



A pilot-scale study on a down-flow hanging sponge reactor for septic tank sludge treatment

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ABSTRACT

A pilot scale study was conducted on a down-flow hanging sponge (DHS) reactor installed at a sewage treatment plant in Banda Aceh, Indonesia for treatment of desludging septic tank wastewater. Raw wastewater with an average biochemical oxygen demand (BOD) and total suspended solids of 139 mg/L and 191 mg/L, respectively, was pumped into the reactor. Two different hydraulic retention times (HRTs, 3 h and 4 h) were investigated, equivalent to organic loadings of 1.11 and 0.78 kg BOD/m³/d, respectively. The average BOD concentration in the final effluent was 46 and 26 mg/L at HRTs of 3 and 4 h, respectively. The concentration of retained sludge along the reactor height was 10.2-18.7 g VSS/L-sponge, and the sludge activities were 0.24-0.32 and 0.04-0.40 mg/g VSS/h for heterotrophs and nitrification, respectively. Values of water hold-up volume, dispersion coefficient, and number of tank in-series found from tracer studies of clean sponge and biomass-loaded sponge confirmed that growth of retained sludge on the sponge module improved hydraulic performance of the reactor. Adoption of the DHS reactor by this Indonesian sewage treatment plant would enhance the role of the current desludging septic tank wastewater treatment system.

Keywords: Domestic wastewater, Down-flow hanging sponge, Septage, Septic tank, Tracer study

1. Introduction

Indonesia is the fourth most populated country in the world, with a population of around 260 million people in 2016 [1]. Moreover, the United Nations (UN) stated that the population of Indonesia is expected to exceed 270 million by 2025, with two-thirds of the population projected to live in urban areas. Such rapidly increasing urbanization must be addressed through improved sanitation standards within urban areas. Indeed, even though Indonesia has been classified as making “good progress” in this area, it did not meet the target of the Millennium Development Goals (MDGs) to halve the proportion of people without access to wastewater facilities by 2015 compared to 1990 [2].

In Indonesia, septic tanks represent the minimal requirement for treatment of domestic wastewater. Standard septic tanks consist of two chambers that provide primary settlement and anaerobic digestion, followed by a percolation area [3]. By 2015, approx-

imately 85% - 90% of urban cities in Indonesia used septic tanks [4]. However, the majority of inhabitants do not utilize a percolation area (also known as a leach field or infiltration area) for various reasons including inadequate land (one of the main reasons), low permeability of subsoil, and/or a high water table. Therefore, septic tank effluent is primarily directly discharged to surface water through the storm drainage network.

A modified septic tank, such as an anaerobic baffled reactor with a simplified sewer connection, was used for some community sanitation systems in Indonesia. The system normally serves between 20 and 100 households, and is handled by a committee of residents who are responsible for its operation and maintenance. Between 2003 and 2011, nearly 400 sites with such systems were implemented [5]. These systems comply with the national discharge standards for domestic wastewater effluents (a maximum of 100 mg/L biochemical oxygen demand (BOD) and 100 mg/L total suspended solid (TSS)) [6], but problems associated with responsibilities for maintenance (human resources), financial management, and the removal and safe dis-



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posal of sludge [5, 7] remain.

During operation and maintenance of a septic tank, it is necessary for desludging to be conducted periodically every 1 to 5 y depending on the tank volume. The desludging process is conducted when half to two-thirds of the total depth between the water level and the bottom of the tank is occupied by sludge and scum [8]. In Indonesia, there are no national or local regulations governing septic tanks, and no specified responsible department for controlling septic tank desludging management. Consequently, septic tank management is taken over by the householder or property owner [4].

Generally, people in Indonesia use a conventional vacuum truck for septic tank desludging (emptying) when the tank has problems (e.g., overflowing or clogging). The collected sludge is then transferred and treated at a septage treatment plant (Indonesian: *Instalasi Pengolahan Lumpur Tinja (IPLT)*). Since 1990, the Ministry of Public Works has constructed around 140 *IPLTs* throughout Indonesia. However, 90% of these are either not operational or are running on very low volumes, and the existing septage sludge management system is performing poorly according to usual technical and financial operation standards [9].

Even though centralized systems for domestic wastewater (grey and black water) treatment have been constructed, by 2006 they covered only 12 of Indonesia's 98 municipalities [10] and this number remains low [4]. Accordingly, less than 1% of the Indonesian total population is being served by such systems. The centralized systems primarily consist of conventional aerated lagoons. However, these systems are plagued by poor sewer network quality, problems with customer pipe connections, high maintenance and operational costs, and the absence of a stable power supply [5, 10].

In Indonesia, the majority of urban inhabitants still appear to depend on onsite sanitation systems (e.g., household or community septic tank), and this is expected to continue [11]. Improper management of desludging wastewater from septic tanks, particularly at the *IPLT* level, generates environmental and health problems. Therefore, based on the current issues described above, it is necessary to develop appropriate (i.e., highly efficient, inexpensive, and low maintenance) technology for treatment of desludging septic tank wastewater.

An overview of septage treatment options in Argentina, Ghana, Thailand, and The Philippines was presented by Ingallinella and colleagues [12]. The options used comprised batch-operated settling-thickening units, Imhoff tanks, non-aerated stabilization ponds, combined composting with municipal organic refuse, extended aeration followed by pond polishing, and anaerobic digestion. In Indonesia, most septage that enters an *IPLT* is treated in an Imhoff tank, followed by a simple aeration step or an anaerobic pond [13].

The down-flow hanging sponge (DHS) reactor has been proposed as a cost-effective sewage treatment system for developing countries [14, 15] after being evaluated long-term [16]. The DHS reactor has advantages over activated sludge systems, including simple operation, easy maintenance, low operation and maintenance costs, and low excess sludge production [17].

The DHS reactor is recognized as a promising post-treatment alternative to the upflow anaerobic sludge blanket (UASB) reactor

[18]. The first full scale DHS reactor (500 m³/d capacity) was implemented at a sewage treatment plant in Karnal, Haryana State, India and evaluated [19, 20]. However, to date, the DHS reactor has mainly been applied as a subsequent post-treatment process of the UASB reactor for treatment of domestic wastewater. In this context, domestic wastewater is defined as wastewater (grey and black) produced by a community and delivered to a centralized treatment plant via a sewer connection system.

There are substantial differences between domestic wastewater (sewage) and septage sludge. For example, the quality of septage sludge (fecal sludge and its wastewater) is influenced by storage duration in septic tanks, temperature, intrusion of groundwater in septic tanks, performance of septic tanks, and tank-emptying method [12]. Therefore, it is necessary to investigate the application of the DHS reactor in the *IPLT* system to determine whether efficiency can improve.

In this study, a DHS reactor was constructed in the real field of a septage treatment plant and continuously monitored. The objective of this study was to evaluate the process performance in terms of organics, ammonia, and suspended solid removal. In addition to performance assessment, the hydraulic behavior, *in situ* activity tests, and sludge profile along the reactor height were investigated.

2. Materials and Methods

2.1. Description of Study-Site and DHS Reactor

The DHS reactor was installed in the *IPLT* of Kampung Jawa located at Banda Aceh, Aceh Province, Sumatra, Indonesia. The *IPLT* consists (in sequence) of a receiving tank, a bio-digester (anaerobic tank), an anaerobic baffle reactor, a horizontal gravel filter, a maturation pond, and a sludge drying bed. The *IPLT* intermittently receives approximately 12,000 to 20,000 liters of septage per day from individual or community (households, offices, schools, hotels, or traditional markets) septic tanks. Septic tanks vary between 3 and 10 y of age and treat black water almost exclusively. The septage is delivered from community septic tanks to the *IPLT* by a conventional vacuum truck. There are no specific regulations concerning septic tank management; therefore, the tank emptying cycle was commonly conducted whenever the user experienced problems.

The DHS reactor received actual septage wastewater from a 2,000 L plastic container tank. The container tank fed the wastewater via a connection to a submersible pump inside the *IPLT*'s receiving tank. The container tank also served as a pre-sedimentation unit of the DHS reactor. The settled solids at the bottom of the tank were removed periodically through a drain valve.

A schematic diagram of the experimental set up is illustrated in Fig. 1. The DHS reactor is made of plexi-glass and had a height of 4 m and an internal diameter of 0.3 m. The reactor consisted of three portions (upper, middle, and lower) connected vertically with a spacing of 5 cm between them to allow continuous ventilation during operation. This space could also be used in approaches to profile sampling. A number of G3-DHS modules filled each section in a random distribution. The modules,

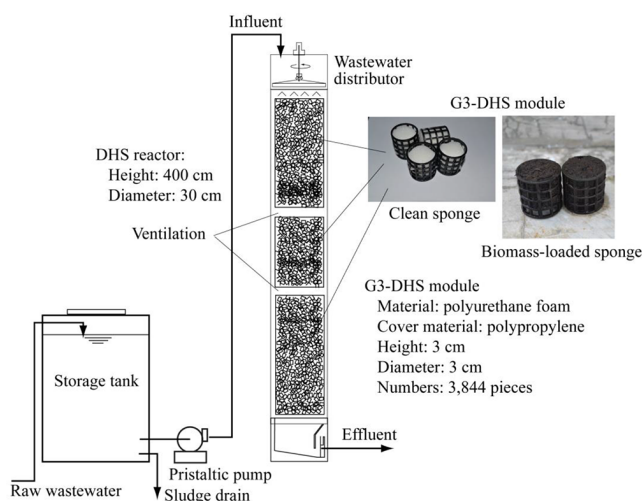


Fig. 1. Schematic diagram of the experimental set up.

which were made of polyether-based urethane foam sponge, have been described in detail elsewhere by Uemura and colleagues [21]. The upper, middle, and lower portions were equipped with 26.5, 16.4, and 34.5 L of sponge modules, respectively. The total volume of the modules was equivalent to the volume of the reactor, which was nearly 28% of sponge occupancy ratio in the reactor column. The DHS reactor was equipped with a distributor at the top of the reactor to allow wastewater to be uniformly distributed.

2.2. Operational Conditions

The DHS reactor was started up without any added seed sludge. The reactor was initially operated at a hydraulic retention time (HRT) of 3 h (phase-1). The influent loading was then reduced to a HRT of 4 h during phase-2. The DHS reactor was continuously operated under ambient conditions. No substantial amount of retained sludge was withdrawn from the reactor during the course of the experiment. The representative specimen of the clean and biomass-loaded G3-DHS module is also presented in Fig. 1.

2.3. Sampling and Analysis

The performance of the DHS reactor was evaluated by analyzing grab samples of influent (septage concentration) and effluent. Dissolved oxygen (DO), pH, and temperature were also measured *in situ*. Relative long-term monitoring was conducted for about 600 d to evaluate the quality performance of the DHS reactor. All samples were analyzed for physico-chemical parameters, namely chemical oxygen demand (COD), BOD, ammonium-nitrogen ($\text{NH}_4\text{-N}$), nitrite-nitrogen ($\text{NO}_2\text{-N}$), nitrate-nitrogen ($\text{NO}_3\text{-N}$), total-nitrogen (TN), TSS, and volatile suspended solids (VSS). All analytical methods adopted for determination of the parameters were based on *standard methods* [22]. A glass fiber filter (GB-140, Advantec, Tokyo, Japan) was used to measure the soluble fraction of COD (soluble-COD).

2.4. *In Situ* Activity Tests

In situ activity tests of the DHS reactor with respect to hetero-

trophs (COD oxidation rate) and autotrophs (ammonia oxidation rate) were determined from the profile test by feeding defined synthetic wastewater into the DHS influent. Feed solutions contained glucose (equivalent to a soluble COD of around 170 mg/L) and ammonium (equivalent to about 30 mg/L). Phosphate buffers and trace materials were supplied according to Ohashi [23]. The experiment was conducted on day 287 and on day 450 at a HRT of 3 h and 4 h, respectively. Samples were collected along the reactor height and filtered shortly after sampling.

2.5. Tracer Studies

A series of tracer studies were conducted to evaluate hydraulic characteristics (i.e., residence time distribution) in the DHS reactor. The studies were conducted by applying an impulse addition of saturated NaCl solution as an inert tracer to the inlet of the DHS reactor. Then, the time-dependency tracer concentration was measured (at the outlet) using a conductivity meter (Corning Pinnacle 541, Cole-Palmer, IL, USA). The mean residence time, which is equivalent to the experimental HRT of the DHS reactor, was calculated from the recorded data of the outlet tracer concentration (residence time distribution-RTD curve). The theoretical HRT was calculated from a setting flow rate and the reactor void volume.

The ratio of the experimental HRT to the theoretical HRT can be assumed to be the water distribution in the DHS reactor. A dispersion number (D/uL) and the number of tanks in-series (N) were estimated using the formula given by Levenspiel [24]. The degree of fluid mixing in the DHS reactor was estimated by the Morrill dispersion index (MDI) approach. The MDI was found from the T10 and T90 parameters, which were determined from the RTD curve by calculating the time interval corresponding to 10% and 90% of the area under the curve, respectively. The ideal plug flow has a MDI of 1 [25].

3. Results and Discussion

3.1. DHS Reactor Process Performance

The performance of the DHS reactor was evaluated continuously for around 570 d. The reactor was operated at a HRT of 3 h for a period of 324 d (phase-1) and 4 h for a period of 246 d (phase-2). The DHS reactor produced a relatively high DO concentration in the effluents, despite no forced aeration being provided. Although the receiving tank of the *IPLT* supplied wastewater with a negligible amount of DO (1.45-1.90 mg/L), the DO concentration increased to 5.85-5.90 mg/L in the DHS reactor effluent. This finding was similar to those obtained in previous experiments investigating the use of DHS reactors to treat anaerobic effluent [20, 26]. The high oxygen level in the wastewater stream in the DHS is valuable to accomplishing satisfactory removal efficiency for organics and ammonia.

The time course of TSS, organics (total-COD and total-BOD), and inorganics ($\text{NH}_4\text{-N}$) removal and $\text{NO}_x\text{-N}$ production is presented in Fig. 2. Most experiments conducted to date have used DHS reactors as post-treatment units for UASB effluent (see review in [27]). Accordingly, they have received low TSS concen

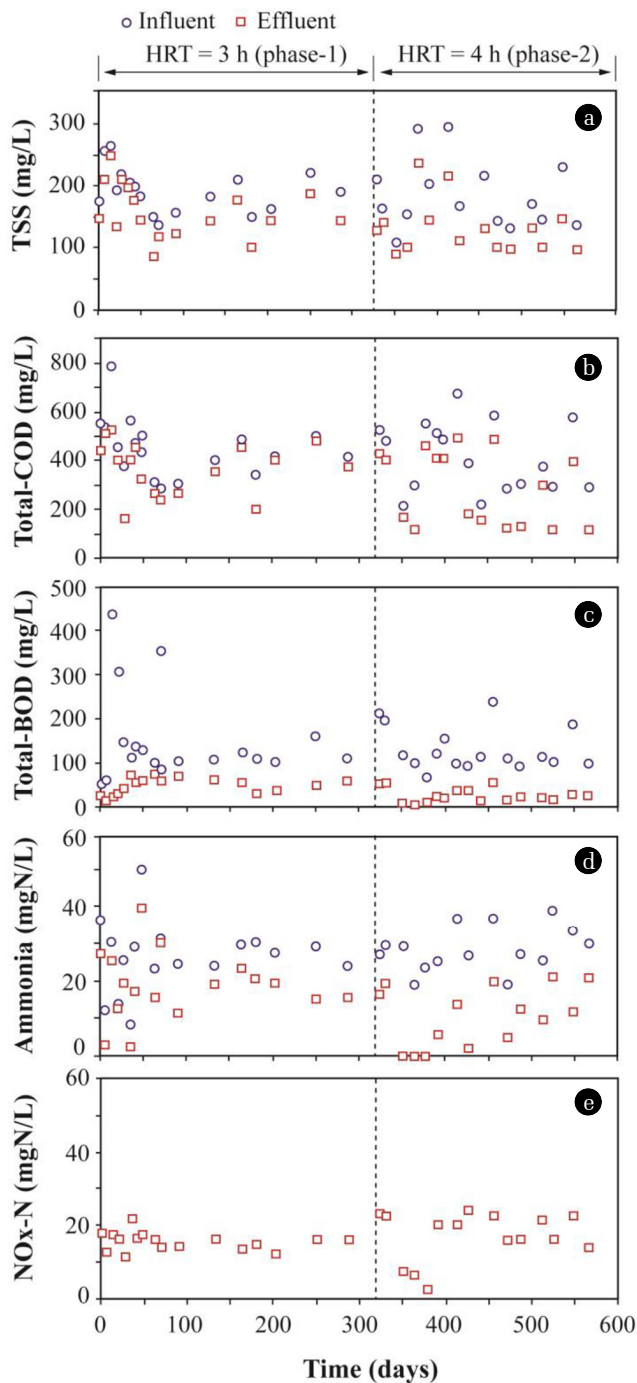


Fig. 2. Time course of (a) TSS, (b) COD, (c) BOD, (d) ammonia in influent and effluent, and (e) $\text{NO}_x\text{-N}$ in effluent for HRTs of 3 h and 4 h.

trations in influent (e.g., 71 ± 37 mg/L [16]), 47 ± 38 mg/L [28], 44 ± 38 mg/L [29], and 53 ± 20 mg/L [20]). In the present experiment, the average TSS concentration in the DHS reactor influent during phase-1 and phase-2 was 191 ± 36 mg/L and 185 ± 56 mg/L, respectively, which was approximately four

to five times higher than those of the previous experiments. As shown in Fig. 2(a), the TSS concentration of the effluent decreased as the HRT increased from 159 ± 36 mg/L (phase-1) to 132 ± 43 mg/L (phase-2).

Fig. 2(b) and Fig. 2(c) show the time course of the total-COD and total-BOD, respectively, of the DHS influent and effluent throughout the experimental period. During phase-1, at a HRT of 3 h, the organic loading rate (OLR) of the DHS reactor was 1.1 kg/m³/d for total-BOD and 3.6 kg/m³/d for total-COD. In this period, the concentration of total-COD and total-BOD in the DHS effluent was 369 ± 108 mg/L and 48 ± 18 mg/L, respectively, while the removal of total-COD and total-BOD by the DHS reactor was $18 \pm 15\%$ and $56 \pm 21\%$, respectively.

At a HRT of 4 h (phase-2), the organic removal efficiency was improved. During this phase, as the OLR of the DHS reactor decreased to 0.8 kg/m³/d of the total-BOD, the total-BOD concentration in the DHS reactor effluent reached 26 ± 15 mg/L, which complied with the Indonesian national discharge standards for domestic wastewater effluent.

Fig. 2(d) shows the time course of $\text{NH}_4\text{-N}$ in the DHS reactor influent and effluent. At a HRT of 3 h, the average $\text{NH}_4\text{-N}$ concentrations were 26 ± 10 mg/L in influent and 18 ± 10 mg/L in effluent, which was equivalent to a $\text{NH}_4\text{-N}$ removal efficiency of $36 \pm 25\%$. The removal efficiency was improved almost two-fold in phase-2 (at a HRT of 4 h), resulting in $\text{NH}_4\text{-N}$ removal of $65 \pm 24\%$. In this phase, the DHS reactor produced final effluent containing 11 ± 8 mg/L $\text{NH}_4\text{-N}$.

The average concentration of $\text{NO}_x\text{-N}$ in the DHS effluent was 15 ± 3 mg/L and 25 ± 8 mg/L for phase-1 and phase-2, respectively (see Fig. 2(e)). The results revealed that the amount of ammonia removed was 0.03 kg/m³/d and 0.08 kg/m³/d for phase-1 and phase-2, respectively. Similarly, the amount of $\text{NO}_x\text{-N}$ produced was 0.02 kg/m³/d for phase-1 and 0.06 kg/m³/d for phase-2. These findings showed that the amount of $\text{NH}_4\text{-N}$ eliminated was greater than the amount of $\text{NO}_x\text{-N}$ produced. Since $\text{NH}_4\text{-N}$ is transformed to $\text{NO}_3\text{-N}$ through $\text{NO}_2\text{-N}$ under aerobic conditions in the nitrification process, and the contribution of nitrogen for cell growth was assumed to be insignificant, this nitrogen imbalance suggested the presence of denitrifiers in the DHS reactor.

The simultaneous existence of nitrifiers and denitrifiers in a DHS reactor may occur as a result of partial distribution of the relevant clusters in aerobic regions of the sponge surface and anoxic portions approximately 0.75 cm from the surface of the sponge [30]. A summary of the water quality of the reactor influent, effluent, and removal is presented in Table 1.

3.2. Water Quality Profile

The stable performance of the DHS reactor during long-term experimental periods can be attributed to its treatment characteristics. To evaluate the treatment characteristics, the water profile samples of DO, pH, soluble-COD, $\text{NH}_4\text{-N}$, and oxidized-nitrogen ($\text{NO}_3\text{-N}$ plus $\text{NO}_2\text{-N}$) were collected from different heights of the DHS reactor (Fig. 3). The samples were observed on day 91 at a HRT of 3 h, and on day 391 at a HRT of 4 h. The results shown in Fig. 3(a) indicate that, even though no external mechanical aeration was installed in the DHS reactor,

Table 1. Results Summary

Parameter	Influent	Effluent	Influent	Effluent
	HRT = 3 h (287 d)		HRT = 4 h (279 d)	
pH (-)	5.45-6.50	6.18-6.42	5.30-5.78	6.28-6.71
DO (mg/L)	1.45 (0.78)	5.90 (0.28)	1.90 (0.14)	5.85 (0.21)
Total-COD (mg/L)	449 (122)	369 (108)	416 (142)	289 (151)
Soluble-COD (mg/L)	226 (54)	177 (57)	204 (90)	142 (86)
Total-BOD (mg/L)	139 (93)	48 (18)	130 (48)	26 (15)
NH ₄ -N (mgN/L)	26 (10)	18 (10)	28 (6)	11 (8)
NO ₂ -N (mgN/L)	0.4 (0.7)	1.1 (0.7)	0.3 (0.4)	0.9 (1.1)
NO ₃ -N (mgN/L)	7 (2)	14 (3)	4 (2)	16 (7)
TN (mgN/L)	37 (9)	35 (11)	38 (8)	7 (11)
TSS (mg/L)	191 (36)	159 (43)	185 (56)	132 (43)
VSS (mg/L)	150 (26)	140 (52)	121 (35)	101 (38)
Removal				
Total-COD (%)		18 (15)		34 (19)
Soluble-COD (%)		22 (14)		33 (12)
Total-BOD (%)		56 (21)		80 (9)
NH ₄ -N (%)		36 (25)		65 (24)
TSS (%)		18 (11)		28 (8)
Total-COD loading (kg/m ³ /d)		3.59 (0.97)		2.49 (0.85)
Total-BOD loading (kg/m ³ /d)		1.11 (0.75)		0.78 (0.29)
NH ₄ -N loading (kg/m ³ /d)		0.21 (0.08)		0.17 (0.04)
Total-COD removal rate (kg/m ³ /d)		0.64 (0.6)		0.76 (0.32)
Total-BOD removal rate (kg/m ³ /d)		0.73 (0.81)		0.62 (0.23)
NO _x -N Production rate (kg/m ³ /d)		0.06 (0.03)		0.08 (0.04)
TN removal rate (kgN/m ³ /d)		0.05 (0.04)		0.06 (0.06)

(): standard deviation

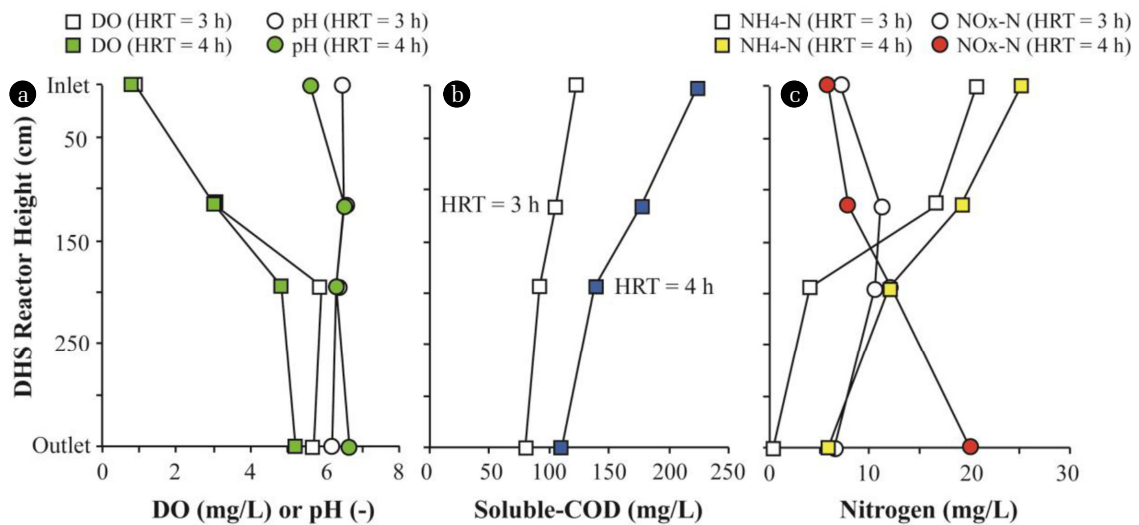


Fig. 3. Profile analysis of (a) DO and pH, (b) soluble-COD, and (c) ammonium and oxidized-nitrogen along the DHS reactor height on day 91 at a HRT of 3 h, and on day 391 at a HRT of 4 h.

the DO concentration increased from 0.9 mg/L at the inlet to 5.9 mg/L at 200 cm from the inlet, then remained constant until the outlet. The results also demonstrate that the DO profiles at different flow rates (HRTs of 3 h and 4 h) were similar.

DO concentrations of water are constantly affected by diffusion and proportional to the partial pressure of oxygen in the air above it. The water flowing over the sponge media captures and delivers air with it, which is then immersed in the water, leading to increased DO concentrations. Araki *et al.* [30] confirmed this phenomenon using a DO microelectrode and found the presence of DO at 5 mm inside the sponge surface of the DHS reactor. The relatively high DO penetration into the sponge media was favorable to treatment of desludging septic tank wastewater that contained a high SS.

The profile analysis (Fig. 3(b)) showed that the soluble-COD concentration of 123 mg/L in the inlet decreased to 80 mg/L in the outlet on day 91 (at a HRT of 3 h). On day 391 (at a HRT of 4 h), the soluble-COD level decreased from 225 mg/L to 110 mg/L in the inlet and outlet, respectively. The removal of soluble-COD on day 91 was 26% and 12% in the upper and the lower part, respectively. Under these conditions, the OLR was 0.98 kg soluble-COD/m³/d. On day 391, the OLR of the DHS reactor was 1.35 kg soluble-COD/m³/d, and the reactor achieved organic removals of 39% and 20% in the upper and lower part, respectively.

These findings indicate that the soluble organic concentrations were primarily removed in the upper part (inlet to 200 cm) of the DHS reactor. Another low portion of the soluble organic fraction was further eliminated from the lower part (200 cm to outlet) of the reactor, indicating that the DO concentration in the upper portion of the DHS reactor was not a limiting factor for biological oxidation of soluble organics.

As shown in Fig. 3(c), slight nitrogen removal occurred in the upper portion (from the inlet to 100 cm), while the majority took place in the middle (from 100 cm to 200 cm) and the lower (from 200 cm to outlet) portions of the reactor for both experiments (on day 91 and day 391). The lower nitrification reaction in the upper portion was due to the presence of inadequate nitrifier clusters and competition by heterotrophs for available oxygen. However, the DO concentration sharply increased in the middle portion and remained constant in the lower portion. The DO concentration reached 5.5 ± 0.4 mg/L in the DHS effluent.

These results indicate that there was better nitrification efficiency in these portions. Nitrification improved in the middle portion when the OLR decreased from 0.98 to 0.85 kg soluble-COD/m³/d at the phase-1 or from 1.35 to 1.05 kg soluble-COD/m³/d at the phase-2. The ammonia was almost completely removed, with only 0.3 mg/L and 5.8 mg/L remaining in the final effluent at HRTs of 3 h and 4 h, respectively.

3.3. Sludge Profiles

As one of the most important characteristics of DHS reactor is to maintain the large amount of the biomass, the sludge accumulation profiles in the sponge module at three different locations (upper, middle, and lower) of the DHS reactor height were evaluated on day 600. The profiles are presented as grams of TSS or VSS per unit of sponge volume.

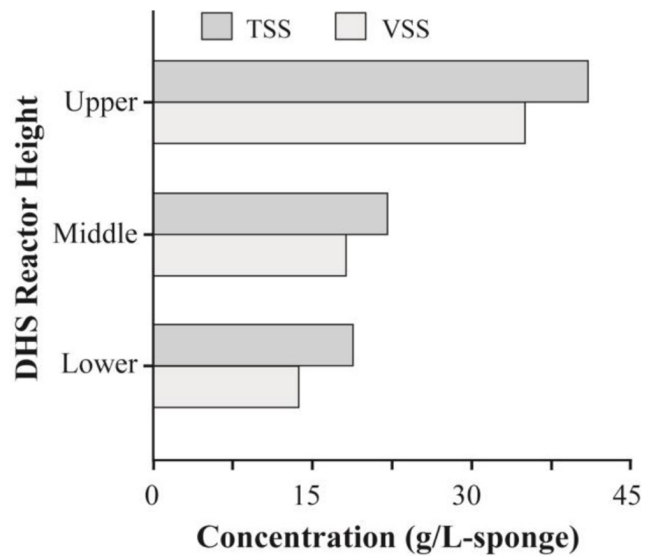


Fig. 4. Sludge profiles along the reactor height were collected on day 600.

As shown in Fig. 4, the concentration of TSS at the upper, middle, and lower portion was 40.7, 22.2, and 18.5 g/L-sponge, respectively. Similarly, the concentration of VSS was 18.7, 11.3, and 10.2 g/L-sponge, respectively. In the current experiment, a higher sludge accumulation was found at the upper portion than at the other locations. This may have occurred because the influent, which had a sludge concentration of 185-191 mg TSS/L, was first treated and filtered in the upper part of the reactor.

Comparison of the sludge retainment with other conventional processes such as a suspended system (activated sludge) [31] and attached growth system (trickling filter) [32] revealed that the accumulation of sludge in the DHS reactor was 5-10 times higher than in the other systems. The longer sludge retention time and higher amount of active biomass in the DHS reactor both improve the removal efficiency of the reactor. Using the Live/Dead bacteria methodology, Machdar [27] concluded that the percentage of active biomass in DHS retained sludge was around 66%.

Even though the DHS reactor received a relatively high TSS from the influent wastewater during the course of the experimental period, the maintenance issues caused by sludge blockage and sloughing, which often arise in conventional trickling filters [33], were not observed in this experiment. Moreover, the macrofauna (worms, flies, or snails) frequently present in DHS sludge were not present in substantial numbers in this experiment.

3.4. *In Situ* Activity Tests

In addition to the sludge amount in the DHS reactor, its sludge activity can influence on process performance. The activities of heterotroph (organic substance oxidation) and autotroph (ammonia oxidation or NO_x-N production) bacteria at three different locations (upper, middle, and lower) along the DHS reactor

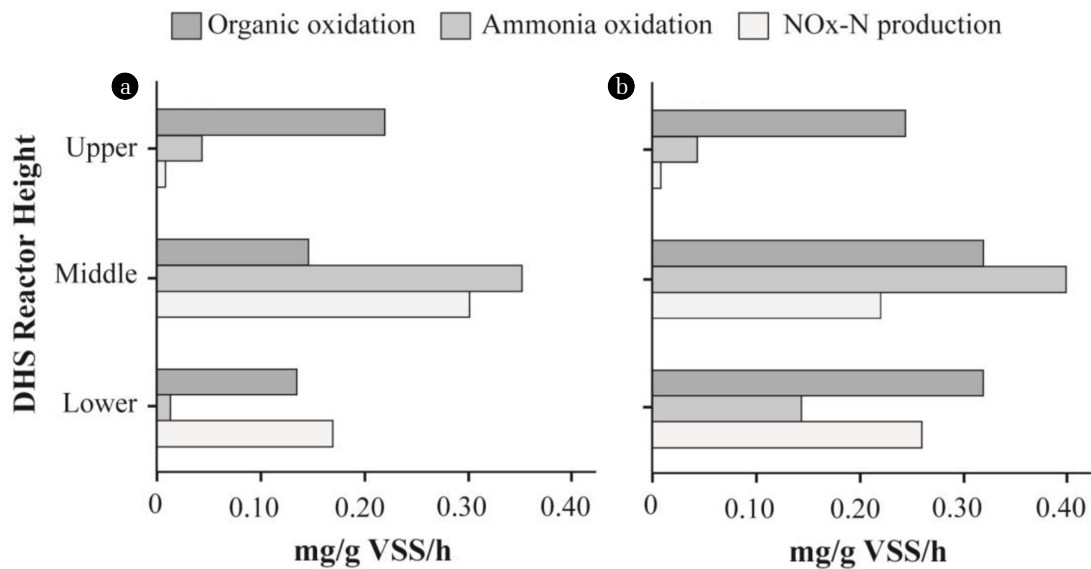


Fig. 5. *In situ* activity tests on (a) day 287 at a HRT of 3 h, and (b) day 450 at a HRT of 4 h.

height are presented in Fig. 5. The activities were measured on day 287 (Fig. 5(a)) and 450 (Fig. 5(b)) at HRTs of 3 h and 4 h, respectively. The activities are given as milligrams of substance removed per gram of VSS in the sponge per hour.

The results show that at a HRT of 3 h (glucose influent loading rate of $1.35 \text{ kg/m}^3\text{-sponge/d}$), the heterotroph activity decreased from 0.22 mg/g VSS/h in the upper portion to 0.14 mg/g VSS/h in the middle portion and 0.13 mg/g VSS/h in the lower portion. However, at a HRT of 4 h (glucose influent loading rate of $1.05 \text{ kg/m}^3\text{-sponge/d}$), the activity recovered along the reactor height, with values of $0.24\text{-}0.32 \text{ mg/g VSS/h}$ being observed.

Comparable results have been found in certain DHS [16] and random package DHS [26, 28, 29]. In these studies, activities were measured along the DHS reactor height based on the oxygen utilization rate. The results revealed that the decrease in tendency activity rate toward the outlet of the DHS reactor was directly proportional to the organic loading rate. Moreover, variations in heterotroph activity along the DHS reactor height can be attributed to the DO concentration in wastewater and the percentage of microorganisms in retained sludge. A reasonable explanation for the fluctuation in heterotroph activities observed is that the quality of the retained sludge was distinct along the reactor height.

Autotroph activities (ammonia oxidation) tended to increase in the middle portion and decrease in the lower portion for the experiments investigated (Fig. 5(a) and Fig. 5(b)). At a HRT of 3 h (ammonia influent loading rate of $0.23 \text{ kg/m}^3\text{-sponge/d}$), the autotroph activity was 0.04 , 0.35 , and 0.16 mg/g VSS/h at the upper, middle, and lower portion, respectively. There was no significant difference at a HRT of 4 h (ammonia influent loading rate of $0.18 \text{ kg/m}^3\text{-sponge/d}$), under which the activity was 0.04 mg/g VSS/h (upper), 0.40 mg/g VSS/h (middle), and 0.14 mg/g VSS/h (lower).

In this experiment, the applied glucose loading at the middle portion at a HRT of 3 h was $1.25 \text{ kg/m}^3\text{-sponge/d}$, while that

at the upper portion at a HRT of 4 h was $1.05 \text{ kg/m}^3\text{-sponge/d}$. These findings demonstrated that the autotrophs still survive at a glucose loading of $1.25 \text{ kg/m}^3\text{-sponge/d}$ if there is sufficient DO available. The results also confirm that the lower autotroph activity in the upper portion was due to the low level of DO derived from the influent that comes from anaerobic treatment (septic tank) effluent. Moreover, the autotroph activity at the upper and middle portions indicates that the amount of ammonia oxidation exceeded the amount of $\text{NO}_x\text{-N}$ (nitrite plus nitrate) production.

These results indicate that the amounts of $\text{NO}_x\text{-N}$ produced (at a HRT of 3 h) were 0.07 and 0.30 mg/gVSS/h at the upper and middle portion, respectively. However, at a HRT of 4 h, the $\text{NO}_x\text{-N}$ production was 0.01 and 0.22 mg/g VSS/h at the upper and middle portion, respectively. Assuming that consumption of nitrogen for cell growth was insignificant, the nitrogen imbalance was due to denitrification.

3.5. Tracer Study

Like other attached growth processes, the treatment efficiency of the DHS reactor is affected by physical contact between wastewater, surrounding air, and microbial cells (active retained biomass). The contact in an attached growth process such as in trickling filter systems primarily relies on the mode of packing material applied [34], which is also true in DHS reactors.

Contact efficiency can be evaluated through tracer studies by calculating the percentage of water hold-up volume or water distribution, i.e. the difference between the actual (experimental) and theoretical HRT [21, 35, 36]. In this experiment, a tracer study was conducted under two different circumstances; namely, with a clean sponge (prior to start up) and a biomass-loaded sponge (during the course of the experimental period). The plots of tracer effluent concentration versus time (RTD curve) including values of N , D/uL , and water hold-up volume under clean sponge condition (CS) and in biomass-loaded sponge (BS) are presented in Fig. 6(a) and Fig. 6(b), respectively.

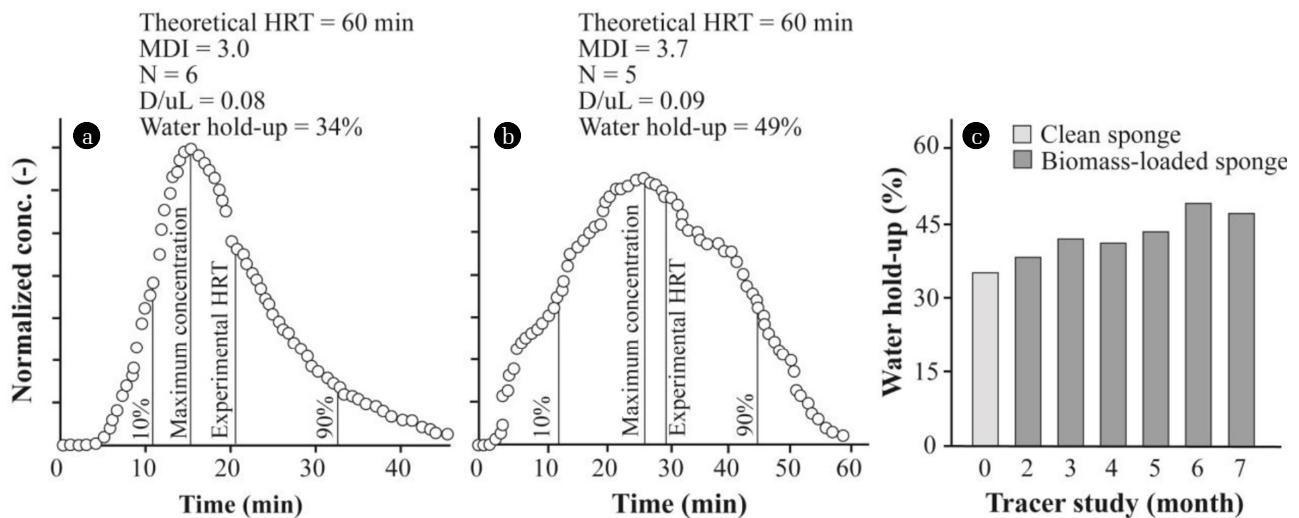


Fig. 6. RTD curves of clean sponge (a), biomass-loaded sponge at 6 mon (b), and increase in water hold-up volume on the DHS reactor (c).

The results demonstrated that the maximum tracer effluent concentration was detected at around 15.5 and 26 min after injection of the inert tracer for the CS and BS condition, respectively. Both values were lower than the experimental HRT of the respective sponge conditions. This appearance was likely because of short circuiting and areas of dead volume in the DHS reactor, which are commonly found in plug flow reactors [37, 38]. Moreover, attenuate peaks and tails in tracer tracking that indicate the presence of a stagnant volume [24] were observed in the RTD curves, even when the sponge was clean. However, the previous interpretation of an interaction between tracer solution and retained sludge in the DHS reactor [21, 39] cannot be applied in this context.

In the case of a clean sponge in the DHS reactor, the tailing phenomenon was likely caused by water held in each clean sponge pore acting as a static volume. The tracer then passes through the sponge pore and is slowly released by diffusion, eventually generating long tracer tracking. A detailed description of the tracer diffusion phenomenon for tailing in clean material was presented by Jimenez [40].

Analysis of the RTD results showed little difference in the MDI under the CS and the BS condition. The Morrill indices were 3.0 and 3.7 for the CS and the BS, respectively. A larger number for the MDI indicates more mixing in the reactor [41], and these results directly correspond to the longer experimental HRT of the BS condition. The dispersion coefficients (D/uL), which represent the tracer spreading process, were 0.08 for the CS and 0.09 under the BS condition.

These results show that the retained sludge improved the dispersion coefficient. In a previous study, the value of the dispersion coefficient in the DHS reactor was between 0.04 and 0.06 for clean sponge conditions [28] and between 0.03 and 0.10 for a loaded-biomass sponge [16]. Moreover, the DHS reactor can be modeled as a plug flow reactor consisting of a series of continuous flow stirred tank reactors (CSTRs). Therefore, a quantitative illustration of the influence of the retained sludge

on the HRT of the DHS reactor is also acquired by estimation of the number of CSTR in-series (N).

As shown in Fig. 6(a) and Fig. 6(b), the number of tanks in-series was 5 and 7 for the CS and the BS condition, respectively. These figures reinforce the favorable effects of the retained sludge on the HRT of the DHS reactor.

The results presented in Fig. 6(c) indicate that the water hold-up volume in the DHS reactor increased with time from the DHS reactor start-up. Specifically, there was an increase in the water hold-up volume from 34% (prior to start-up) to 49% (at 6 mon). During this period, there was no significant sludge withdrawal. The hold-up volume of the DHS reactor with a similar module treating municipal sewage at a theoretical HRT of 0.5 h was found to be about 63.3% [39]. The lower hold-up volume in the present study was probably due to the different characteristics of the retained sludge.

4. Conclusions

A pilot scale DHS reactor operating for 600 d for treatment of desludging septic tank wastewater exhibited stable and efficient performance removal. The final effluent of the DHS met the Indonesian National Discharge Standards. The reactor profile showed retained sludge quantities and activities comparable to those observed in other investigations using similar DHS modules.

The adoption of a DHS reactor in Indonesian *IPLT* would enhance the role of desludging septic tank wastewater treatment systems. Moreover, DHS reactors could play a crucial role in development of an appropriate concept for domestic wastewater treatment systems, especially in communities in low-income regions.

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