text{Rest of energy} = 150.32\ \text{KWh/d}$$

This energy may be stored or discharged to the public network. The annual pay-back gained from the produced energy is $1,500 ($0.30 per capita). This will reduce the annual cost of operation to only $0.15 per capita, which is considered a very cost-effective module of operation of such plants. Based on the cost–benefit analysis, it is obvious that the integrated anaerobic treatment system proved to be very cost effective compared to the conventional aerobic treatment process.

5. Conclusions

- The results of this study showed that low-strength wastewater can be effectively treated using integrated anaerobic treatment unit consistng of three successive compartments mainly PS, packed bed anaerobic sludge blanket and IPS operated at low HRT for P-UASB of 4 h with an average OLR of 2.03 COD/m^3/day. The quality of treated effluent in terms of COD, BOD and TSS removal rate were 78, 79 and 91%, respectively.
- The packing material was added in the settling zone in the UASB section. The main objective of it is to prevent wash out of sludge and reduce the level of suspended solids and COD load in the effluent.
- Results indicated that there is no need for PS in case of treating low-strength wastewater.
- The treatment unit removed considerably the pathogenic species as represented by FC and helminthes ova.
- The integrated system proved to be very cost effective compared with conventional aerobic wastewater treatment system.

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