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Sewage treatment using an integrated system consisting of anaerobic hybrid reactor (AHR) and downflow hanging sponge (DHS)

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ABSTRACT

This paper presents an evaluation of a combined wastewater treatment train consisting of an anaerobic hybrid reactor (AHR) followed by a downflow hanging sponge (DHS) system. The combined system was operated at a total constant hydraulic retention time (HRT) of 8 h (AHR: 6.0 h and DHS: 2.0 h) and an average organic loading rate of 1.9 kg COD/m^3.d for AHR and 2.1 kg COD/m^3.d for the DHS. The combined system was able to remove 95 and 89% of the BOD$_{5\text{total}}$ and COD$_{\text{total}}$ with residual values in the final effluent of only 10 and 49 mg/L, respectively. Ammonia concentration was reduced by 83%. The geometric mean of faecal coliform count was reduced by 4.7 log$_{10}$. Residual count in the final effluent ranged from 10^2 to 10^3 MPN/100 ml. Average concentration of trapped biomass amounted to 20 g VSS/L of sponge volume. The SRT of DHS system was 121 d. Calculated average sludge yield coefficient for the DHS system was 0.08 g TSS/g COD$_{\text{removed}}$. Analysis of wastewater samples collected at the outlet of each segment along the DHS revealed that most of the organic matter, as expressed by the COD fractions values is removed in the 1st and 2nd segments of DHS system. This was followed by nitrification in the next two segments.

Keywords: Sewage treatment; AHR; DHS; Nitrification; Faecal coliform

1. Introduction

Environmental management is one of the most pressing issues in Egypt. Among the challenges facing the planners and managers is the need to ensure ongoing basic human services such as the provision of water and sanitation. The low coverage of rural areas with appropriate sanitation systems presents a major challenge. A situation which is attributed to the replication of centralized, highly engineered human waste management systems. Therefore, emergent trends for the implementation of low-cost, decentralized naturally-based infrastructure are recently getting more attention in Egypt [1].

High rate anaerobic treatment systems have gained popularity over the past decade, mainly through their intensively improved treatment efficiency. An up-flow anaerobic sludge blanket (UASB) and anaerobic filter (AF) have led the way in this category. Retention of biomass in the UASB reactor is based on the development of a micro-flora that is able to form a granular sludge which is retained in the reactor by its sedimentation characteristics [2]. In the AF, biological growth forms a layer or biofilm over an inert support material having a high surface/volume ratio [3]. However, shortcomings in their operation have presented themselves during operation, among which is the high level of suspended solids in the effluent. Also, occasional washout of sludge in the UASB reactor at low temperature has been reported. For mini-

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mizing the limitations of these systems, The anaerobic hybrid reactor (AHR) has been proposed to combine the advantages of both UASB and AF in one reactor [4,5]. AHR is a combination of UASB reactor and AF [6]. A layer of biomass carrier is situated in the upper part of the AHR. This layer separates the biogas bubbles from the biomass and acts as a support material for the biomass growth as well. The layer even has a notable efficiency as a suspended solids (SS) separator [7]. The use of packing media only in the top portion of the reactor minimizes channelling problem associated with AF and loss of biomass due to floatation associated with poorly performing UASB reactors. Elmitwalli et al. [5] compared a UASB and an AHR, both inoculated with granular sludge operated at 8.0 h HRT for the treatment of pre-settled sewage at a temperature of 13°C. The media used in the AHR consisted of vertical reticulated polyurethane foam sheets with knobs. The AHR removed 64% of the COD_{total}, which was higher by only 4% than that obtained by the UASB reactor. HutnÏan et al. [8] compared the performance of the UASB reactor with the AHR at different organic loading rates and constant temperature of 37°C. The results obtained indicated a washout of sludge in the UASB at an OLR of 6 kg COD/m^3.d. In the AHR washout started to occur at an OLR of 12 kg COD/m^3.d. Oleszkiewicz and Thadani [9] observed the superior organic removal of an AHR relative to that of a UASB whereas it was comparable to an anaerobic filter system [10]. Accordingly, the AHR reactor could be applied successfully for pre-treatment of domestic wastewater, but additional post-treatment is required for removal of the remaining portion of COD, TSS, ammonia and pathogenic bacteria.

In this study, the down-flow hanging sponge (DHS) reactor was selected as a post-treatment step. The principle of this system is the use of a polyurethane sponge (CF-type) as a medium to retain biomass. The concept is somewhat similar to that of trickling filter, except that the packing material is sponge, which has a void space of more than 90%, resulting in a significant increase in the available surface area, consequently an increase in the amount of entrapped biomass and longer solid retention time (SRT). The direction of the wastewater movement in DHS is from the top downwards from one segment to the other. When the wastewater trickles from one segment to the next one, it comes into contact with air. This repeated phenomenon maintains the DO concentration in the wastewater at high levels. By virtue of this, there is no need of any external aeration. Good performance of this system can be attributed to the large amount of active biomass retained in the sponge materials, which amounted to 19 g VSS/L of sponge volume [11]. The value is 5–10 times higher than that of activated sludge system [12] or trickling filter [13] treating domestic wastewater. Consequently, DHS is capable of removing large amount of organic material in short period of time varying from 1.3 to 2.7 h [14–17].

The main objective of this study is to assess the performance of the combined system (AHR-DHS), treating domestic wastewater under local environmental conditions.

2. Methodology

A schematic diagram of the combined system used in this study is presented in Fig. 1. It consists of an anaerobic hybrid reactor (AHR) followed by a downflow hanging sponge (DHS) reactor. The AHR was fed continuously with raw municipal wastewater from a near-by sewer network. The effluent of the AHR was fed by gravity to DHS via distributor (19 rpm) located at the top of the DHS.

2.1. Anaerobic hybrid reactor (AHR)

The AHR reactor was seeded with sludge collected from the aeration tank of the wastewater treatment plant situated in Zeneen, Cairo, Egypt. The sludge had a concentration of 7.3 g/l for total solids at 105°C, 6.1 g/l for volatile solids at 550°C and 135 ml/g MLSS for SVI. The total amount of sludge added to the reactor was approximately 81 L which represents 41% of the total reactor volume. AHR had a working volume of 0.2 m^3, and a height of 4 m. The AHR consists of two parts; the 1st part represents the sludge bed of the reactor with an internal diameter of 0.2 m. The 2nd one represents the upper part of the reactor with internal diameter of 0.3 m. This part was packed with polyurethane foam (PF) in form of vertical curtain sheets to avoid clogging of the reactor and prevent washout of the biomass. The ratio of packing media to reactor volume was 14%. The characteristics of PF are summarized in Table 1.

2.2. Downflow hanging sponge (DHS) reactor

The total capacity of the DHS was 133 L; internal diameter of 0.22 m and height of 3.5 m. It consisted of four identical segments connected vertically. Each segment was equipped with 6 L of PF warped with perforated polypropylene plastic material, randomly distributed in the whole reactor. The packing media represented 18%

Table 1
Characteristics of the used polyurethane foam (CF-type) for AHR and DHS reactor

Parameters	Value
Specific surface area, m^2/m^3	256
Density, kg/m^3	30
Void ratio	0.9
Pore size, mm	0.63

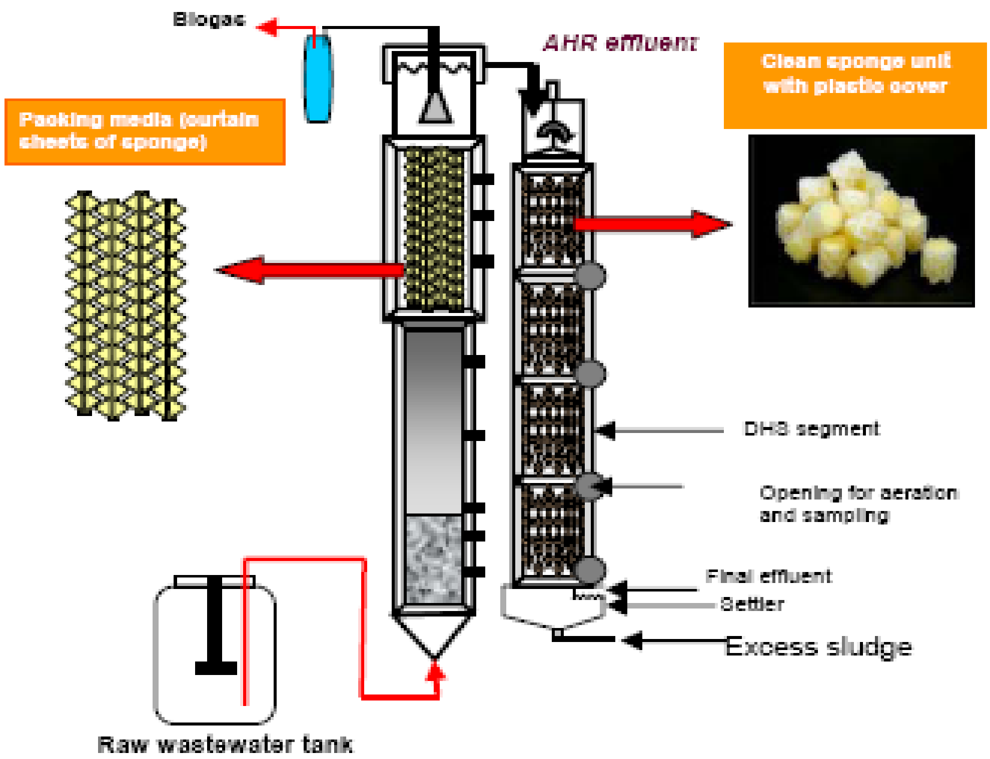

Fig. 1. Schematic diagram of integrated system consisted of AHR–DHS.

of the total liquid reactor volume. The characteristics of the PF are shown in Table 1.The dimension of the used PF (cylindrical shape) was 35 mm height × 22 mm diameter. The oxygen is naturally diffused through four windows located at different levels of 0.7, 1.4, 2.1 and 3.3 m along the DHS system.

To determine the nitrification rate and organic matter removal along the DHS reactor, wastewater samples were collected from the outlet of each segment and subjected to immediate analysis for COD_{total}, $COD_{soluble}$, ammonia, nitrite and nitrate. Moreover, biomass retained in the sponge was monthly harvested from DHS segments. The sludge was squeezed by distilled water and the weight of total solids and volatile solids were determined. The weight of biomass was related to sponge volume (g/L of sponge).

Table 2
Operating conditions of the whole treatment system (AHR-DHS)

Parameters	AHR (pre-treatment system)	DHS (post-treatment system)
HRT, h	6	2
Up-flow velocity (V_{up}), m/h	0.67	—
Down-flow velocity(V_{down}), m/h	—	1.75
Flow rate (Q), m^3/d	0.792	0.288
Organic loading rate (OLR), kg COD/m^3.d	1.9	2.1

2.3. Operating conditions

The combined AHR–DHS, system was continuously operated for 12 months. The total system was located outdoor and operated at ambient temperature ranging from 14°C in winter and 40°C in summer. The operational conditions are given in Table 2.

2.4. Analytical methods

The performance of the whole system was monitored by analyzing samples of raw wastewater and effluents of each treatment step. Dissolved oxygen, pH and temperature were measured regularly in situ. The physicochemical analysis covered: total chemical oxygen demand (COD_{total}), total biochemical oxygen demand (BOD_{5total}), ammonia-nitrogen (NH_4-N), nitrite-nitrogen (NO_2-N), nitrate-nitrogen (NO_3-N), total Kjeldahl nitrogen (TKN), and total phosphorous (TP). Raw samples were used for determination of COD_{total} and 0.45 μm membrane filtered samples for $COD_{soluble}$. The $COD_{particulate}$ was calculated by the difference between COD_{total} and $COD_{soluble}$. Faecal coliform (FC) was analyzed as indicator organisms. All analytical procedures were carried out according to APHA [18].

2.5. The specific methanogenic activity (SMA)

SMA was performed in duplicate in serum bottles (working volume, 250 mL) according to the reported methods [19–22]. The methanogenic activity of the biomass, harvested from sludge blanket and from curtain sponge sheets was measured using acetate solution (2000 mg COD/L) as a substrate. The inorganic nutrients and trace mineral solutions were added (based on 2000 mg COD/L) for the growth of anaerobic micro-organisms. The culture media for the SMA test were initially neutralized by using (1:1) HCl and (10 N) NaOH solutions. Based on the cumulative methane production rate curve over time, the SMA of the biomass, expressed as g CH4-COD/g VSS.d was determined [23]; SMA was calculated from the following equation:

$$\text{SMA} = (1/X)(24k)\left(Y_{\text{CH}_4}\right) \tag{1}$$

where X is the total biomass (g VSS) in the serum bottle measured after the test, k is the slope of the linear zone of the cumulative methane production curve (mL/h), and Y_{CH4} is the methane yield per gram of COD removed at 35°C.

3. Results and discussion

3.1. The performance of the integrated system AHR–DHS

3.1.1. Carbonaceous matter removal

The $\text{COD}_{\text{total}}$, $\text{BOD}_{\text{5total}}$, $\text{COD}_{\text{soluble}}$ and $\text{COD}_{\text{particulate}}$ removal data found in the total process are presented in Table 2 and Figs. 2a, b, c and d, respectively. In general, the efficiency of the AHR reactor was quite satisfactory. $\text{BOD}_{\text{5total}}$ and $\text{COD}_{\text{total}}$ removal values were 62±13% and 62±10%, respectively. The DHS reactor was capable of promoting an additional removal of carbonaceous material. The combined system achieved $\text{BOD}_{\text{5total}}$ and $\text{COD}_{\text{total}}$ removal of 95±2% and 89±3%, producing an effluent with a good quality. Residual $\text{BOD}_{\text{5total}}$ and $\text{COD}_{\text{total}}$ values were 10 mg /L and 49 mg /L. The performance of the DHS was comparable to that of the curtain-type DHS reactor [15]. However, the system was operated at higher organic load (3.1 kg COD/m^3.d) compared to the load applied in this study (2.1 kg COD/m^3.d). The results presented in Table 2 furthermore show that the total system achieved an excellent removal of $\text{COD}_{\text{particulate}}$ i.e. only 17 mg/L of $\text{COD}_{\text{fraction}}$ remained in the final effluent.

3.1.2. Nutrients removal

The concentrations of TP in sewage, AHR effluent and the final effluent are given in Fig. 3a. Phosphorus uptake in the AHR was relatively low. The average recorded percentage removal was only 11%.This can be due to relatively low biomass production in anaerobic systems [24].

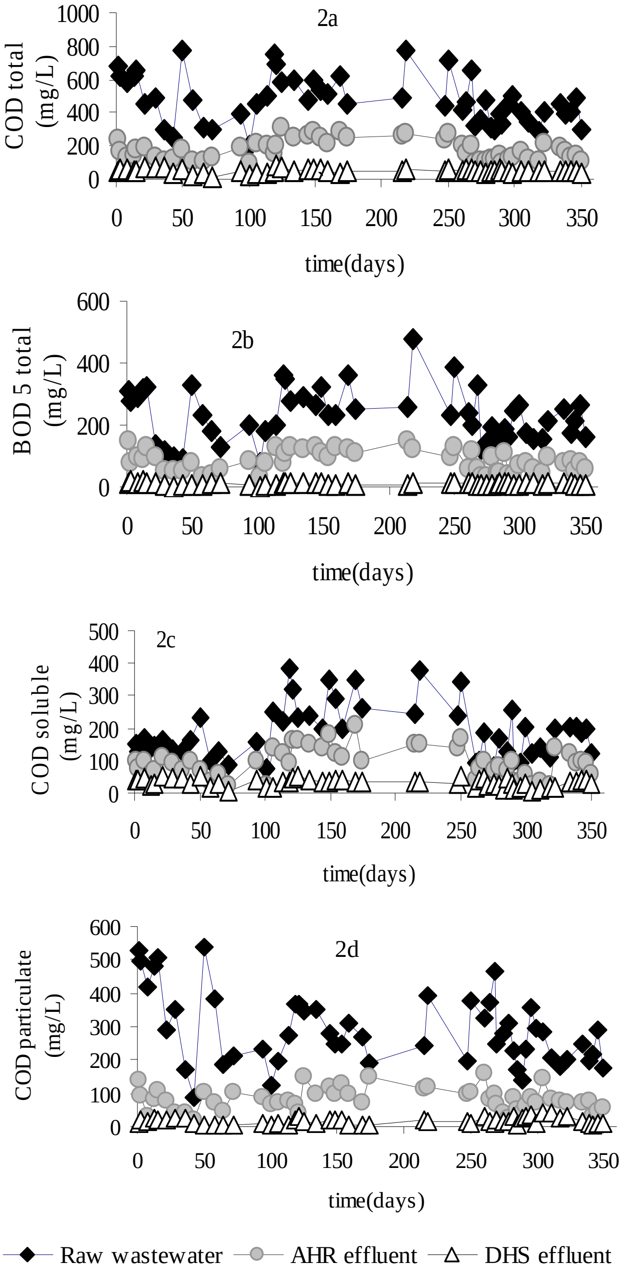

Fig. 2. Time course of: (a) $\text{COD}_{\text{total}}$; (b) $\text{BOD}_{\text{5total}}$; (c) $\text{COD}_{\text{soluble}}$ and (d) $\text{COD}_{\text{particulate}}$ in the whole treatment system.

Despite the increase of ammonia concentration in the AHR effluent, a nitrification rate of 0.30±0.05 kgNH$_4$-N/m^3.d was achieved in the DHS system when operated at OLR of 2.1 kg COD/m^3.d (Fig. 3d). From the data presented in Table 3 and Fig. 3c, it is also clear that the combined system is quite effective in eliminating 72% of the total Kjeldahl nitrogen (TKN) (Fig. 3c).

The results presented in Fig. 3b show that 83%of ammonia was eliminated in the whole system. The con-

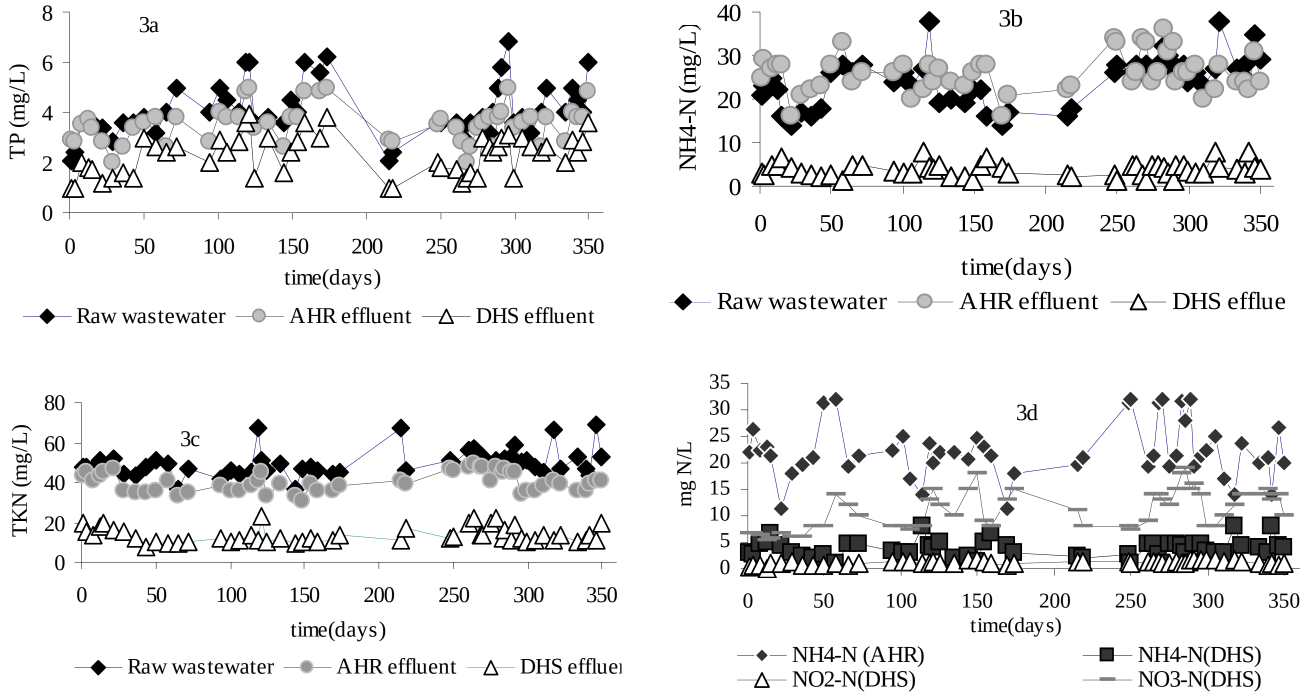

Fig. 3. Time course of: (a) TP; (b) NH_4-N; (c) TKN and (d) nitrification process in the whole system.

Table 3
Summary of the performance of the combined system operated at a total HRT of 8 h (AHR: 6h and DHS: 2h)

Parameters	Raw wastewater	AHR effluent	R%	DHS effluent	*R* %	Overall removal efficiency
pH	7.3	6.9	—	7.4	—	—
DO, mgO_2/L	—	—	—	7.2±0.32	—	—
BOD_{5total}, mgO_2/L	229±85	84±34	62±13	10±4	87±6	95±2
COD_{total}, mgO_2/L	476±142	175±60	62±10	49±12	69±11	89±3
$COD_{soluble}$, mgO_2/L	186±83	92±46	50±15	32±12	60±15	80±9
$COD_{particulate}$, mgO_2/L	290±108	83±34	69±14	17±10	75±18	93±5
TKN, mg-N/L	50±7	40±5	18±10	14±4	66±7	72±8
NH_4-N, mg-N/L	24±6	26±4	—	4±1.7	85±8	83±9
NO_2-N, mg-N/L	—	—	—	1.1±0.4	—	—
NO_3-N, mg-N/L	—	—	—	11±4	—	—
TP, mg-P/L	4±1	3.5±0.7	11±18	2.2±0.8	36±16	45±13
FC, MPN/100 ml	$9.4\times10^6\pm8\times10^6$	$1.7\times10^5\pm 9.2\times10^4$	—	$5\times10^2\pm1.5\times10^2$	—	—

centrations of ammonia and nitrate in the effluent of DHS system were 4 and 11 mg/L, respectively. The results show that the reduction in ammonia nitrogen (22 mg N/L) was greater than the amount of oxidized nitrogen production (12.1 mg N/L) as shown in Fig 3d. Since the utilization of nitrogen for cell buildup is negligible; denitrification is the dominant mode of total nitrogen removal in DHS [11]. The same phenomenon has been observed by other authors [15,25,26]. Araki et al. [27] suggested that the internal part of the sponge maintains anoxic environment where denitrification prevails, whereas up to the depth of approximately 0.75 cm from the surface of the sponge, aerobic environment prevails. Nitrifiers in this region convert ammonium nitrogen into oxide forms, which are then transferred to the anoxic zone where they are denitrified. In this way DHS allows both nitrification and denitrification to take place within a single system.

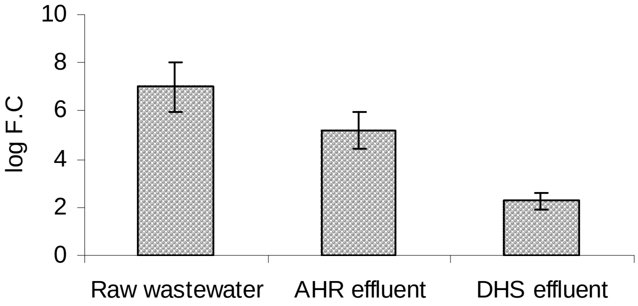

Fig. 4. $\log_{10}$ faecal coliform in raw wastewater, AHR effluent and the final effluent.

3.1.3. Faecal coliform

The results of faecal coliform examinations (Fig. 4) revealed a reduction of 1.8 $\log_{10}$ in the AHR. On the other hand the faecal coliform counts substantially dropped by 4.7 $\log_{10}$ with residual count ranging from 10^2 to 10^3 MPN/100 ml in the DHS effluent. This value was higher than the results obtained by Tandukar et al. [25,26]. One likely reason of higher performance of AHR–DHS system could be the higher amount of retained sludge and longer SRT in the whole system. The mechanism of faecal coliform removal in the downflow hanging sponge (DHS) system treating up-flow anaerobic sludge blanket (UASB) reactor effluent was investigated by Tawfik et al. [28]. The results obtained revealed that the most important removal mechanism of faecal coliform in the DHS system is adsorption, followed by predation. Die-off is a relatively minor removal mechanism in the DHS system.

3.2. Wastewater characteristics along the height of DHS system

The profile of DO concentration along the height of DHS shows a gradual increase as the wastewater flows downwards (Fig. 5a). DO in the final effluent was found to be 7.2 mg/L. By virtue of this unique phenomenon, there is no need of any external aeration in the DHS reactor. The cost of aeration and the associated assemblies required by conventional treatment systems for e.g. activated sludge system is reduced substantially.

Assessment of the wastewater quality along the height of the DHS system indicated that about 51% of COD_{total}

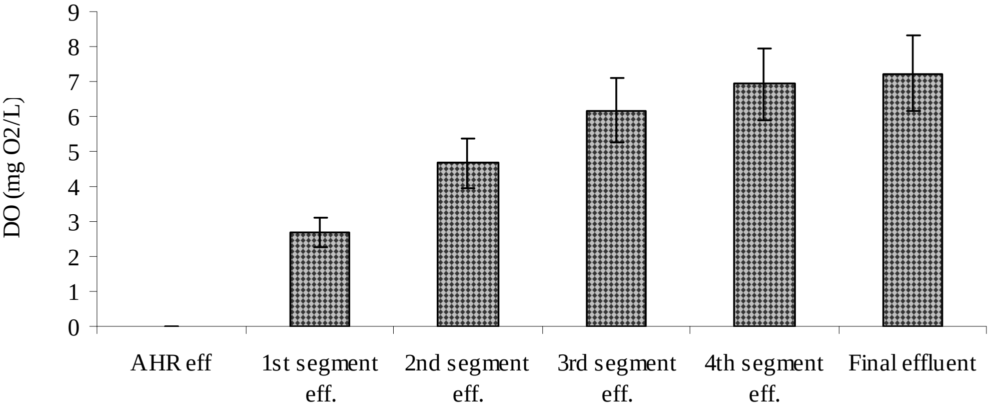

Fig. 5a. DO concentration along the height of DHS reactor.

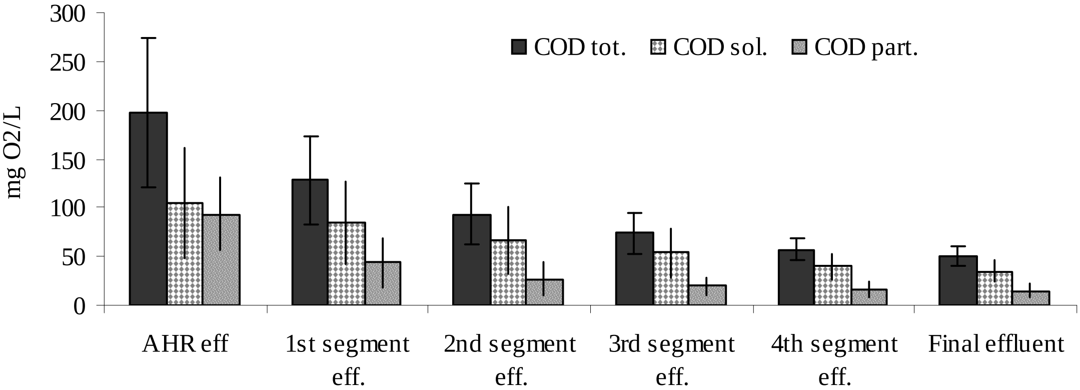

Fig. 5b. COD fractions along the height of DHS system.

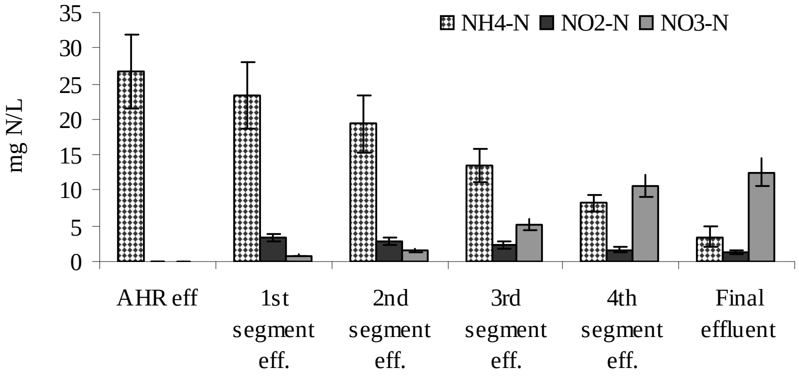

Fig. 5c. Nitrification efficiency along the height of DHS system.

and 70% $COD_{particulate}$ were removed in the upper half of the DHS reactor (Fig. 5b). This was due to physical entrapment of particulate matter followed by biological oxidation. As a result, the lower half of DHS receives lower organic load which is a suitable condition for nitrification. The available data showed that 58% of ammonia was nitrified in the lower part (Fig. 5c).

3.3. Sludge retention and excess sludge production in DHS

After reaching steady state conditions, sludge analysis revealed remarkable differences in sludge characteristics along the DHS reactor (Table 4 and Fig. 6). Average concentration value of sludge inside DHS sponge was around 20 g VSS/L of sponge volume (Fig. 6). Based on the available results, the calculated SRT for DHS was 121 days.

Excess sludge production from DHS system was only 0.08 kg TS/kg $COD_{removed}$. In other words, it was only 8% of the total COD removed. This value was higher than the results obtained by Tandukar et al. [26] (2.5% of the total COD removed) and lower than that obtained by Tawfik et al. [17] (9% of the total COD removed). Lower biomass production in DHS is due to a higher degree of mineralization of the sludge, which is attributed to longer SRT [29]. On the other hand, the nature of sludge produced by attached growth system, e.g. DHS, consists of sloughed particles, which is usually denser and in many cases reduces settling problems and precludes bulking and foaming problems found in ASP [30].

High amount of active biomass retained in the sponge of DHS and corresponding longer SRT ensures a high degree of treatment at minimum operational control. These properties are important to hedge against any hydraulic or organic overload to the system during the real operation as well as to reduce sludge production [26].

Table 4
Characteristics of retained sludge in the DHS

Parameter	Retained sludge			
	1st segment	2nd segment	3rd segment	4th segment
TSS, g/l	27±2.6	25±2.2	22±1.9	19±1.8
VSS, g/l	24±2.2	21±1.8	18±2.2	15±1.9
VSS/TSS	0.87±0.01	0.82±0.01	0.82±0.05	0.77±0.03

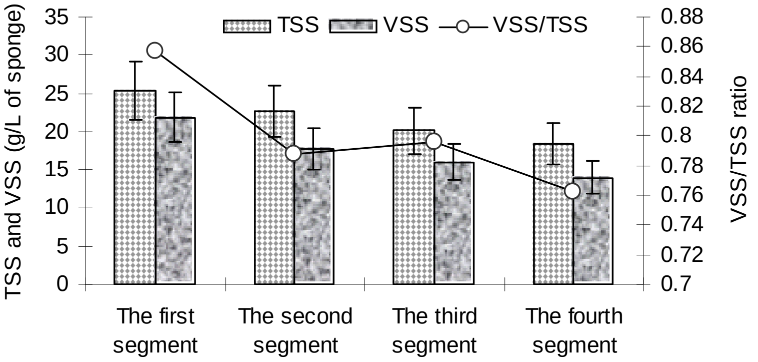

Fig. 6. TSS, VSS and VSS/TSS ratio of retained sludge in DHS system.

3.4. Specific methanogenic activity (SMA) in the AHR

The SMA test is used to establish the degree of biodegradability of various substrates and evaluate the maximum potential utilization rate of intermediate metabolites [31]. The available data show that specific methanogenic activity of sludge taken from PF of AHR was higher (0.149 g CH_4-COD/g VSS d) than that of sludge taken from lower part of AHR (0.124 g CH_4-COD/g VSS d).

Büyükkamaci and Filibeli [32] investigated volatile fatty acid (VFA) formation during anaerobic degradation in an anaerobic hybrid reactor, the results showed that methanogenic bacteria were more active in the upper part of the reactor and VFAs decreased throughout the reactor from bottom to top. Lower VFA formation in the fixed bed region of the reactor can be explained by the advantages of immobilized microorganism culture. Immobilization provides high cell concentrations, eliminates cell washout problems at low hydraulic residence times, provides favorable micro-environmental conditions (that is, cell-cell contact, nutrient-product gradients, pH gradients) for cells, resulting in better performance of the biocatalysts [33].

4. Conclusions and recommendation

- From the available data, the integrated system consisting of AHR–DHS show good performance for removal of COD_{total} (89%), $COD_{particulate}$ (93%), BOD_{5total} (95%), ammonia (83%) and faecal coliform (99.994%) removal. The results for nitrogen balance revealed that around 34% of the total influent nitrogen to DHS system remained unaccounted for.
- Anaerobic hybrid reactor (AHR) does not show any operational problems such as, sludge washout. Therefore it is recommended to apply such a system as an enhanced primary treatment step. Moreover, the use of polyurethane foam (sponge) as a curtain sheets overcome the clogging problems in the reactor.
- The major part of the organic matter is removed in the first and second segment of DHS system and that little additional removal occurs in the subsequent segment. In the third and fourth segment of DHS system a high nitrification rate was achieved.
- Significant differences in TSS and VSS were found between the sludge accumulated in the various segments of the reactor. In the segments from 1 to 4 of the reactor, the biomass which developed had volatile solids of 24, 21, 18, 15 and g/L of sponge, respectively.
- The DHS system holds an advantage that it does not need any external forced aeration, which is an advantage as the capital, operational and maintenance costs associated with the aeration devices are cut to zero. It has also been proved that the production of excess sludge is low, which is equally noteworthy.
- The proposed system can thus be recommended as a techno-economically feasible novel sewage treatment system, especially for small communities such as rural areas. However, further studies are recommended using higher organic loading rates.

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