Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2017.20815

91 (2017) 48–54
October

Treatment performance of practical-scale down-flow hanging sponge reactor using sixth-generation hard sponge media

Tsutomu Okubo[a,*], Akinori Iguchi[b], Masanobu Takahashi[c], Kengo Kubota[d], Shigeki Uemura[a], Hideki Harada[e]

[a]*Department of Civil Engineering, National Institute of Technology, Kisarazu College, 2-11-1 Kiyomidaihigashi, Kisarazu, Chiba 292-0041, Japan, Tel./Fax: +81-438-30-4165; email: okubo@c.kisarazu.ac.jp (T. Okubo), Tel./Fax: +81-438-30-4152; email: uemura@c.kisarazu.ac.jp (S. Uemura)*
[b]*Faculty of Applied Life Science, Niigata University of Pharmacy and Applied Life Sciences, 265-1 Higashisima, Akiba-ku, Niigata, Niigata 956-8603, Japan, Tel./Fax: +81-250-25-5145; email: a_iguchi@nupals.ac.jp*
[c]*Sewage Works Department, Nihon Suido Consultants Co., Ltd., 1-23-101 Esakacho, Suita, Osaka 564-0063, Japan, Tel. +81-6-6339-7442; Fax: +81-6-6385-3946; email: takahashi_ma@nissuicon.co.jp*
[d]*Department of Civil Engineering, Tohoku University, 6-6-06 Aoba, Aramaki, Aoba, Sendai, Miyagi 980-8579, Japan, Tel./Fax: +81-22-795-5011; email: kengo.kubota.a7@tohoku.ac.jp*
[e]*New Industry Creation Hatchery Center, Tohoku University, 6-6-04 Aoba, Aramaki, Aoba, Sendai, Miyagi 980-8579, Japan, Tel./Fax: +81-22-795-3176; email: hideki.harada.e3@tohoku.ac.jp*

Received 6 December 2016; Accepted 10 April 2017

ABSTRACT

A down-flow hanging sponge (DHS) reactor with a lateral partition was filled with sixth-generation sponge media (DHS-G6), polyethylene sponges stiffened with epoxy resin, and third-generation sponge media (DHS-G3), polyethylene sponges wrapped in a plastic net, in a continuous experiment at a sewage treatment plant in India to assess and compare the treatment performances of the two sponge media. No clear differences between the different media were found in the removal of biochemical oxygen demand (BOD), ammonium nitrogen, and fecal coliform. The best performance was obtained at a hydraulic retention time of 2 h. The concentrations of respective components in the water treated by the DHS-G3 and DHS-G6 were as follows: BOD, 5 and 7 mg L^{-1}; ammonium nitrogen, 4 and 6 mg N L^{-1}; and fecal coliform, 3.2×10^4 100 mL^{-1} and 3.9×10^4 100 mL^{-1}. Performance levels fully satisfying the Indian discharge standards were obtained for removal of BOD and ammonium nitrogen, but not fecal coliform.

Keywords: Sewage treatment; Down-flow hanging sponge; Sponge media; Removal of organics; Nitrification

1. Introduction

A down-flow hanging sponge (DHS) reactor was developed as a method for post-treatment of the effluent from an up-flow anaerobic sludge blanket (UASB) reactor and has provided a treatment performance equivalent to that of the activated sludge process (ASP) during a 5-year demonstration experiment in India [1,2]. Since DHS reactors use a trickling filter-type method for post-treatment of the UASB effluent, they have several favorable characteristics: the aerobic process of DHS reactors does not require external aeration (energy consumption is 10%–20% less than that of the ASP); they generate less excess sludge (16%–50% less than that of the ASP); they require less space than other post-treatment processes for UASB; and maintenance of the reactors is simple [3].

* Corresponding author.

Presented at the 13th IWA Specialized Conference on Small Water and Wastewater Systems & 5th IWA Specialized Conference on Resources-Oriented Sanitation, 14–16 September, 2016, Athens, Greece.

1944-3994/1944-3986

The properties of the sponge media at the core of DHS reactors must be improved, especially in terms of the workability of the media, to facilitate construction of large-scale reactors and improve their treatment performance. Currently, the best packing arrangement with regard to workability is "random packing" employing third-generation sponge (G3) media [4] and sixth-generation sponge (G6) media [5].

The G3 medium is a soft polyurethane sponge. To prevent compaction of the sponge, the exterior is covered with a cylindrical polyethylene net [4]. In contrast, the G6 medium is a polyethylene sponge stiffened with epoxy resin. The reinforcement with epoxy resin reduces porosity, but this configuration has the advantage of not needing a plastic net to protect against compaction [5].

We have been conducting demonstration experiments with a DHS reactor at a sewage treatment plant in Karnal, India [1,2,6]. This study describes a continuous experiment with a practical-scale, re-built DHS reactor. Specifically, a lateral partition was installed in the reaction zone in an existing DHS reactor, and each half was filled with either G3 or G6 media in a random-packing arrangement. The objective was to compare and evaluate the treatment performance of these sponge media.

2. Experimental method

2.1. DHS reactor

Fig. 1 shows images and specifications of the G3 and G6 media, and a schematic diagram of the practical-scale DHS reactor used for this study. This reactor was installed in a sewage treatment plant in Karnal, India, that employs UASB reactors. The reaction zone of the DHS reactor consisted of a concrete cylinder (5.5 m in diameter and 5.3 m high), with a reactor tower volume of 126 m^3 [1,2]. Gaps of 15–28 cm were set between the filled layers to promote oxygen uptake by the water sprayed on the DHS. Ventilation ports were also incorporated into the reactor to improve oxygen uptake. To compare the performances of the sponges, a lateral partition was installed in the reaction zone, and each half of the reactor was filled with either G3 or G6 media.

2.2. Sponge media

The G3 medium consists of a soft, cylindrical sponge (32 mm in diameter and 32 mm high) made of polyurethane, and is wrapped in a polyethylene net to prevent compaction (Fig. 1) [6]. The porosity of the G3 medium is quite high (98%). A preliminary continuous experiment was conducted in the practical-scale DHS reactor for 491 days using only G3 media [6]. Rebuilding the reactor to contain both G3 and G6 media required approximately 2 months, so all the G3 media were temporarily removed from the reactor and stored in a moist environment to prevent them from drying. Before re-filling the reactor, nine G3 media were randomly selected for determination of sludge concentration. The mean sludge concentration was 13.7 g of volatile suspended solids m^{-3} sponge. A total of 796,000 G3 media were required to fill one side of the reactor. The filling ratio was 32.5%.

The G6 medium, consisting of a polyethylene sponge coated with epoxy resin, is shaped like a hexagonal prism (32 mm high and 42 mm wide), and has an 18-mm-diameter hole in the center to increase its surface area (Fig. 1). This design helps maintain aerobic conditions by exposing more of the sponge surface to air [5]. The G6 media are hard, which eliminates the need for an outer plastic net to prevent compaction, but the epoxy coating reduces their porosity to 70%.

The G6 media were free of sludge when first placed in the reactor. A total of 486,000 G6 media were used to fill the other side of the reactor, for a total effective volume of 19.3 m^3. The filling ratio was 30.6%. The filling conditions for the two sponge media were nearly identical, allowing for comparison of their treatment performances. Hereinafter, the sides of the DHS reactor filled with G3 and G6 media are referred to as DHS-G3 and DHS-G6, respectively.

2.3. Operating conditions

The DHS reactor was operated under three conditions in this experiment: from the beginning to day 111 (Phase 1), the flow rate was 500 m^3 d^{-1} (hydraulic retention time [HRT] based on sponge volume, 1.97 h for DHS-G3, 1.85 h for DHS-G6); from day 112 to day 317 (Phase 2), the flow rate was 1,000 m^3 d^{-1} (HRT, 0.98 h for DHS-G3, 0.93 h for DHS-G6);

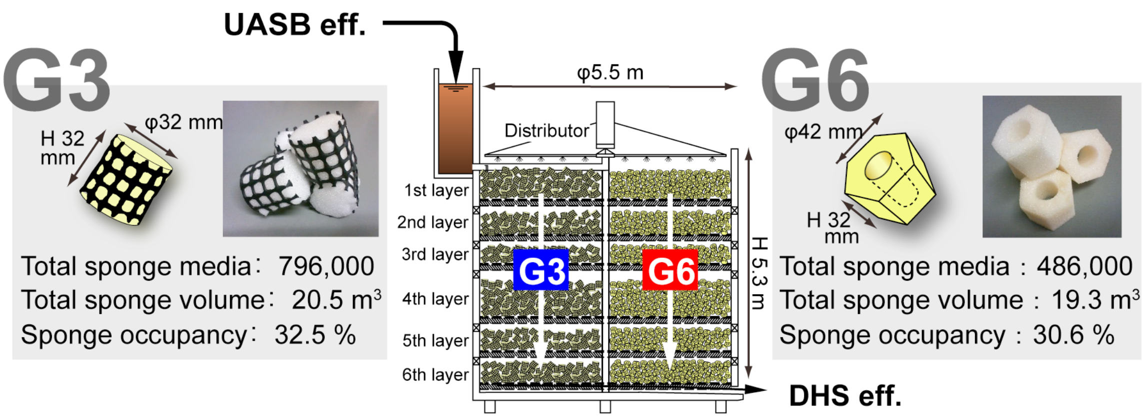

Fig. 1. Images and specifications of the third-generation (G3) and sixth-generation (G6) media, and a schematic diagram of the down-flow hanging sponge (DHS) reactor filled with these media.

and from day 318 to day 390 (Phase 3), the flow rate was 750 m^3 d^{-1} (HRT, 1.31 h for DHS-G3, 1.24 h for DHS-G6).

2.4. Analytical methods

The sewage and the effluents from UASB, DHS-G3, and DHS-G6 were analyzed. The effluent samples from DHS-G3 and DHS-G6 were taken directly from the bottom layer of each stack. The unfiltered chemical oxygen demand (COD), ammonium nitrogen (NH_4^+–N), nitrate-nitrogen (NO_3^-–N), and total nitrogen (TN) were determined using the potassium dichromate method, the salicylic acid process, cadmium reduction method, and the nitrogen tube test, respectively. All of these measurements were carried out using a DR-890 Portable Colorimeter (Hach, Colorado, USA). The unfiltered biochemical oxygen demand (BOD) was analyzed by adding *N*-allylthiourea to prevent the overestimation caused by nitrification [7]. The most probable number (MPN) of the fecal coliform (FC) was determined using Difco-A1 medium (Becton, Dickinson and Company, New Jersey, USA).

3. Experimental results and discussion

3.1. Treatment performance during continuous operation

Fig. 2(A) shows the daily variation in temperature of the incoming sewage. The temperature fluctuated between approximately 14°C and 33°C throughout the year. The temperatures of the UASB effluent and incoming sewage were approximately the same, while the DHS effluent was found to be approximately 2°C cooler than the sewage or the UASB effluent.

Fig. 2(B) shows the change in BOD over time. The mean BOD throughout the test period was 153 mg L^{-1} (standard deviation of ±58 mg L^{-1}) in the sewage and 66 (±17) mg L^{-1} in the UASB effluent. In comparison, the BOD of the DHS effluent was 5 (±4) mg L^{-1} from DHS-G3 and 7 (±5) mg L^{-1} from DHS-G6 in Phase 1, 7 (±3) mg L^{-1} from DHS-G3 and 7 (±3) mg L^{-1} from DHS-G6 in Phase 2, and 12 (±7) mg L^{-1} from DHS-G3 and 11 (±5) mg L^{-1} from DHS-G6 in Phase 3.

As mentioned above, some sludge was attached to the G3 media at the beginning of the experiment, but these media were not in contact with wastewater for 2 months. Consequently, the attached sludge was considered to be inactive. Although the continuous operation of DHS-G6 was started with no sludge attached to the G6 media, both DHS-G3 and DHS-G6 reached stable BOD treatment performances quite soon after the start of operation. This is a typical characteristic for DHS at start-up and is probably attributable to the physical elimination of organics due to adsorption and filtering [6]. Thereafter, the sludge attached to the G6 media gradually thickened, and the contribution of biodegradation to removal of BOD increased.

The BOD loading per sponge was 1.59 (±0.5) kg BOD m^{-3} sponge d^{-1} in DHS-G3 and 1.69 (±0.5) kg BOD m^{-3} sponge d^{-1} in DHS-G6 during Phase 2, and 1.10 (±0.3) kg BOD m^{-3} sponge d^{-1} in DHS-G3 and 1.17 (±0.3) kg BOD m^{-3} sponge d^{-1} in DHS-G6 during Phase 3. The effluent BOD concentrations in each DHS were somewhat worse in Phase 3 than in Phase 2, although BOD loadings were significantly lower in Phase 3 than in Phase 2 (critical region, $p < 0.05$). One of the reasons for this was probably a reduction in the activity of the attached sludge due to a 13-d period (from day 323 to day 335) during which operation of the DHS was stopped to repair a water pump. Furthermore, high ambient temperatures during this period may have desiccated the attached sludge. Nevertheless, the effluents from both DHS-G3 and DHS-G6 throughout the experimental period satisfied the Indian discharge standard for a BOD of 30 mg L^{-1}. In terms solely of BOD removal, these results clearly indicate that the discharge standard could be met by operating the reactor at a short HRT of approximately 1 h.

The geometric mean levels of FC during this experiment were 1.9×10^7 MPN 100 mL^{-1} in sewage, 1.3×10^7 MPN 100 mL^{-1} in UASB effluent, 3.2×10^4 MPN 100 mL^{-1} (Phase 1), 3.8×10^4 MPN 100 mL^{-1} (Phase 2), and 8.2×10^5 MPN 100 mL^{-1} (Phase 3) in the effluent from DHS-G3 and 3.9×10^4 MPN 100 mL^{-1} (Phase 1), 4.9×10^4 MPN 100 mL^{-1} (Phase 2), and 1.9×10^5 MPN 100 mL^{-1} (Phase 3) in the effluent from DHS-G6 (Fig. 2(C)). The mechanism of FC removal in the DHS reactor is related to inactivation of FC after adsorption into the retained sludge or predation by protozoa, as described in a previous report [4]. We expected treated levels of approximately 10^4, but levels satisfying the Indian standard for religious ablutions (1.0×10^3 MPN 100 mL^{-1}) were not achieved.

Fig. 2(D) shows the variations in NH_4^+–N over time. The mean NH_4^+–N levels throughout the experimental period were 24 (±8) mg L^{-1} for sewage (data not shown) and 26 (±7) mg L^{-1} for UASB effluent. The NH_4^+–N in the UASB effluent tended to increase after day 100 when the temperature of sewage decreased. A previous study also showed that NH_4^+–N tends to increase as sewage temperature decreases and conversely decrease as sewage temperature increases [2]. Since NH_4^+–N in the UASB effluent showed the same pattern of fluctuation, it might have been affected by variations in the temperature of the incoming sewage. While effluents from both DHS-G3 and DHS-G6 during the experimental period showed mean NH_4^+–N levels around 5 mg L^{-1} in Phases 1 and 2, these levels increased to around 14 mg L^{-1} in Phase 3. Focusing on the start-up period, NH_4^+–N levels in the effluents of DHS-G3 and DHS-G6 tended to decrease until day 25 and stabilized thereafter. This indicates that the nitrifying bacteria quickly proliferated until around day 25, contributing to the stable nitrification performance. This is attributed to the porosity of the sponge media with high void volume, which provides locations for nitrifying bacteria to attach and proliferate [5]. The deterioration in water quality in Phase 3 must also be due to the desiccation of attached sludge while the reactor operation was stopped, and to the inactivity of the nitrifying bacteria. Another potential reason for the decline in nitrification performance is the nitrifying bacteria being overwhelmed by the proliferation of heterotrophic bacteria due to operation during Phase 2 under high BOD loading conditions. On the other hand, TN removal of 30%–40% was confirmed at each phase in both reactors. Areas deep inside the sponge media may provide an anaerobic environment that is favorable for denitrifying bacteria [8,9].

Fig. 3 shows the variation in the NH_4^+–N removal vs. HRT in DHS reactors with various types of sponge media in practical-scale experiments previously conducted in Karnal, India. This figure indicates that the NH_4^+–N removal can likely be improved if the HRT is lengthened, with removal

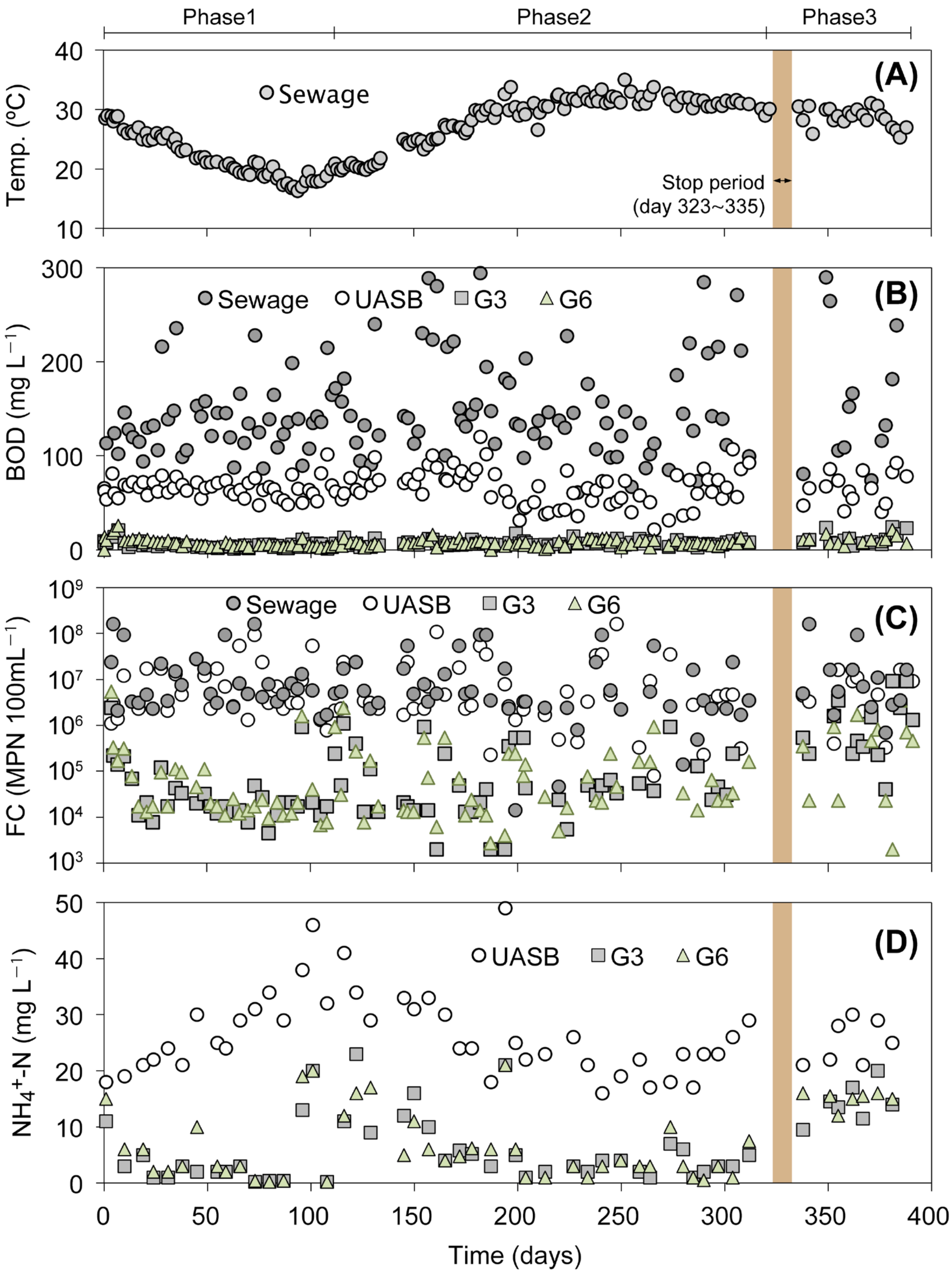

Fig. 2. Changes in sewage temperature (A), biochemical oxygen demand (BOD) (B), fecal coliform (FC) (C), and NH_4^+–N (D) during the experimental period. The brown area indicates a 13-day period (from day 323 to day 335) during which operation of the DHS reactor was stopped to repair a water pump.

levels exceeding 80% when the HRT of the DHS is controlled to be longer than approximately 1.5 h.

Moreover, an assessment of the effect of relatively low temperature on nitrification under identical BOD loading conditions in Phase 2 (water temperatures in the range 20°C–35°C) revealed a tendency for the NH_4^+–N removal to decrease as the water temperature decreases (Fig. 4). Some decreases in the NH_4^+–N removal were also observed when the water temperature was higher than 30°C, but these seem to have been due to unexpected increases in the concentration of organic compounds or of NH_4^+–N. The tendency of the nitrification to decrease during increasing organic loading or decreasing temperature has been previously reported [6].

3.2. Changes in water quality parameters in the direction of flow through the DHS

Fig. 5 shows the changes in dissolved oxygen, BOD, NH_4^+–N, and NO_3^-–N in the direction of flow through DHS-G3 and DHS-G6 between day 116 and day 213. Both DHS-G3 and DHS-G6 showed a similar tendency in all the parameters. On day 116, when the UASB effluent had a relatively high BOD of 60 mg L^{-1}, BOD decreased in a nearly linear manner from the DHS influent to the DHS effluent (water from the sixth sponge layer). On day 213, when the incoming water had the relatively low BOD of 38 mg L^{-1}, the degradation also tended to decrease linearly through the first and second layers, but the degradation pattern became more moderate in the third layer in which the BOD had decreased below 15 mg L^{-1}. The final BOD in the effluent was 5 mg L^{-1}. As seen on day 116, low-quality UASB effluent may worsen the quality of DHS effluent. Maintenance and management of the upstream UASB reactor is essential to obtain high-quality effluent by DHS treatment.

Nitrification was promoted as the concentration of organic substances decreased in the downstream direction, as noted in a previous study [10]. The NH_4^+–N removal rates of both DHS-G3 and DHS-G6 reached 0.7 kg N m^{-3} sponge d^{-1} on day 116. At the beginning of operation of DHS-G6, the reactor was filled with clean sponge media without any attached sludge, but the profile on day 116 indicated the same level of substrate degradation as in DHS-G3.

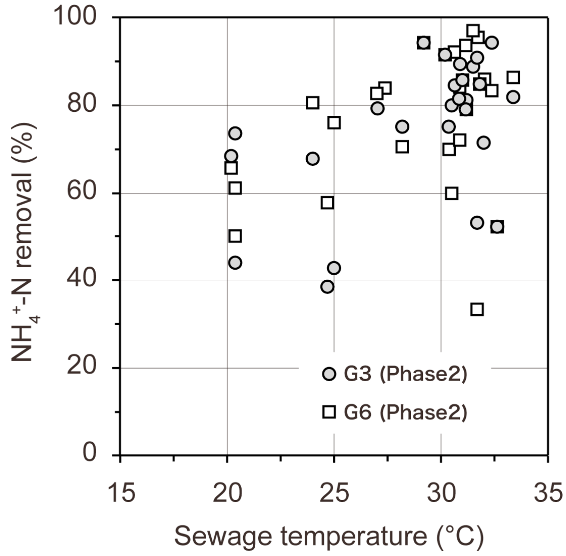

Fig. 4. Relationship between NH_4^+–N removal and sewage temperature during Phase 2 (from day 112 to day 317).

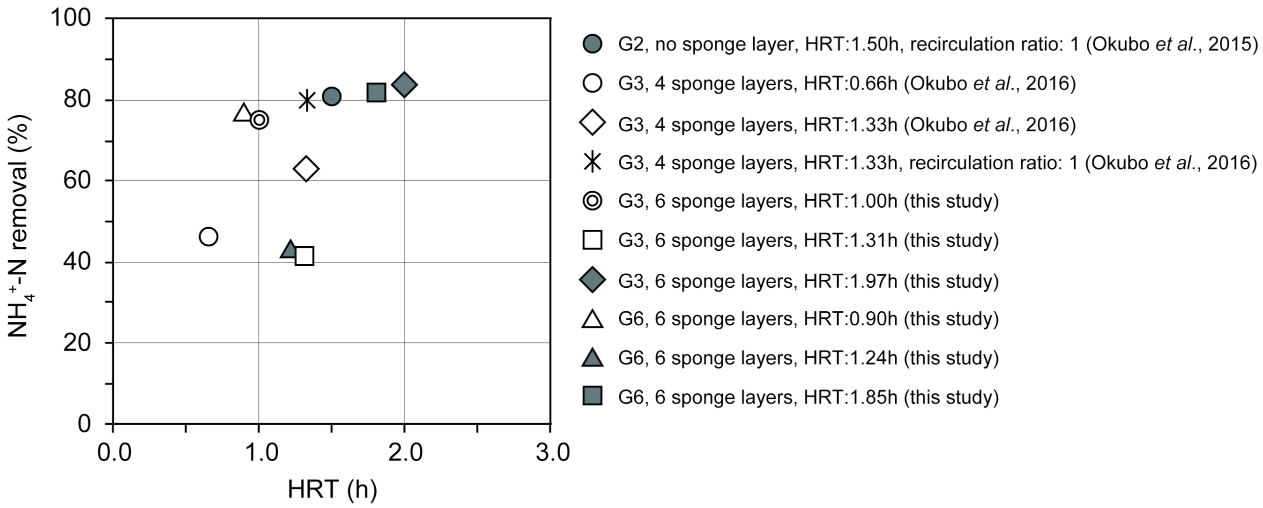

Fig. 3. Relationship between NH_4^+–N removal ratio and hydraulic retention time (HRT) obtained in experiments using practical-scale down-flow hanging sponge reactors with various types of sponge media.

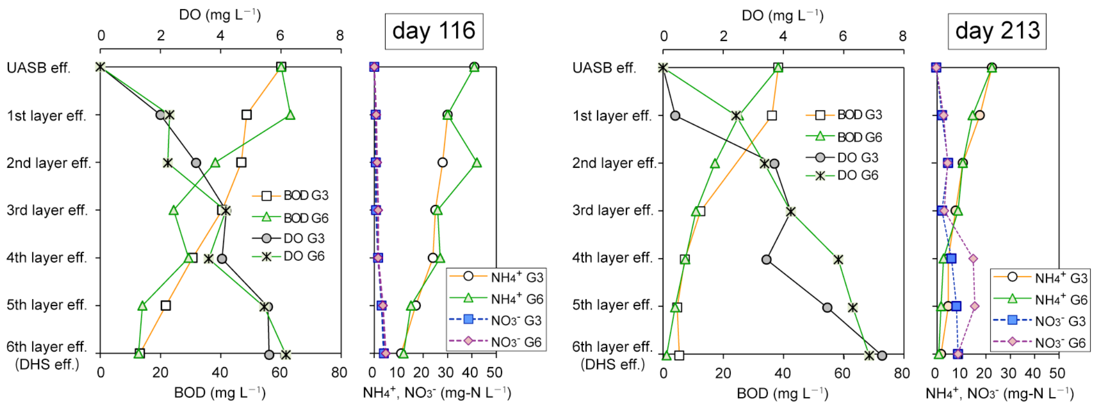

Fig. 5. Changes in water quality parameters in the downstream direction in third- and sixth-generation down-flow hanging sponge reactors (DHS-G3 and DHS-G6, respectively).

Table 1
Summary of water quality parameters during a continuous experiment using third- and sixth-generation down-flow hanging sponge reactors (DHS-G3 and DHS-G6, respectively)

Parameters	Sewage	UASB effluent	G3			G6		
			Phase 1	Phase 2	Phase 3	Phase 1	Phase 2	Phase 3
Temperature (°C)	26 (5)	26 (5)	19 (5)	26 (4)	28 (1)	19 (5)	26 (4)	28 (1)
COD_{Cr} (mg L^{-1})	402 (139)	175 (42)	25 (13)	32 (9)	40 (16)	34 (18)	34 (9)	40 (15)
BOD (mg L^{-1})	153 (58)	66 (17)	5 (4)	7 (3)	12 (7)	7 (5)	7 (3)	11 (5)
FC (MPN 100 mL^{-1})	1.9×10^7	1.3×10^7	3.2×10^4	3.8×10^4	8.2×10^5	3.9×10^4	4.9×10^4	1.9×10^5
NH_4^+–N (mg L^{-1})	24 (8)	26 (7)	4 (6)	6 (6)	14 (3)	6 (7)	6 (5)	15 (1)
NO_3^-–N (mg L^{-1})	3 (1)	2 (3)	3 (4)	11 (6)	3 (1)	6 (6)	12 (7)	3 (2)
TN (mg L^{-1})	41 (9)	39 (9)	26 (8)	30 (9)	27 (4)	30 (8)	31 (9)	29 (3)
Removal		UASB	UASB + G3			UASB + G6		
			Phase 1	Phase 2	Phase 3	Phase 1	Phase 2	Phase 3
COD_{Cr} (%)		53 (14)	93 (5)	91 (4)	89 (6)	90 (7)	91 (4)	89 (5)
BOD (%)		54 (15)	96 (4)	95 (3)	93 (3)	94 (4)	95 (3)	93 (4)
FC (log_{10})		0.5	2.4	2.2	1.1	2.3	2.1	1.6
NH_4^+–N (%)		–	84 (22)	75 (16)	36 (16)	82 (18)	77 (16)	36 (19)
TN (%)		13 (8)	40 (18)	34 (17)	34 (7)	30 (13)	30 (17)	29 (7)
BOD loading (kg BOD m^{-3} sponge d^{-1})			0.8 (0.1)	1.6 (0.5)	1.1 (0.3)	0.9 (0.1)	1.7 (0.5)	1.2 (0.3)
SS loading (kg SS m^{-3} sponge d^{-1})			0.8 (0.2)	1.5 (0.6)	0.8 (0.2)	0.8 (0.2)	1.6 (0.7)	0.9 (0.2)

Note: Numbers in parentheses represent standard deviations.

3.3. Summary of DHS-G3 and DHS-G6 treatment performances

Table 1 shows the results from this study. The listed values for sewage and UASB effluent are averages throughout the test period, while those from DHS-G3 and DHS-G6 are averages for each phase. Except for FC, the effluent quality obtained in both systems well satisfied the Indian discharge standards (BOD ≤ 30 mg L^{-1}; NH_4^+–N ≤ 50 mg L^{-1}; FC ≤ 10^3 100 mL^{-1}). The lowest concentrations of FC in this study were found under the flow rate condition of 500 m^3 day^{-1} (Phase 1); NH_4^+–N levels were also good, at approximately 5 mg L^{-1}. Therefore, the overall assessment of the removal of organics, FC, and NH_4^+–N suggests that an HRT of approximately 2 h should be an appropriate operating condition.

Analysis of variance in the effluent quality from DHS-G3 and DHS-G6 did not reveal any significant differences in any of the quality items (critical region, $p > 0.05$), indicating that DHS-G3 and DHS-G6 have similar treatment performances.

4. Conclusion

The performances of practical-scale DHS-G3 and DHS-G6 for the treatment of municipal sewage in India were evaluated simultaneously. There were no clear differences in removal of organics, FC, or NH_4^+–N between these DHS processes. The best performance was obtained at an HRT of 2 h for both DHS-G3 and DHS-G6, and the quality of the effluent from both well satisfied the Indian discharge standards for BOD and NH_4^+–N, but not FC.

Acknowledgments

This study was supported in part by research grants from the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT), the Japanese Ministry of Land, Infrastructure, Transport and Tourism (MLIT), Japan Society for the Promotion of Science (JSPS), and the Science and Technology Research Partnership for Sustainable Development (SATREPS).

References

[1] T. Okubo, T. Onodera, S. Uemura, T. Yamaguchi, A. Ohashi, H. Harada, On-site evaluation of the performance of a full-scale down-flow hanging sponge reactor as a post-treatment process of up-flow anaerobic sludge blanket reactor for treating sewage in India, Bioresour. Technol., 194 (2015) 156–164.
[2] T. Onodera, T. Okubo, S. Uemura, T. Yamaguchi, A. Ohashi, H. Harada, Long-term performance evaluation of down-flow hanging sponge reactor regarding nitrification in a full-scale experiment in India, Bioresour. Technol., 204 (2016) 177–184.
[3] S. Uemura, H. Harada, Application of UASB Technology for Sewage Treatment with a Novel Post Treatment Process, Environmental Anaerobic Technology, Applications and New Developments, Imperial College Press, London, UK, 2010.
[4] A. Tawfik, F. El-Gohary, A. Ohashi, H. Harada, Optimization of the performance of an integrated anaerobic-aerobic system for domestic wastewater treatment, Water Sci. Technol., 58 (2008) 185–194.
[5] T. Onodera, M. Tandukar, D. Sugiyana, S. Uemura, A. Ohashi, H. Harada, Development of a sixth-generation down-flow hanging sponge (DHS) reactor using rigid sponge media for post-treatment of UASB treating municipal sewage, Bioresour. Technol., 152 (2014) 93–100.
[6] T. Okubo, K. Kubota, T. Yamaguchi, S. Uemura, H. Harada, Development of a new non-aeration-based sewage treatment technology: performance evaluation of a full-scale down-flow hanging sponge reactor employing third-generation sponge carriers, Water Res., 102 (2016) 138–146.
[7] APHA, Standard Methods for the Examination of Water and Wastewater, 21st ed., American Public Health Association, Washington, D.C., USA, 2005.

[8] N. Araki, A. Ohashi, I. Machdar, H. Harada, Behaviors of nitrifiers in a novel biofilm reactor employing hanging sponge-cubes as attachment site, Water Sci. Technol., 39 (1999) 23–31.
[9] N. Ikeda, T. Natori, T. Okubo, A. Sugo, M. Aoki, M. Kimura, T. Yamaguchi, H. Harada, A. Ohashi, S. Uemura, Enhancement of denitrification in a DHS reactor by effluent recirculation, Water Sci. Technol., 68 (2013) 591–598.
[10] M. Tandukar, S. Uemura, I. Machdar, A. Ohashi, H. Harada, A low-cost municipal sewage treatment system with a combination of UASB and the "fourth-generation" downflow hanging sponge reactors, Water Sci. Technol., 52 (2005) 323–239.