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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

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ABSTRACT

A practical-scale down-flow hanging sponge (DHS) reactor using third-generation (G3) sponge carriers was applied for treatment of the effluent from an up-flow anaerobic sludge blanket (UASB) reactor treating municipal sewage. The process performance of the DHS reactor filled with G3 sponge carriers (DHS-G3) was evaluated by conducting an on-site experiment in India over one year. The performance of the DHS-G3 for removal of organic matter and ammonium-nitrogen at a relatively short hydraulic retention time (HRT) of only 0.66 h satisfied the Indian effluent quality standards except for fecal coliform. The removal rate constants for total biochemical oxygen demand (BOD) and fecal coliform determined based on the water quality profiles along the DHS-G3 almost reached equilibrium approximately four months after the start of operation, i.e., 2.45 h^{-1} for BOD and 2.30 h^{-1} for fecal coliform, respectively. The oxygen utilization activity of retained sludge was determined to assess the distribution of heterotrophic and autotrophic bacteria along the DHS-G3. Nitrification was promoted in the lower portion of the DHS-G3 reactor in the duration with low organic load, while it decreased when the organic load was increased, probably due to proliferation of heterotrophic bacteria.

1. Introduction

The activated sludge process, currently the most popular method for wastewater treatment, consumes enormous quantities of energy, 70% of which is used for aeration (Fayolle et al., 2007). In contrast, the up-flow anaerobic sludge blanket (UASB) reactor is an economical treatment process that requires no power for aeration, and is becoming a core process in developing countries in tropical and subtropical regions (Sperling et al., 2008). UASB reactors built in India are designed for a hydraulic retention time (HRT) of 8.5 h and have ponds downstream for polishing the UASB-treated water (designated in India as “Final Polishing Units”, FPUs; design HRT = 24 h). However, water treatment by the UASB-FPU combined systems has been unable to satisfy current Indian effluent quality standards (Okubo et al., 2015). The FPU also requires very large areas of land (Sato et al., 2006). Thus, the FPU process cannot really be called an optimal post-treatment technology.

Our research group has been conducting basic research since the latter 1990s on the down-flow hanging sponge (DHS) process as an efficient post-treatment technology that does not detract from the economic superiority of UASB. To date, after improvements to the shape of the sponge carrier and to the filling method, the concept has evolved from its first generation (G1) to the sixth generation (G6) (Tandukar et al., 2007; Onodera et al., 2014). Parallel to those experiments, full-scale DHS reactors have been constructed in a sewage treatment plant in India, and verification tests have been conducted under local environmental conditions (Okubo et al., 2015; Onodera et al., 2016).

DHS is an aerobic biological treatment method that employs polyurethane sponges, which can be manufactured in developing

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countries, as the carrier for retaining the bacteria. The reactor is filled with these carriers in a way that exposes them to air. The water then trickles down through the sponges, facilitating aerobic conditions. In a continuous long-term experiment of a DHS reactor using the second-generation, curtain-type sponge carrier (G2) in India, this reactor (DHS-G2) was shown to be very economical and to achieve high performance in removal of organic matter and nitrogen (Okubo et al., 2015; Onodera et al., 2016).

However, DHS-G2 had some disadvantages that made it unworkable; (1) to make a sponge module, the triangle sponge bars must be tilled on both sides of the plastic sheets, (2) a hook attached to the upper part of each sponge module must be hung on a bar that is equipped to the upper part of the reactor column, (3) multiple iterations of tilling sponges and hanging the hooks are time-consuming and increase costs, and (4) because the bars and hooks are always exposed to UASB-treated sewage, corrosion is inevitable, leading to failure of the sponge modules.

To overcome these drawbacks of the G2 carrier, a third-generation (G3) carrier was developed, which is cylindrical in shape and is composed of polyurethane sponge supported by a polyethylene plastic net to prevent compaction of the sponge. The DHS-G3 reactor only requires filling the reactor column with the G3 carriers (Tawfik et al., 2008).

Thus, in this study, a full-scale DHS-G3 reactor was installed at an Indian sewage treatment plant site and continuously monitored. The characteristics of the DHS-G3 reactor at the start of operation were identified, and the reduction rate constants of biochemical oxygen demand (BOD) and fecal coliform (FC) were calculated using the profile along the main axis of the reactor with respect to time elapsed. The distribution of heterotrophic and autotrophic bacteria along the DHS-G3 was clarified by determining the oxygen utilization activity of retained sludge on different substrates. The reactor was also operated with recirculation during an experimental period at increased load, and its capabilities under these conditions were compared and evaluated.

2. Material and methods

2.1. Full-scale DHS-G3 reactor

Prior to this experiment, a long-term continuous experiment was carried out using DHS-G2 constructed at a sewage treatment plant in Karnal, India (Okubo et al., 2015; Onodera et al., 2016). The reactor was then replaced with G3 carriers, and operation was restarted. Fig. 1 shows an overall view of the full-scale reactor and a view of the reactor interior after it had been filled with the carriers. The reactor portion of the DHS reactor consisted of a concrete cylinder (5.5 m in diameter and 5.31 m in height) with an empty capacity of 126 m^3. A clarifier was installed under the reactor. The reactor interior was vertically divided into four layers by reinforcement frames and nets. The four layers were equally filled with the G3 sponge carriers. In a previous study, we incorporated 33 and 38 ventilation windows measuring 0.2 m $\times$ 0.3 m into the middle and lower sections of the concrete cylinder, respectively. In this study, we increased the number of ventilation holes to 104, which were incorporated between the sponge layers to provide more ventilation to the reactor interior.

The DHS influent (i.e., UASB effluent) was pumped to the top of the reactor, and the water was uniformly sprayed onto the sponge carriers at the top of the reactor from a moving sprinkler, which rotated by the water head differential. The rotational speed of the sprinkler head was set to 8.5 rpm by adjustment of a valve in the sprayer nozzle. After sprinkling, the UASB effluent flowed downward through the sponge carriers under the force of gravity, passed into the clarifier, and flowed out as DHS effluent after it passed through the basin.

Fig. 2a is a diagram of the structure of the G3 carrier showing its dimensions. The G3 sponge carrier is cylindrical, 32 mm in diameter and 32 mm long, and is composed of polyurethane sponge supported by a polyethylene plastic net to prevent compaction of the sponge (specific surface area: 1.87 cm^2 cm^{-3}). Fig. 2b shows a close-up photograph of the polyurethane sponge. The long and short axes of 100 of the sponge pores were measured, and the mean value was 0.46 (standard deviation: $\pm$0.10) mm.

A total of 1,076,000 of the G3 sponges were loaded into the reactor to equally fill the four layers (269,000 $layer^{-1}$). The height of each layer was approximately 600 mm. Gaps measuring 450–700 mm were left between each layer to allow ingress of oxygen into the down-flowing water. The total effective sponge volume was 27.7 m^3 (91.1 m^2 m^{-3} reactor working volume). Thus, relative to the empty volume (126 m^3) of the DHS reactor, the sponge filling accounted for 22.3% (the sponge filling ratio relative to the effective reactor volume in each layer was 48.6%).

Table 1 presents the operating conditions for the DHS reactor. Three conditions were employed to observe the effect of recirculation and increased load on treatment performance. Since the UASB effluent is mixed with a part of the treated water at a reservoir just before the sprinkler due to recirculation, the influent of the DHS is expected to contain much more dissolved oxygen (DO). Therefore, it was predicted that this would have a beneficial effect

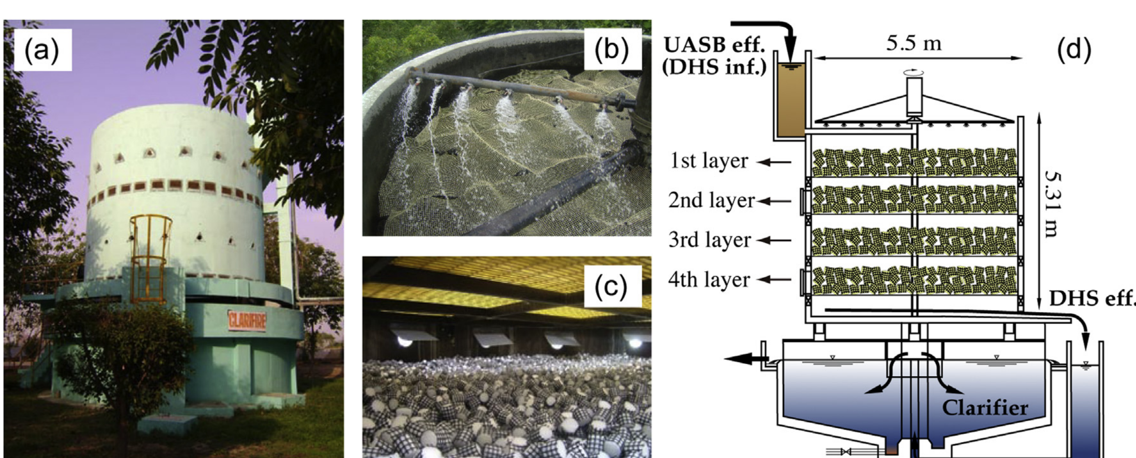

Fig. 1. Photographs of the entire reactor (a), the distribution device (b), the reactor filled with sponge carriers (c), and a schematic diagram of the DHS reactor (d).