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Enhanced denitrification in Downflow Hanging Sponge reactors for decentralised domestic wastewater treatment

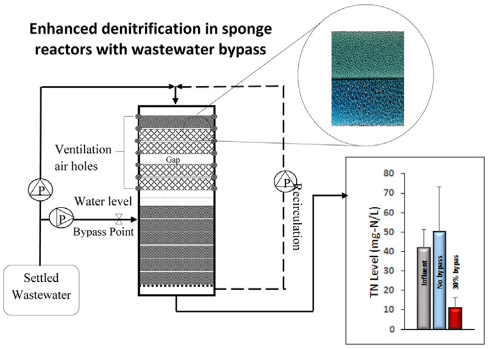
Catherine A. Bundy [a,1], Dong Wu [a,b,1], Mui-Choo Jong [a,1], Stephen R. Edwards [a], Ziauddin S. Ahammad [c], David W. Graham [a,*]

[a] *School of Civil Engineering & Geosciences, Newcastle University, Newcastle upon Tyne, United Kingdom*
[b] *Key Laboratory for Urban Ecological Processes and Eco-Restoration, School of Ecological and Environmental Science, East China Normal University, Shanghai, China*
[c] *Department of Biochemical Engineering and Biotechnology, Indian Institute of Technology Delhi, Hauz Khas, New Delhi, India*

HIGHLIGHTS

- Past Downflow Hanging Sponge (DHS) designs have displayed limited denitrification.
- Poor denitrification occurs due to C-limitation and excess DO in lower sponges.
- A raw wastewater bypass was introduced to provide additional C and reduce DO.
- COD and TN removal rates of >84% and ~74% were achieved with a 30% v/v bypass.
- DHS reactors with bypass are suitable for decentralised treatment applications.

GRAPHICAL ABSTRACT



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ABSTRACT

Enhanced aerobic/anoxic Downflow Hanging Sponge (DHS) bioreactors were assessed for carbon (C) and total nitrogen (TN) removal for decentralised domestic wastewater treatment applications. The initial design included upper aerobic and lower anoxic sponge layers, and effluent recirculation, and achieved >80% COD_s and >90% NH_4-N removal. However, effluent TN was higher. It was concluded the anoxic layer was C-limited for denitrification, therefore an influent bypass was added to the anoxic layer to provide supplemental C. Differed bypass ratios were compared, including 0%, 10%, 20% and 30% (% of total influent), and effluent TN declined with increasing bypass; i.e., 50.1 ± 23.3 mg-N/L, 49.9 ± 27.8 mg-N/L, 31.9 ± 18.4 mg-N/L and 10.7 ± 5.8 mg-N/L, respectively, and all reactors removed >80% COD_s. This design has potential because it uses limited energy, tolerates variable flows, and simultaneously removes C and TN; all key for effective decentralised treatment applications.

1. Introduction

Billions of people worldwide do not have adequate domestic wastewater treatment, which leads to the spread of infectious disease and an estimated 2.1 million deaths every year (World Health Organisation (WHO), 2015). Despite some progress, the United Nations Millennium Development Goal (MDG) of halving the pro-

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[*] Corresponding author at: School of Civil Engineering & Geosciences, Cassie Building, Newcastle University, Newcastle upon Tyne NE1 7RU, United Kingdom.
E-mail address: david.graham@newcastle.ac.uk (D.W. Graham).

[1] Contributed equally to the work and manuscript.

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portion of people without sustainable access to safe drinking water and basic sanitation has not been achieved for waste treatment, especially in Sub-Saharan Africa and South-East Asia (United Nations, 2015). Further, some emerging countries, such as China, have developed increasingly stringent laws on effluent discharges to the environment, particularly related to total nitrogen (TN) releases (Chan et al., 2009). As a consequence, domestic waste treatment is generally increasing, although often only in places where centralised sewage collection systems are feasible. This is largely because effective waste treatment in peri-urban and rural areas is still limited, especially waste treatment that removes TN (Jin et al., 2014; Lu, 2014), and few treatment options can remove both carbon (C) and TN that also are amenable to decentralised applications (Massoud et al., 2009; Naik and Stenstrom, 2016).

One possible option is Down-flow Hanging Sponge (DHS) bioreactors. This technology was originally visualised for decentralised use, and employs porous sponges and passive aeration to treat wastes (Agrawal et al., 1997; Tandukar et al., 2006; Tawfik et al., 2006). In principle, microbial consortia develop biofilms within the sponges (Mahmoud et al., 2011), metabolising C and secondary nutrients in the wastewater; transforming them into water, biomass and evolved gases (Uemura et al., 2010). DHS reactors have advantages over other treatment options, especially for low-income areas (Machdar et al., 2000; Tandukar et al., 2005), because they can be compact, are low maintenance, and operate with minimal energy input (Ahammad et al., 2013). Further, they utilise relatively short Hydraulic Retention Times (HRT) (Uemura et al., 2012) and have longer Sludge Residence Times (SRT), permitting the potential for higher Organic Loading Rates (OLR) and less sludge production compared with suspended-culture options (Tawfik et al., 2008).

Although previous DHS designs have shown effective C and ammonia (NH_3) removal (Onodera et al., 2014; Uemura et al., 2010), they display limited denitrification and often have elevated TN levels in effluents (Chuang et al., 2007). However, previous designs tend to entirely expose the sponge media to air to maximise passive aeration (Ikeda et al., 2013; Mahmoud et al., 2011; Uemura et al., 2010), which restricts denitrification because the reaction pathway requires anoxia. Limited denitrification diminishes the value of DHS reactors for decentralised use because of high TN releases, which is very pertinent to Chinese applications. Therefore, an alternate DHS reactor design was conceived that includes aerobic and anoxic modular sub-systems, which are driven by a raw wastewater bypass that provides extra C to the lower layers. The bypass is designed to encourage anoxia and alleviate C-limitation on denitrification (Isaacs and Henze, 1995; Shackle et al., 2000), increasing TN removal from the system.

2. Materials and methods

2.1. DHS reactor configurations

All DHS reactors tested included: 1) an upper sponge layer exposed to air, allowing passive aeration for nitrification; and 2) a lower sponge layer, partially submerged by effluent from the preceding aerobic layer, encouraging anoxic conditions for denitrification. However, detailed designs varied among experiments, employing different sponge densities (coarse vs fine; 20 vs 45 pores per inch, PPI, respectively) and recirculation ratios (0–100%), and the possible inclusion of a raw wastewater bypass (0–30% by volume).

Two sets of reactor experiments were performed, designated as Phase 1 and Phase 2. In Phase 1, quadruplicate bench-scale DHS reactors were operated using different combinations of sponge density (fine vs coarse); effluent recirculation ratios (see Fig. 1a); and steady and non-steady flow regimes. The Phase 1 reactors were physically identical 0.5 m tall × 140 mm diameter glass cylinders with working volumes of 3-L and inverted conical settlers at their bottoms. Reactors were designed in pairs based on combinations of different density sponges (R1 and R4 had coarse-coarse sponges and R2 and R3 had coarse-fine sponges; see Fig. 1a). R3 and R4 were operated with internal recirculation, whereas R1 and R2 had no recirculation to contrast the effect of waste recirculation on DHS reactor performance under differing flow conditions.

Phase 2 work used the same basic reactor design, except only the “best” sponge configuration and recirculation ratio from Phase 1 were employed. However, OLR was doubled, the reactors were made of PVC pipe (Crosslings, UK) instead of glass, and reactors were equipped with additional influent bypass lines to feed raw wastewater to the anoxic layer (Fig. 1b). The only difference among the four Phase 2 reactors was the percent of influent bypassed to the anoxic layer; either 0%, 10%, 20% and 30% of the total influent (by volume; designated R-S0, R-S10, R-S20 and R-S30, respectively). The reactors had side-holes every 30 mm (depth) on two sides that could be left open for added aeration, sealed with water-tight Suba-Seal (Sigma Aldrich, UK) closures, fitted with sampling ports (Point A and Point B), or used for bypass introduction. During these experiments, seals, taps and effluent tubing were positioned to maintain standing water depth of 240 mm in each column, fully submerging the lower sponge layer.

2.2. Inoculum and domestic wastewater

Settled domestic wastewater (post primary clarification; called “raw” here) was collected weekly from a municipal wastewater treatment plant (WWTP) in North East England (Tudhoe Mill, Northumbrian Water limited, UK) to serve as influent to the DHS reactors. Mean characteristics of the wastewater over the two Phases are summarised in Table 1. Samples were always collected at 9:00 AM on Tuesdays to minimise variations in reactor influent properties.

Reactors in both phases were seeded with nitrifying return active sludge (RAS) from the same WWTP (procedures are summarised in Supplementary Information; SI). However, Activated Sludge (AS) was used for reactor acclimation. AS and “raw” wastewater were collected in tandem during acclimation, and stored at 3–5 °C in sealed (raw wastewater) of unsealed (AS) containers prior to use. The raw wastewater was transferred every second day to an 18-L carboy retained in a fridge (4 °C) located near the reactors for short-term storage. Common waste was fed in parallel via influent pumps to all reactors, which were maintained at room temperature for all experiments (22–23 °C).

2.3. Polyurethane sponge media

Sponge cylinders 30-mm thick were cut to tightly fit inside the reactor columns. Each 30-mm cylinder had a working volume of 4.62×10^{-4} m^3. Phase 1 assessed the relative effect of using coarse versus fine density sponges for the upper and lower layers of the reactors (see Fig. 1a). Regardless of density, each sponge layer included three stacked sponge cylinders (90 mm total), making total sponge depths 180 mm. A similar, but slightly different sponge stacking/orientation was used in Phase 2. Specifically, the “aerobic” layer contained five stacked sponges, including four coarse-sponge cylinders (120 mm depth) topped by one fine sponge-cylinder. The lower sponge layer included six fine-sponge cylinders (180-mm depth). The fine-sponge layer at the reactor top was to screen out colloidal solids and better distribute raw feed within the aerobic sponges.

The aerated sponge layers were supported by PVC-coated wire mesh and hung suspended the top of the reactors with PVC coated