

Evaluating the resilience of a full-scale down-flow hanging sponge reactor to shock-loadings

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ABSTRACT

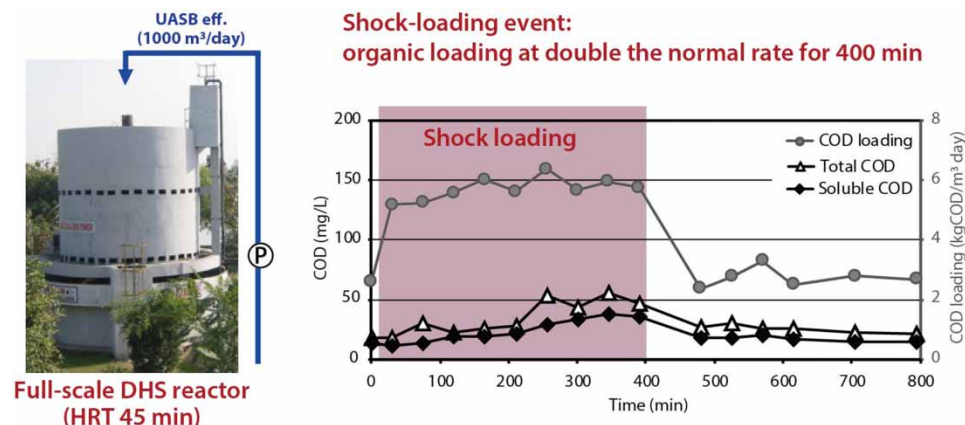
The effect of shock-loading on the performance of a full-scale down-flow hanging sponge (DHS), used to treat effluent from an up-flow anaerobic sludge blanket treating municipal sewage, was evaluated. This full-scale DHS reactor comprises a polyurethane sponge that retains the sludge. It has a capacity of 500 m³/day and, at the time of this study, had been operating at a sewage treatment plant in India for more than 1,300 days. The DHS reactor was exposed to shock loadings of organics at double the normal rate for 400 min under summer and winter conditions. The results showed that the DHS reactor maintained stable operation under the organic shock loading and that it returned to a steady state soon after restart, confirming that the reactor was resilient to organic shock loadings.

Key words: developing countries, down-flow hanging sponge (DHS), sewage treatment, shock-loading, UASB post-treatment

HIGHLIGHTS

- A full-scale down-flow hanging sponge reactor was evaluated in India.
- The DHS reactor was exposed to double organic rate for 400 min.
- The DHS reactor produced stable effluent quality under shock loadings.
- The DHS achieved a steady state soon after shock loadings under summer and winter.
- The full-scale experiment verify that the DHS was resilient to shock-loadings.

GRAPHICAL ABSTRACT



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INTRODUCTION

Appropriate wastewater treatment is a challenge for developing countries where budgets, technical skills, and land are limited. There is an urgent need to install treatment systems that will neither fail nor cause problems in the future. In recent years, up-flow anaerobic sludge blankets (UASB) and post-treatment processes have been combined and widely used to treat sewage in developing countries (Kassab *et al.* 2010; Chernicharo *et al.* 2015; Mai *et al.* 2018).

The down-flow hanging sponge (DHS) reactor has shown promise as a post-treatment process (Kassab *et al.* 2010; Hatamoto *et al.* 2018; Tyagi *et al.* 2021). The configuration of a DHS reactor is similar to that of a trickling filter, except that the packing material in a DHS reactor is polyurethane sponge. The sponge media is a unique feature of the DHS reactor (Agrawal *et al.* 1997; Machdar *et al.* 2000; Tawfik *et al.* 2006; Onodera *et al.* 2013). Researchers have been studying the performance of DHS reactors for more than two decades (Hatamoto *et al.* 2018; Tyagi *et al.* 2021). Tandukar *et al.* (2007) found that the quality of the effluent from the DHS process was comparable to that from the activated sludge process, while Tanaka *et al.* (2012) found that the performance of a pilot-scale DHS reactor with a flow rate of 50 m³/day was better than that of the activated sludge process, and that it used approximately 75% less energy and produced 85% less excess sludge. DHS reactors have been successfully trialed at the pilot scale in Thailand (Onodera *et al.* 2014a; Miyaoka *et al.* 2017a). Full-scale DHS reactors have performed well with a flow rate of 500 m³/day over more than 1,800 days (Okubo *et al.* 2015, 2016; Onodera *et al.* 2016a, 2016b) and with flow rates of between 1,000 and 5,000 m³/day over periods of more than 600 days (Nomoto *et al.* 2017).

The polyurethane sponge used in the DHS reactor is insoluble, non-biodegradable, low cost, and mechanically stable. It has a void ratio of more than 95%, which means that it provides a three-dimensional space on which biomass can grow and be retained within the reactor. Because of these unique characteristics, it differs from the stone and plastic media used in trickling filter systems, and can retain wastewater for longer than a trickling filter using modular or random plastic media (Onodera *et al.* 2014b). The dissolved oxygen (DO) content of the sewage remains high as it passes through the sponge media inside the reactor because the oxygen is supplied naturally from the atmosphere. Studies have shown that the sponge media can retain sludge at a concentration of approximately 20–30 g VSS/L sponge, which is considered high (Machdar *et al.* 2000; Tandukar *et al.* 2005; Onodera *et al.* 2013). Despite the high sludge concentration, the sewage flows smoothly through the sponge media with biomass, and does not block inside the sponge media or pond in the reactor. This means that there is no need for reactor backwashing during operation and maintenance, because there is a balance between accumulation and degradation under long sludge retention times (SRTs) (Onodera *et al.* 2013), with degradation resulting from the low food/microorganism ratio, high endogenous respiration, and high density and diversity of high trophic organisms (Onodera *et al.* 2013). Molecular surveys have confirmed that the populations of eukaryotes in this type of sludge are very diverse (Matsunaga *et al.* 2014; Miyaoka *et al.* 2017b; Onodera *et al.* 2021).

To guarantee that a DHS reactor will operate successfully over the long term, the treatment system must be sufficiently robust to cope with shock loadings. For instance, in developing countries, power outages can occur frequently (Onodera *et al.* 2016b) and sewage treatment processes must cope with high loadings in subsequent operations. Previously, researchers have evaluated how shock loadings affected the process performance using lab-scale DHS reactors (Tandukar *et al.* 2006b). However, there is little knowledge of how full-scale DHS reactor performance is affected by shock loadings and this remains a key area for research.

The aim of this study was to evaluate the resilience of a full-scale DHS reactor in a sewage treatment plant in India to shock loadings. The reactor was exposed to shock loadings of organics at double the normal rate for 400 minutes under summer and winter conditions. The process performance was evaluated with respect to organics removal and nitrification.

METHODS

Reactor configuration

The full-scale DHS reactor was set up at a sewage treatment plant in Karnal, India. The sewage treatment plant comprises a UASB reactor and a stabilization pond. The effluent from the UASB reactor is the influent for the DHS reactor. The configuration of the UASB and the stabilization pond are reported in detail elsewhere (Okubo *et al.* 2015; Onodera *et al.* 2016a).

The structure of the DHS reactor is shown in Figure 1. It comprised a concrete column, 5.5 m high and 5.3 m in diameter, with a rotary distributor at the top. The sponge medium was the hanging curtain type, made by tiling polyurethane sponge bars (triangular prism: 25 mm) onto both sides of a plastic sheet, the upper part of which was reinforced with plastic bars and hooks. The sponge bars were horizontally tiled on the sheets in the upper and lower sponge modules at intervals of 10 and 15 mm, respectively. The sponge curtains (sponge medium) were hung at suitable intervals to allow fresh air to flow through the open spaces between them. The sponges in the upper and lower sponge modules had a total volume of 31.1 m³, and occupied volumes of 12.6 and 18.5 m³, respectively – 24.7% of the total reactor volume. Void spaces comprised 98% of the polyurethane sponge (Onodera *et al.* 2016a).

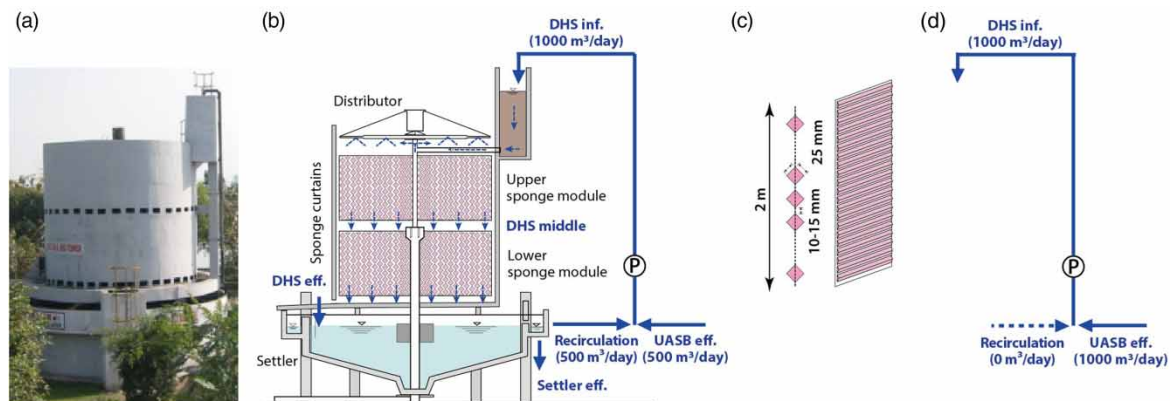


Figure 1 | Schematic diagram of the full-scale DHS reactor: (a) overview, (b) schematic diagram and flow under normal conditions, (c) sponge curtain, (d) flow under shock-loading.

Operational conditions

The full-scale DHS reactor was operated under ambient temperature conditions and fed with influent wastewater at 1,000 m³/day. The influent was a 50:50 mixture of UASB and DHS effluents (recirculation ratio: 100%). The flow rate of the UASB effluent was 500 m³/day. The DHS effluent was recirculated to the DHS reactor at a rate of 500 m³/day. The influent wastewater (UASB effluent and DHS effluent) was supplied to the DHS reactor by the distributor and then flowed down through the sponge modules. The DHS reactor was operated at an HRT of 1.5 hours, based on the sponge volume. Before the shock-loading experiment, the DHS had been operating successfully. The details of the DHS reactor have been reported elsewhere (Okubo *et al.* 2015; Onodera *et al.* 2016a).

Shock-loading event

The shock-loading event was carried out under summer and winter conditions, when the wastewater was at temperatures of 30 and 18 °C, respectively. For the shock-loading experiment, the recirculation of the DHS effluent was stopped, meaning that the influent wastewater consisted of UASB effluent without DHS effluent. The flow rate was 1,000 m³/day and the HRT 0.75 hours. The organic loading rate (OLR) was approximately twice the normal OLR. The shock-loading was carried out for 400 minutes. The UASB and DHS effluents were sampled at intervals before and after shock-loading. The changes in water quality at different heights in the reactor before, during, and after shock-loading was determined at –0, 180 and 530 minutes, respectively.

Water quality analysis

The temperature, pH, and DO were measured immediately after sampling. The pH was measured using a meter (B212, Horiba, Kyoto, Japan). The COD (dichromate approach), ammonium nitrogen (NH₄⁺-N), and nitrate nitrogen (NO₃⁻-N) contents were determined using a water quality analyzer (DR-890, Hach, Loveland, Colorado, USA). Soluble samples were obtained by filtering through a glass filter (0.4 µm, GB-140, Advantec, Tokyo). The DO content was measured using the titration method (APHA 1998).

RESULTS

Changes in water quality during the shock-loading event

The resilience of the full-scale DHS reactor to the shock loading was evaluated under stable operating conditions. The effluent quality from the DHS reactor during and after shock loading in the summer is shown in Figure 2. The effluent quality and removal efficiency were summarized in Table 1. In the summer, the average total and soluble COD concentrations of the DHS effluent for the month before the shock loading were 26 (standard deviation ± 4) and 14 (± 5) mg/L, respectively. Under shock loading, the total and soluble COD concentrations in the

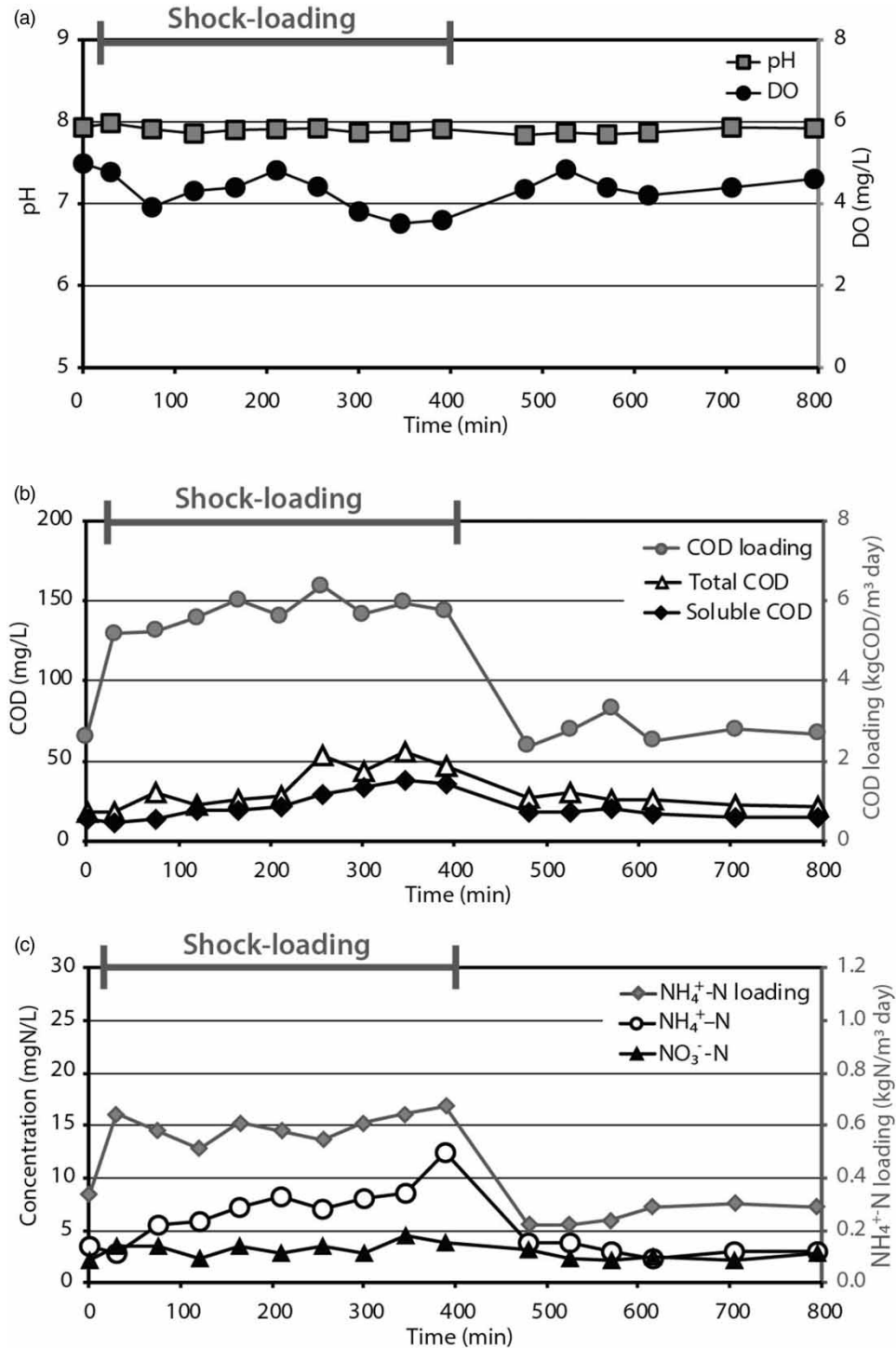


Figure 2 | Changes in the effluent quality in response to the shock loading in summer: (a) pH and DO, (b) COD and (c) nitrogen compounds.

Table 1 | Summary of the water quality and removal efficiency before, during, and after the shock-loadings. Normal condition: one month before the shock-loadings. After shock-loadings: 400 min after the shock-loadings.

		Total COD (mg/L)		Removal (%) by DHS	Soluble COD (mg/L)		Removal (%) by DHS	NH ₄ ⁺ -N (mg/L)		Removal (%) by DHS
		UASB eff.	DHS eff.		UASB eff.	DHS eff.		UASB eff.	DHS eff.	
Summer	Normal conditions	159	26	83.1	87	14	84.0	22.2	3.2	85.8
	Shock loading	177	36	79.9	91	25	73.2	18.7	7.3	60.9
	After shock loading	170	26	84.7	83	17	79.3	16.3	3.2	79.9
Winter	Normal conditions	227	49	77.9	105	29	72.7	32.8	8.5	73.9
	Shock loading	210	72	65.6	107	37	65.2	31.9	18.2	44.8
	After shock loading	253	63	75.2	114	30	74.0	31.5	15.5	50.8

DHS effluent were up to 56 and 38 mg/L, respectively. The total and soluble COD removal efficiencies of the DHS reactor therefore decreased from 83% to 80% and from 84% to 73%, respectively. The NH₄⁺-N concentration in the effluent for the month before the shock loading was 3.2 (± 0.9) mg/L but was 12.5 mg/L during shock loading, meaning that the removal efficiency of NH₄⁺-N decreased from 86% to 61%. Even though the influent loading of 5.7 kgCOD/m³ day was higher than previously (2.6 kgCOD/m³ day), the effluent quality remained at a suitable level and the total COD level in the effluent was maintained for between 250 and 400 minutes after shock loading started. The results suggest that the DHS reactor can deal with higher loadings of COD and NH₄⁺-N than those received under normal operating conditions. The effluent quality also returned to the pre-shock loading levels after shock loading finished, which shows that the DHS reactor was very resilient to the high organic loading rates and recovered quickly after 400 minutes of shock loading.

The quality of the effluent from the DHS reactor during and after shock loading in the winter is shown in Figure 3. The removal efficiencies of COD and NH₄⁺-N were lower in winter than summer. The average total and soluble COD concentrations in the effluent before shock loading were 49 (± 7) and 29 (± 7) mg/L, but were 72 and 37 mg/L during shock loading, respectively, so the removal efficiencies of total COD and soluble COD decreased from 78% to 66%, and from 73% to 65%, respectively. The NH₄⁺-N concentration in the DHS effluent increased from an average of 8.5 (± 3.0) mg/L before shock loading to 18.2 mg/L during shock loading, and the removal efficiency decreased from 74% to 45%. As in the summer, the COD removal efficiency recovered soon after shock loading ended, but the NH₄⁺-N removal efficiency only reached normal levels 400 minutes after shock loading ended. The DHS performance during shock loading seems to be more sensitive in winter than summer, suggesting an influence of temperature.

Removal efficiency and removal rate

The loading and removal rates for total COD and NH₄⁺-N during the summer period are shown in Figure 4, and were determined before, during, and after shock loading. The removal rates for total and soluble COD were 2.14 (± 0.39) and 1.17 (± 0.15) kg COD/m³ day before the shock loading, respectively. During shock loading, the respective removal rates increased to 4.54 and 2.13 kg COD/m³ day. The results clearly show that the total and soluble COD removals of the DHS reactor were enhanced during the shock loading event. The NH₄⁺-N removal rates before and during shock-loading were 0.31 and 0.36 kg N/m³ day, respectively.

The loading and removal rates of total COD and NH₄⁺-N during the winter period are shown in Figure 5. As in the summer, the removal rates of total COD, soluble COD, and NH₄⁺-N increased during shock loading. The removal rates of total COD, soluble COD, and NH₄⁺-N ranged from 2.85 to 4.42 kg COD/m³ day, 1.23 to 2.24 kg COD/m³ day, and from 0.39 to 0.44 kg N/m³ day under normal and shock-loading conditions, respectively. As in the summer, the COD removal rate was approximately twice the rate during normal operation. The NH₄⁺-N removal rate was higher in the winter than summer, perhaps because the NH₄⁺-N concentration in the influent was higher in winter.

Water quality in the DHS reactor

The water quality at different heights in the reactor during summer and winter is presented in Figures 6 and 7. The pH and DO are shown in figures (A), (B), and (C) and the COD, NH₄⁺-N, and NO₃⁻-N in (D), (E), and (F). The

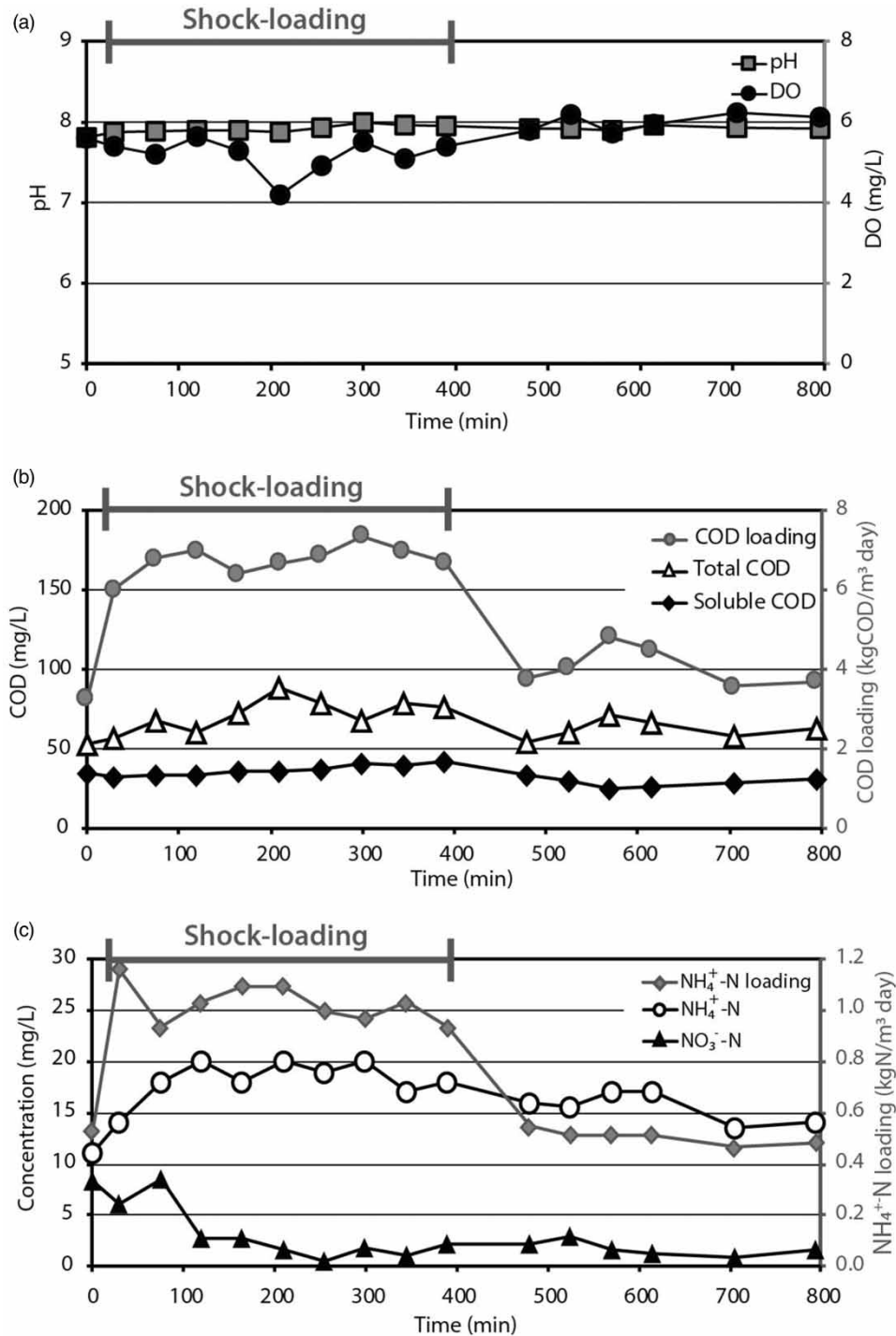


Figure 3 | Changes in the effluent quality in response to the shock-loading in winter: (a) pH and DO, (b) COD and (c) nitrogen compounds.

water quality was compared before, during, and after shock-loadings. During shock-loadings, the influent consisted of UASB effluent only.

In the summer, the DO concentration was more than 3 mg/L in the middle section of the DHS reactor, even though there was no DO in the DHS influent (Figure 6(a)–6(c)). Despite the higher loading rate during shock loading, the DO concentration in the middle section was similar to normal conditions. The change in COD shows that most of the organic matter was removed in the upper section of the reactor during normal conditions (Figure 6(d)–6(f)). Although the influent COD concentration was approximately double the normal concentration, the COD concentration in the middle section was similar under normal and shock loading conditions

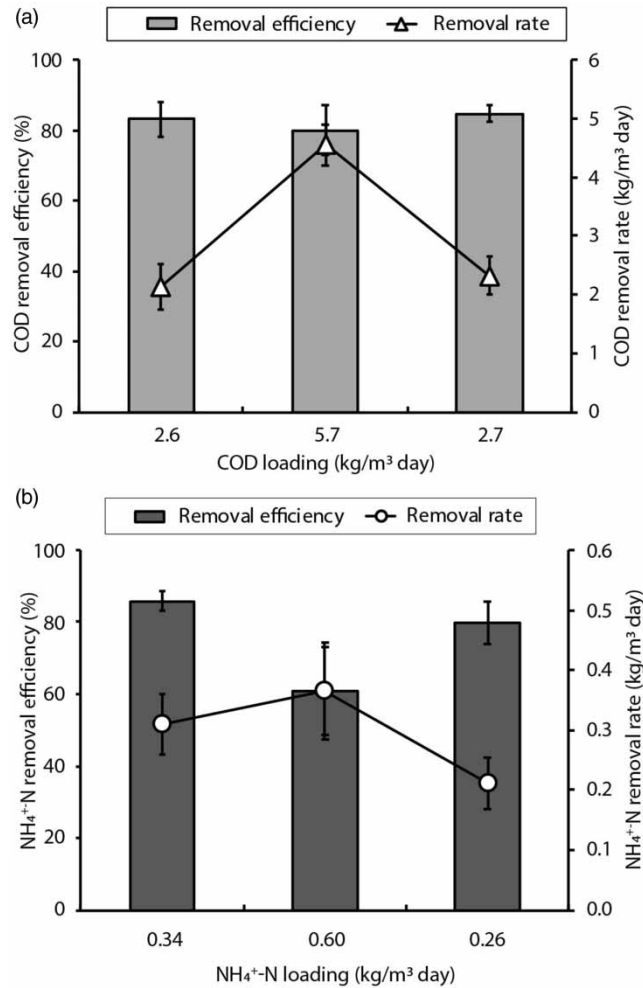


Figure 4 | Removal efficiency and removal rates during normal and shock loading conditions in summer: (a) COD and (b) NH₄⁺-N.

(Figure 6(e)). This indicates that the upper module of the DHS reactor was capable of dealing with high organic loadings. The NH₄⁺-N was removed through the upper and lower modules of the DHS reactor under normal conditions (Figure 6(d) and 6(f)). The NH₄⁺-N in the DHS effluent during shock loadings was relatively higher than under normal conditions (Figure 6(e)).

In the winter, the DO concentration exceeded 5 mg/L in the middle section of the DHS reactor irrespective of shock loadings (Figure 7(a)–7(c)). The COD concentration in the middle section increased, meaning that the organic loading imposed on the lower module of the DHS reactor increased (Figure 7(e)). The reactor's lower module effectively removed the organic component during shock loading, and may have helped to maintain the effluent quality then. NH₄⁺-N was also removed through the upper and lower modules during shock loading (Figure 7(d)–7(f)). The NO₃⁻-N in the effluent was lower than NH₄⁺-N removed in the DHS. Thus, some NO₃⁻-N may be removed by denitrification. This decrease in NO₃⁻-N could be attributed to denitrification deep within the sponges under anoxic conditions (Araki *et al.* 1999).

DISCUSSION

Results show that the effluent COD concentration was comparable during shock loading event and in normal operation. The results also show that the DHS returned to a steady state soon after normal operation resumed. In addition, the results suggest that the DHS reactor could operate effectively with higher loadings under normal operating conditions.

The reactor's high resilience to shock loading might be attributed to its characteristics. It has a high potential for DO uptake without using forced ventilation or an aerator (Machdar *et al.* 2000; Onodera *et al.* 2014b). The

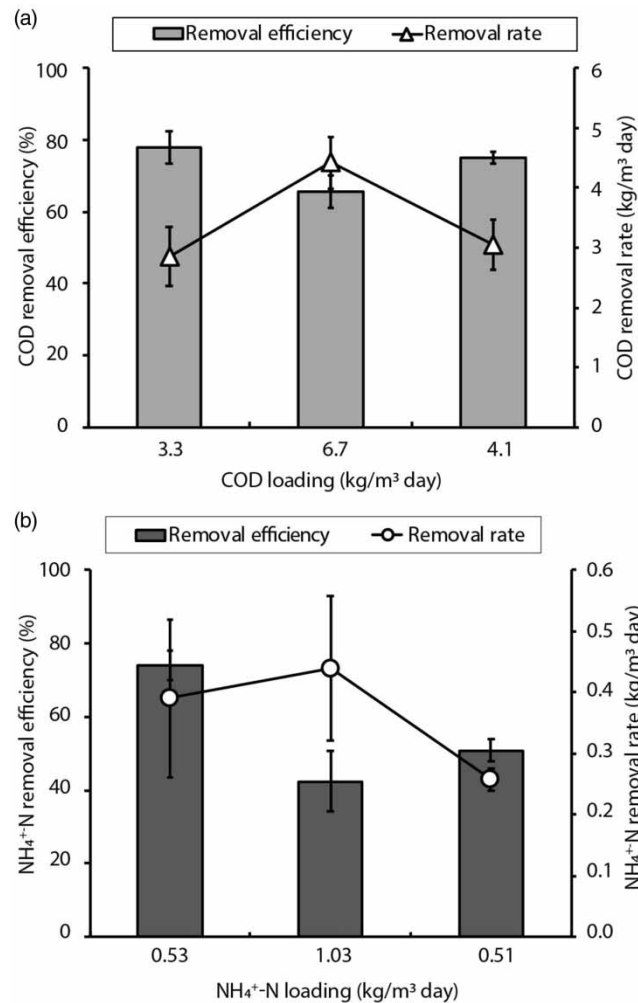


Figure 5 | Removal efficiency and removal rates in normal and shock-loading conditions in winter: (a) COD and (b) NH₄⁺-N.

sludge concentration within the sponge media is also high (Tandukar *et al.* 2005; Onodera *et al.* 2013) and the long HRT for both the retained sludge and wastewater meant enhanced contact (Tandukar *et al.* 2006a; Onodera *et al.* 2014b).

Under shock loading, the DO concentrations were 3 mg/L in the middle section of the DHS and in its effluent (Figures 6 and 7(b)). This indicates that the DO was high enough even though the organic concentrations were doubled. The DO concentration is important for aerobic organisms that carry out the organic removal and nitrification. Even with low microbial activity, the DO concentration was much higher during winter than summer (Figures 2 and 3(a)). A previous experiment showed that the DO concentration affected process performance, particularly nitrification (Onodera *et al.* 2014b). Therefore, the high potential for DO uptake may lead to higher organic and ammonium removal efficiencies even under shock-loading conditions.

The sludge concentration was high in the sponge media inside the DHS reactor. While the concentration of the influent entering the DHS was relatively low and stable during the entire experimental period, the sludge concentrations in the sponge ranged from 23 to 46 g VSS/L sponge (Onodera *et al.* 2016a). Higher sludge concentrations result in lower food/microorganism ratios and higher SRTs (Tandukar *et al.* 2006a). We assumed that fluctuations in the influent concentrations were tolerated because of the high sludge concentration.

The shock loading was conducted on a temporary basis to evaluate the resilience of the DHS reactor to an increased organic loading rate from day 1,358 to day 1,523 – that is, 165 days. We believe that the data obtained in the full-scale reactor were reliable and represented a real-life scenario. At pilot scale, DHS reactors are tolerant to hydraulic shock loadings (Tandukar *et al.* 2006b). Also, process outages in developing countries are often caused by facility inspections, handling accidents, and power cuts, so the system must be sufficiently robust to cope with process outages. A previous study verified that the DHS reactor could withstand a 10-day outage

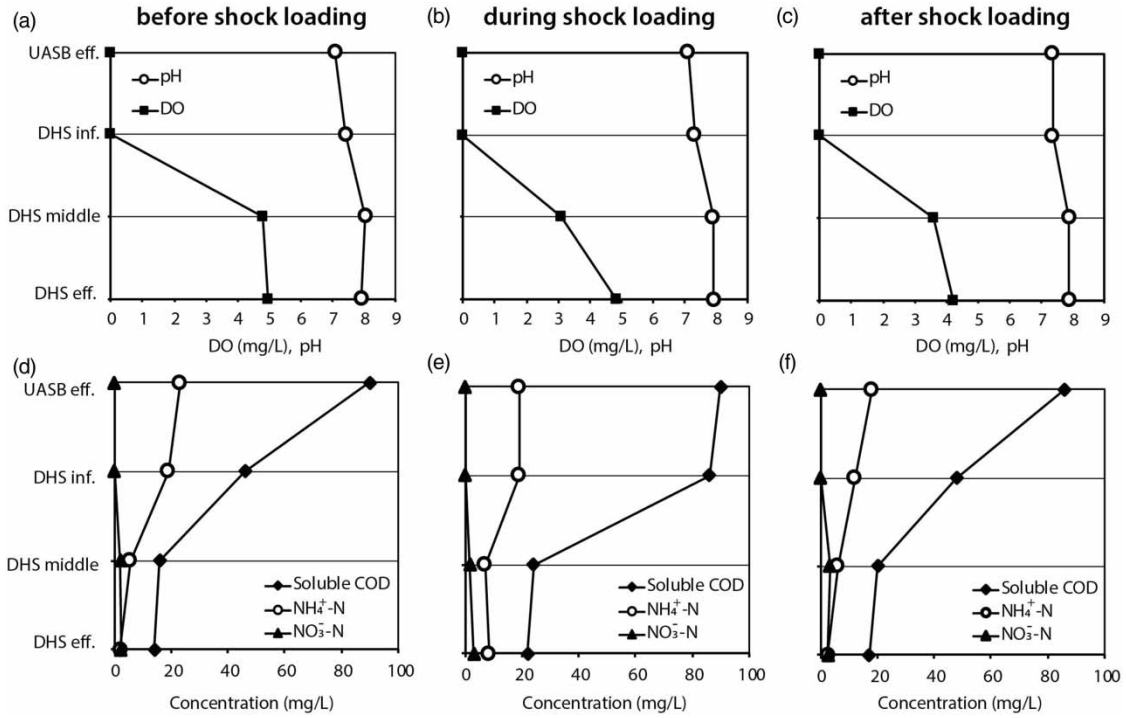


Figure 6 | Changes in the water quality at different heights in the full-scale DHS reactor in summer: (a) pH and DO before shock loading, (b) pH and DO during shock loading, (c) pH and DO after shock loading, (d) soluble COD and nitrogen compounds before shock loading, (e) soluble COD and nitrogen compounds during shock loading, (f) soluble COD and nitrogen compounds after shock loading. The changes in water quality at different heights in the reactor before, during, and after shock loading was conducted at -0, 180 and 530 minutes, respectively.

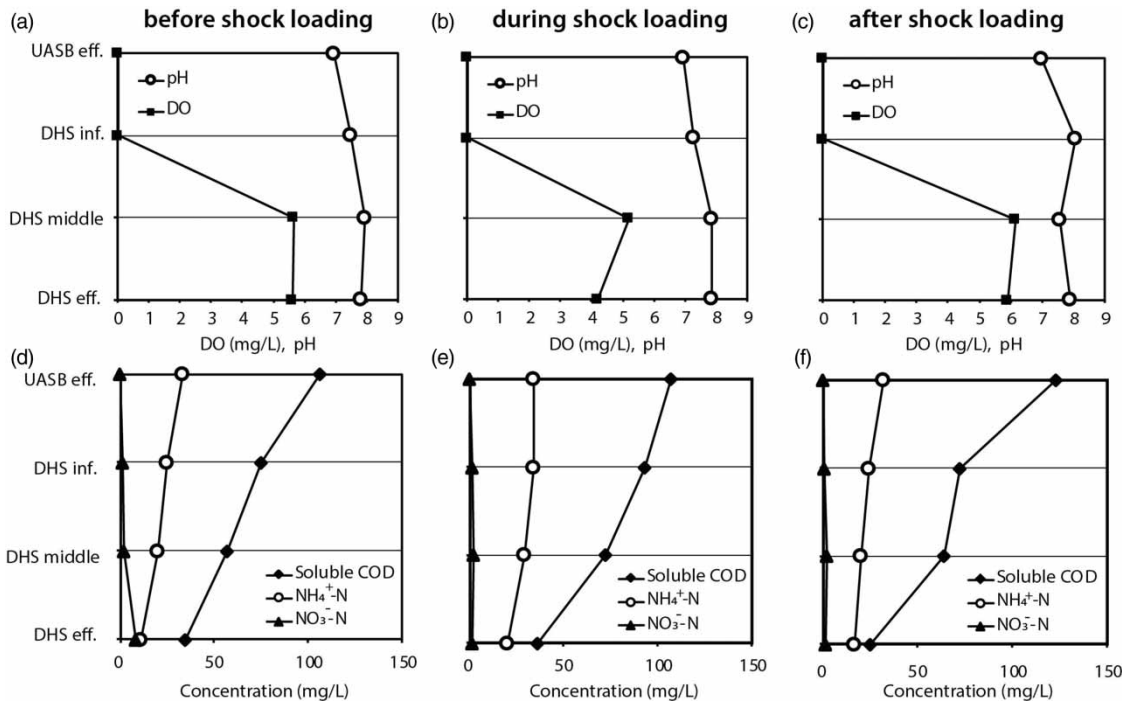


Figure 7 | Changes in water quality at different heights in the full-scale DHS reactor in winter: (a) pH and DO before shock loading, (b) pH and DO during shock loading, (c) pH and DO after shock loading, (d) soluble COD and nitrogen compounds before shock loading, (e) soluble COD and nitrogen compounds during shock loading, (f) soluble COD and nitrogen compounds after shock loading. The changes in water quality at different heights in the reactor before, during, and after shock loading was conducted at -0, 180 and 530 minutes, respectively.

(Onodera *et al.* 2016b). Upon restarting after a power outage, it is assumed that the volume of influent sewage and loadings would be higher than under normal conditions. This study verifies the high tolerance of full-scale DHS systems for shock loadings, so its results and those of other previous studies (Okubo *et al.* 2015; Onodera *et al.* 2016a) show that a DHS reactor can be added to sewage treatment systems in developing countries, as a sustainable sewage treatment process, to solve sanitation problems. The resilience of different types of sewage treatment processes in developing countries could be assessed and compared in future studies.

CONCLUSIONS

A full-scale DHS reactor was exposed to a double loading of organics for 400 minutes under summer and winter conditions at a sewage treatment plant in India. The reactor remained stable and achieved a steady state soon after it was restarted. The results show that this system is resilient to fluctuating conditions.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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