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Assessment of the performance of a down-flow hanging sponge system for treatment of agricultural drainage water

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ABSTRACT

The performance of down-flow hanging sponge (DHS) system for the treatment of agricultural drainage water has been investigated for six months. The reactor was operated at a hydraulic retention time (HRT) of 2.0 h, sludge residence time of 88.5 d, and food to micro-organism ratio of 0.24 kg COD/kg MLVSS/d. The results obtained showed that the average total chemical oxygen demand (COD_{tot}) and biochemical oxygen demand (BOD_5) concentrations measured in the final effluent of the system were 62.4 and 17.1 mg/l, respectively, corresponding to the overall removal efficiency of 73.1% for COD_{tot} and 86.7% for BOD_5. The reactor provided a final effluent containing a low concentration of 14.7 mg/l for total suspended solids (TSS). Moreover, 84% of ammonia–nitrogen was eliminated at organic loading rate (OLR) of 3.0 kg COD/m^3 d. The calculated nitrification rate of the DHS system according to the nitrate and nitrite production amounted to 0.16 kg NH_4–N/m^3 d. Based on these results, the reactor achieved an effluent quality complying for reuse in agricultural purposes. The effect of shock load on the performance of DHS system was investigated. The results revealed that reducing the HRT from 2.0 to 0.5 h and increasing the OLR from 3.80 to 15.33 kg COD/m^3 d would increase the COD and ammonia–nitrogen levels in the effluent from 28 to 81 mg/l and from 1.68 to 3.08 mg/l, respectively. However, the COD and ammonia–nitrogen removal efficiency returned to their original values within 3.0 and 1.0 h, respectively.

Keywords: Agricultural drainage water; Down-flow hanging sponge; Nitrification; Shock load

1. Introduction

Egypt is consistently reported as one of the most water-stressed countries. The limited amounts of rainfall make the country dependant mainly on water from the River Nile. Egypt's Nile water quota is 55.5 billion m^3/y, which constitutes about 90% of the total water resources. The amount of deep groundwater aquifer is considerable huge, but the cost of pumping and conveyance is limiting factors. Coastal-scattered winter rainfall contributes less than 1.5 billion m^3/y

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on average [1]. The allocation of total water resources among agriculture, industry, and domestic uses is within the ratio of 85, 9 and 6% respectively [2].

Since the agriculture sector in Egypt is the huge consumer of water, similar to the most developing countries, reutilization of agricultural drainage water (ADW) has become mandatory to cope with the issue of limited water resources. During the last few decades, the Egyptian Ministry of Water Resources and Irrigation has adopted different strategies aimed at increasing the use of ADW especially for new land reclamation projects. The amount of annually reused drainage water at present is 7.07 billion cubic meters (BCM/y), which are directly recycled via controlled mixing with Nile water. The main intentions of the future strategies for drainage water reuse in Egypt are to increase the amount of drainage water reuse to around 9.0 BCM/y by year 2017 [3]. However, spreading pollution in the drainage system threatens the application of this strategy. The agricultural drains receive effluents from sewage and some industries. Moreover, the excessive use of fertilizers and pesticides is another major source of water pollution [4]. The amount of the wastewater discharged into receiving drains far exceeds the natural ability of these water bodies to attenuate the pollutions. This violates the water quality standards and makes drains water unsuitable for reuse [5]. This compelling situation gives the process of upgrading the ADW via treatment a great importance [6].

Various aerobic treatment processes have been proposed for treatment of ADW, such as activated sludge process (ASP) [7], trickling filter (TF) [8], aerobic and anaerobic lagoons [6], and wetland systems [9]. However, there is a need to develop an appropriate treatment system, which is techno-economically affordable. In this study, the innovative treatment system namely, down-flow hanging sponge (DHS) system is proposed. The DHS system composed of polyurethane material (CF sponge) as the packing material of which micro-organisms attach and as the porous media for solids retention. Wastewater is trickled from the top of the reactor, and is purified by the micro-organisms within and on the surface of the sponge medium as it flows down through the reactor [10]. Because the sponge medium of the DHS reactor hangs freely in the air where it is exposed to the atmosphere, oxygen is naturally dissolved into the wastewater flowing through the reactor, obviating the need for external aeration or other energy inputs [11–14]. Furthermore, since the DHS reactor supports large amounts of biomass as well as a wide range of microbial diversity both within and on the surface of the sponge medium, ecosystems with extremely long food chains can become established, which reduces excess sludge production [15,16]. Also, the DHS combines long sludge residence time (SRT) (100 d) and short hydraulic retention time (HRT) (2.0 h) [17] and provides small footprints for the bioreactor.

The main advantages of using DHS systems comprise: (1) a rapid and dense colonization; (2) a high specific surface area of the packing material which can reach up to 2,400 m^2/m^3 and high porosity of 97%; (3) a sufficiently long biomass retention time allowing the application of a higher loading rate; (4) a high process stability and no oxygen requirement; and (5) a low production of waste sludge [12]. The first and second generations of DHS system (cube and curtain type) were investigated by [11,17]. Tawfik et al. and Tandukar et al. [12,18] investigated the third and fourth generations, random and array type for post-treatment of anaerobically pretreated sewage effluent. All DHS generations achieved a high performance for COD removal (85%) and nitrification efficiency (83%).

The main objective of this study is to assess the performance of DHS system for treatment of ADW at HRT of 2.0 h and organic loading rate (OLR) of 3.0 kg COD/m^3 d for reutilization the treated effluent for agricultural production processes. Emphasis is made on the removal efficiency of the COD, biochemical oxygen demand (BOD_5), total suspended solids (TSS), NH_4–N, and total Kjeldahl nitrogen (TKj–N). Furthermore, the characteristics of the formation biomass along the DHS system height were investigated. Also, the effect of shock load on the performance of DHS system was evaluated taking into consideration the temporal fluctuations of the ADW quality.

2. Materials and methods

2.1. Characteristics of the ADW

ADW was collected from Edku agricultural drain, which situated in the western delta of the Nile River, Egypt. The drainage canal is highly contaminated with domestic wastewater. ADW is classified as a medium strength wastewater and had the following characteristics (Table 1). The salinity of the investigated ADW represented by total dissolved solids (TDS) was about (1,211 ± 765 mg/l).

2.2. Experimental set-up of the pilot plant

A pilot-scale DHS system with a capacity of 33 l was designed and fabricated from polyvinyl chloride (Fig. 1). The DHS system had an internal diameter and height of 0.15 and 1.8 m, respectively. This DHS

Table 1
Main characteristics of the ADW used in the experiments

COD (mg/l)	
Total	249.4 ± 100.2
Soluble	133.2 ± 53.9
Particulate	116.2 ± 90.4
BOD_5 (mg/l)	162.1 ± 31.1
Nitrogen (mg/l)	
NH_4–N	15.7 ± 6
TKj–N	28.4 ± 6.6
TSS (mg/l)	157.7 ± 63
TDS (mg/l)	1,211 ± 765
pH	7.48 ± 0.3
DO (mg/l)	0.05 ± 0.05

module column consists of three identical segments connected vertically, each segment equipped with 1.77 l of sponge randomly distributed. The total volume of the sponge amounted to 5.3 l. The dimensions of the used sponge (cylindrical shape) amounted to 50 mm height × 20 mm diameter. The sponge was wrapped with perforated plastic material to avoid clogging and facilitate the air diffusion through the sponge. The reactor was filled with 16% porous polyurethane sponge (CF type) with the following criteria: surface area = 256 m^2/m^3, density = 30 kg/m^3, void ratio = 0.9, and pore size = 0.63 mm. A circular plates provided with holes were used to support filling material and to separate the reactor segments. The ADW lifted to the distributor which located on the top of the DHS system. The oxygen was naturally diffused through windows located at different levels of the DHS system.

2.3. Operational conditions

The DHS system was fed with ADW and continuously operated for 180 d at a temperature of 25 ± 4 ℃. The operational conditions for DHS are presented in Table 2. During the experiment, the effect of shock loads on the performance of DHS system we examined. The flow rate increased from 0.063 to 0.254 m^3/d. This corresponds to the reducing the HRT from 2.0 to 0.5 h, and increasing the OLR from 3.80 to 15.33 kg COD/m^3 d for 3.0 h

2.4. Sampling and analytical methods

Routine monitoring analysis of dissolved oxygen (DO), total chemical oxygen demand (COD_{tot}), BOD_5, TSS, ammonia–nitrogen (NH_4–N), nitrite–nitrogen (NO_2–N), nitrate–nitrogen (NO_3–N), TKj–N in the ADW, and the effluent of the DHS system was carried out according to "Standard Method for Examination of Water and Wastewater" APHA [19]. A raw sample was used for total COD (COD_{tot}) and 0.45 μm membrane filtered sample for soluble COD (COD_{sol}). The COD particulate (COD_{part}) was calculated by the difference between COD_{tot} and COD_{sol}.

The biomass retained in the sponge was harvested at various DHS segments. The sponge media with sludge were carefully removed from the reactor. The sludge was squeezed and washed with distilled water. Then, total solids (TS) and volatile solids (VS) were measured in paired samples. TS and VS were calculated according to sponge volume. TS and VS were determined as prescribed in "Standard Method for Examination of Water and Wastewater" APHA [19].

2.5. Calculations

The SRT of the DHS system was calculated according to the following equation. It is assumed that the effluent VSS had the same SRT as the excess sludge.

$$\mathrm{SRT} = \frac{VX}{(Q_w X_w + Q_e X_e)} \tag{1}$$

where V is sponge volume of DHS system (l); X is the average sludge concentration in DHS system (mg VSS/l); Q_w is theexcess sludge from the reactor (l/d); X_w is the concentration of the excess sludge discharged from the reactor (mg VSS/l). Q_e is the effluent discharged from the reactor (l/d); and X_e is the concentration of the effluent discharged from the reactor (mg VSS/l).

The following equation was used for calculating the food to micro-organism (F/M) imposed to the reactor.

$$\mathrm{F/M} = \frac{Q\ \mathrm{COD_{in}}}{VX} \tag{2}$$

where Q is influent discharge to the reactor (l/d); and COD_{in} is concentration of the influent discharged to the reactor (mg COD/l).

3. Results and discussion

3.1. Performance of DHS system

3.1.1. DO, organic matter and TSS removal

Table 3 shows mean influent and effluent concentrations of DO during the whole experimental period. The results showed that the DO concentrations were

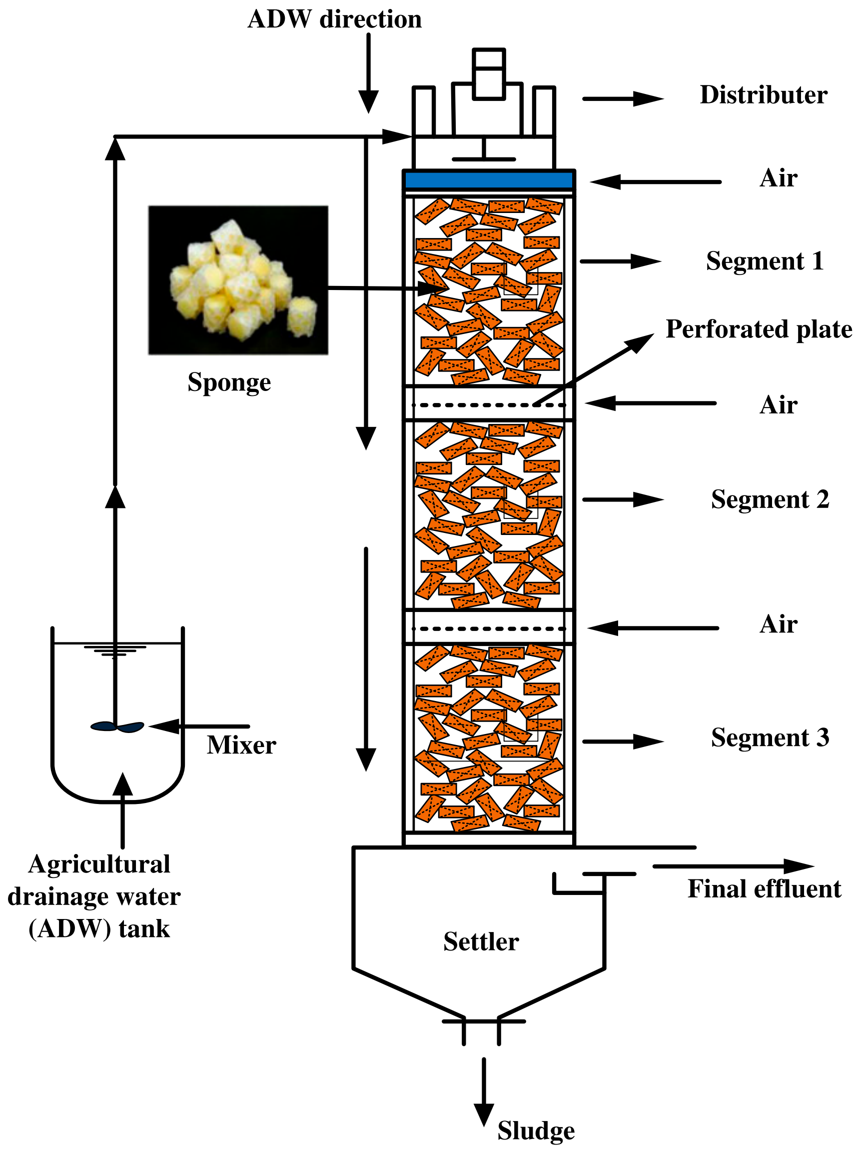

Fig. 1. Schematic diagram for the experimental setup of the DHS system fed with ADW.

Table 2
Operational conditions of DHS system fed with ADW

HRT* (h)	2
HLR ($m^3/m^2/d$)	3.57
Flow rate (l/d)	63.13
SRT (d)	88.5
OLR (kg COD/m^3 d)	3.0
Nitrogen loading rate (kg N/m^3 d)	0.34
F/M (kg COD/kg MLVSS/d)	0.24

Notes: HRT*: hydraulic retention time; HLR: hydraulic loading rate; SRT: sludge residence time; OLR: organic loading rate; and F/M: food to micro-organisms.

hardly detected in the influent (0.05 mg/l), while it significantly increased up to 4.6 mg/l in the treated effluent. This increase in the DO concentration can be explained by the freely hanging of the sponge medium in the DHS system, which allows the atmospheric oxygen to naturally dissolve into the ADW flowing through the reactor. Consequently, the DHS system does not require any external aeration and thus the cost associated with energy and devices required for aeration and their maintenance are cut to zero.

The COD_{tot}, COD_{sol}, COD_{part}, and BOD_5 removal data found in the DHS system are depicted in Table 2 and Fig. 2(a)–(c). The results clearly revealed that the reactor achieved a substantial reduction of COD_{tot}, COD_{sol}, COD_{part}, and BOD_5 resulting in an average effluent concentrations of only 62.4, 37, 25.4, and 17.1 mg/l, respectively. This is corresponding to

Table 3
Performance of DHS system treating ADW at an HRT of 2 h and SRT of 88.5 d

Parameter	ADW (mg/l)	DHS eff. (mg/l)	Removal efficiency (%)	Egyptian standard (law 48/1982)
DO	0.05 ± 0.05	4.6 ± 0.4	–	4.0
COD_{tot}	249.4 ± 100.2	62.4 ± 24.4	73.1 ± 10	80
COD_{sol}	133.2 ± 53.9	37 ± 15.3	69.3 ± 15.4	–
COD_{part}	116.2 ± 90.4	25.4 ± 16.8	68.5 ± 24.6	–
BOD_5	162.1 ± 31.1	17.1 ± 6.7	86.7 ± 2.9	40
TSS	159.7 ± 63	14.7 ± 7	90.6 ± 3.3	50

average removal efficiencies of 73.1, 69.3, 68.5, and 86.7%, respectively. This high performance can be attributed to the long SRT of 88.5 d imposed to the DHS system. The results presented in Table 3 and Fig. 2(d) furthermore show that the reactor achieved an almost complete removal of TSS (90.6%). Only 14.7 mg TSS/l remained in the final effluent. This high TSS removal efficiency can be attributed to bio filtration through the packing media that serve two purposes: (1) physical retention of suspended particles by filtration through packing media; and (2) biological conversion of course volatile suspended solids by the attached micro-organisms.

In spite of a high fluctuations of influent COD and TSS, the DHS reactor effluent was noticeable unchangeable as shown in Fig. 2(a) and (d). This indicates that the ability of DHS system to overcome the shock loads and the difference in the influent characteristics. Moreover, the DHS system achieved a higher removal efficiency of COD (73.1%) and TSS (90.6%) as compared to other systems i.e. ASP (67 and 71%) [7], TF (65 and 80%) [8], aerobic lagoons (62 and 68%) [6], and wetland systems (50 and 87%) [9]. The latter system was utilized to improve the water quality in Bahr El Baqar drain, which located at the northeastern edge of the Nile Delta, and was operated at a low HLR of 0.024–0.357 m^3/m^2 d.

3.1.2. *Nitrification efficiency and nitrogen removal*

The results presented in Table 4 and Fig. 3 show a nitrification rate of 0.16 ± 0.06 kg NH_4–N/m^3 d was achieved in the DHS system, when operated at an OLR of 3.0 kg COD/m^3 d, eighty-four percent of ammonia was removed. The concentrations of ammonia–nitrogen in the effluent of DHS system amounted to 2.6 mg/l. Production of NO_x–N (NO_2–N + NO_3–N) concentration in the DHS reactor effluent was 11 mg/l. Interestingly, the NO_x–N concentration of the final effluent of DHS system was relatively high, with almost 70% of ammonia–nitrogen being converted to NO_x–N.

The available data for nitrogen balance revealed that around 13.4% of the influent NH_4–N to DHS system remained unaccounted. According to [20], ammonia–nitrogen can be adsorbed in the biomass. It is known that the biomass consists mainly of bacterial cells and extracellular polymeric substances which all have a negative charge. Consequently, various actions of mono-, di-, and tri-valent can be bound, including ammonia. Another explanation for the gap in the ammonia balances could be due to denitrification in the anoxic part of the biomass of the DHS system [14,18]. Araki et al. [21] found that the internal part of the sponge in the DHS system maintains an anoxic environment, whereas up to the depth of approximately 0.75 cm from the surface of the sponge, an aerobic environment prevails. From the data presented in Table 3 and Fig. 4, it is also clear that the system is quite effective in eliminating the course of TKj–N. The system provided 8.6 mg/l for TKj–N in the final effluent, corresponding to 68.9% removal efficiency.

3.2. *Retained biomass along DHS system height and excess sludge*

The characteristics of the formation biomass along the DHS system height were measured and illustrated in Fig. 5. The results obtained showed that there was a little difference in TS and VS in the sludge accumulated in first and second segments of the reactor. However, there was a significant decrease in TS and VS concentration in the third segment, i.e. TS increased from 25.1 g/l (segment 1) to 27.4 g/l (segment 2), then significantly decreased to 5.64 g/l in segment 3. The biomass in terms of VS content (%) in the segment 1, 2, and 3 was 62, 64, and 76%, respectively. These results are comparable to those obtained by Machdar et al. [11] who found that the fraction of VS of the biomass was 66%. The DHS had an average sludge concentration of 12.44 g VS/l. Based on the amount of retained sludge and the sludge eluted in the effluent and the excess sludge, SRT for DHS was calculated to be 88.5 d. If compared to activated

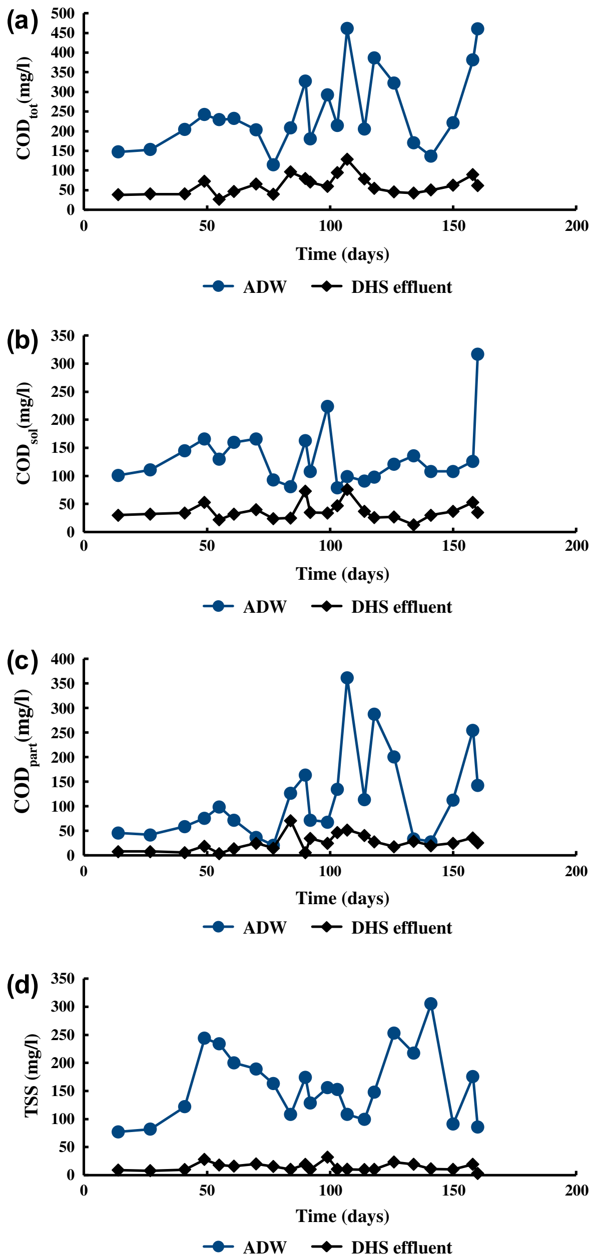

Fig. 2(a)–(d). Variation of COD_{tot}, COD_{sol}, COD_{part}, and TSS in the influent and the effluent of DHS system treating ADW.

Table 4
The average nitrogen balance in the DHS system treating ADW

Parameter	ADW (mg/l)	DHS eff. (mg/l)	Removal efficiency (%)
NH_4–N	28.25 ± 10.3	3.9 ± 1.9	85.2 ± 17.4
NO_2–N	–	1.2 ± 0.9	–
NO_3–N	–	15.9 ± 8.4	–
TKj–N	52.7 ± 8.7	16.8 ± 2.8	67.8 ± 8.7

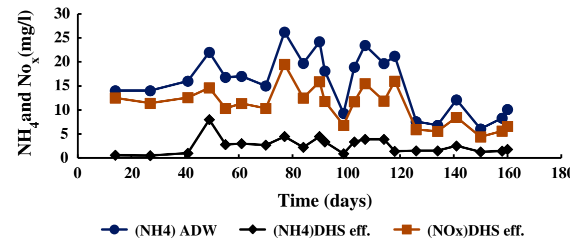

Fig. 3. Nitrification efficiency of the DHS system treating ADW at OLR of 3.0 kg COD/m^3 d.

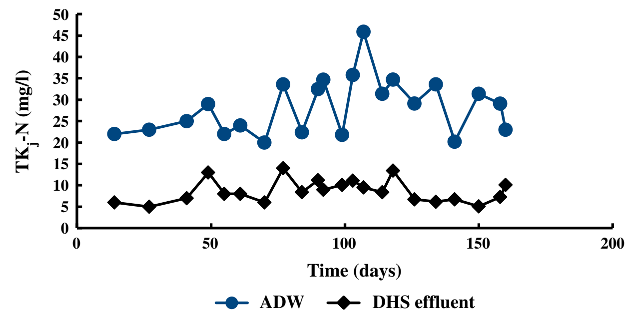

Fig. 4. Time course of TKj–N in the influent and the effluent of DHS system treating ADW at OLR of 3.0 kg COD/m^3 d.

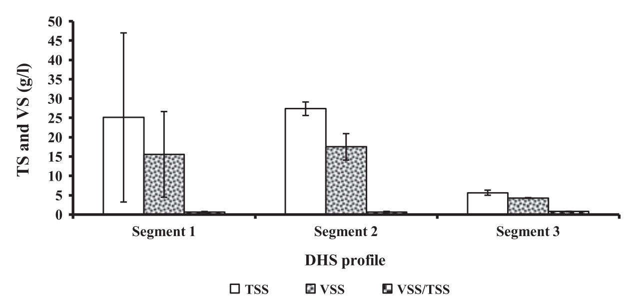

Fig. 5. Biomass characteristics along DHS system height.

sludge plant (ASP), the concentration of retained sludge in DHS was nine times higher and SRT 18–30 times longer. Concentration of retained sludge in the aeration tank of ASP was 1.4 g/l with the SRT of 3–5 d. 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.

Excess sludge production in biological treatment process is inevitable and any suggestion that a biological process can take place without producing excess sludge appears to violate basic principles and would be considered heresy in the Engineering world [18]. However, the amount and quality of sludge production can be varied with the selection of treatment system and operating conditions. The observation suggested that the excess sludge production from DHS system was negligible. No biomass production in DHS is due to the very large value of retained sludge in the sponge of DHS, which increasing the sludge degradation over the sludge accumulation.

3.3. Effect of hydraulic shock load on the performance of the DHS system

The DHS system was used to examine the effect of hydraulic and organic shock loads on the reactor performance in terms of COD and nitrification efficiency. The DHS was continuously operated at HRT of 2.0 h and the imposed hydraulic shocks corresponding to a HRT of 0.5 h. From the results presented in Fig. 6(a) and (b) it appears that, in general, lowering the HRT from 2.0 to 0.5 h results in: (1) the COD levels in the effluent increased from 28 to 81 mg/l, corresponding to a decrease in the removal efficiency from 91.2 to 74.4%; (2) the ammonia–nitrogen concentration in the effluent significantly increased from 1.68 to 3.08 mg/l; and (3) the removal efficiency dropped from 88.2 to 78.4%. After returning to the reference HRT of 2 h, the COD percentage removal returned to their original values within 3.0 h reaching to 90.2%, resulting in a residual concentration of 31 mg COD/l in the treated effluent. The ammonia–nitrogen concentration in the effluent returned to their original values of 1.5 mg NH_4–N/l within 1.0 h. The high amount of active biomass retained in the sponge of DHS and corresponding longer SRT is the explanation of the fast system return to its original performance. 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 [15]. Moreover, the recovery of ammonia–nitrogen in only 1 h reflects the quick response of autorotrophs to the change in the HRT and HLR. It is obvious that segmented of DHS system decreases the detrimental effect of shock load on the performance of the system.

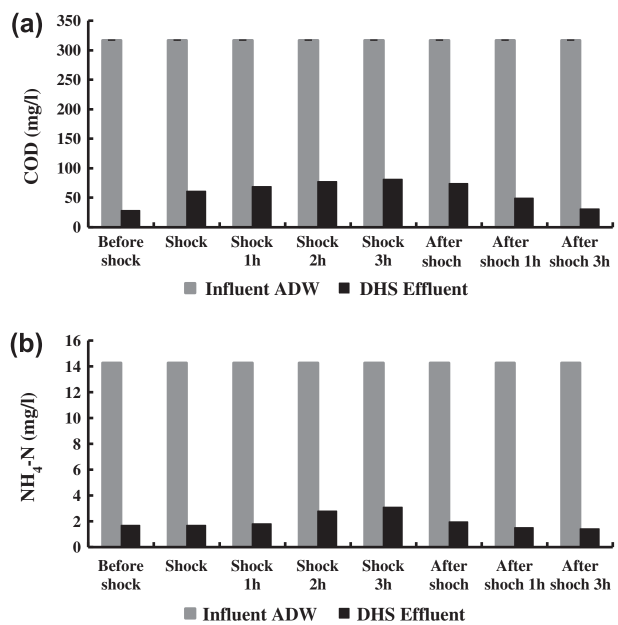

Fig. 6(a) and (b). Effect of the hydraulic shock load on the COD and ammonia–nitrogen removal in the DHS system treating ADW.

The results revealed that COD removal and nitrification efficiency were significantly deteriorated during the hydraulic shock load condition. Although the biofilm growth is directly related to the loading rate, this deterioration could be attributed to the lower contact time between the micro-organisms and the substrate at short HRT and high HLR conditions imposed to DHS system.

4. Conclusions

(1) Based on the results obtained here, a DHS system looks the best solution as a low cost and low energy requirement for treatment of ADW. It comprise the most efficient process COD_{tot} (73.1%), BOD_5 (86.7%), TSS (90.6%), ammonia (84%), and TKj–N (67.8%).
(2) The results for nitrogen balance revealed that around 13.4% of the total influent nitrogen to DHS system remained unaccounted.
(3) High amount of active biomass retained in the sponge of DHS and corresponding longer SRT ensures a high degree of treatment as well as reduces sludge production.
(4) The COD removal and nitrification efficiency were deteriorated during the hydraulic shock load condition; this deterioration was attributed to the lower contact time between the micro-organisms and the substrate at low imposed HRT in the DHS system.

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