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Nitrogen dynamics and removal in a horizontal flow biofilm reactor for wastewater treatment

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ABSTRACT

A horizontal flow biofilm reactor (HFBR) designed for the treatment of synthetic wastewater (SWW) was studied to examine the spatial distribution and dynamics of nitrogen transformation processes. Detailed analyses of bulk water and biomass samples, giving substrate and proportions of ammonia oxidising bacteria (AOB) and nitrite oxidising bacteria (NOB) gradients in the HFBR, were carried out using chemical analyses, sensor rate measurements and molecular techniques. Based on these results, proposals for the design of HFBR systems are presented.

The HFBR comprised a stack of 60 polystyrene sheets with 10-mm deep frustums. SWW was intermittently dosed at two points, Sheets 1 and 38, in a 2 to 1 volume ratio respectively. Removals of 85.7% COD, 97.4% 5-day biochemical oxygen demand (BOD_5) and 61.7% TN were recorded during the study.

In the nitrification zones of the HFBR, which were separated by a step-feed zone, little variation in nitrification activity was found, despite decreasing *in situ* ammonia concentrations. The results further indicate significant simultaneous nitrification and denitrification (SND) activity in the nitrifying zones of the HFBR. Sensor measurements showed a linear increase in potential nitrification rates at temperatures between 7 and 16 °C, and similar rates of nitrification were measured at concentrations between 1 and 20 mg NH_4-N/l. These results can be used to optimise HFBR reactor design. The HFBR technology could provide an alternative, low maintenance, economically efficient system for carbon and nitrogen removal for low flow wastewater discharges.

1. Introduction

The on-site remediation of low flow wastewater sources requires robust, effective systems that are easy and economic to operate and maintain, and employ simple technologies (Crites and Tchobanoglous, 1998). Technologies vary from septic tanks with percolation areas to package aeration systems with polishing filters such as sand, soil and peat filtration systems (Johnson and Atwater, 1988; Corley et al., 2006). Treatment systems can vary from activated sludge (e.g. continuous flow or sequencing batch reactor) or attached growth systems (e.g. trickling filters or rotating biofilm contactors) or a combination thereof (USEPA, 1980).

To meet the stringent standards for wastewater treatment in the EU, small-scale systems are required to incorporate steps that ensure efficient nitrogen (N) removal, primarily involving the elimination of ammonium-nitrogen (NH_4-N) and in sensitive areas a reduction in nitrate-nitrogen (NO_3-N) (Water Framework Directive, 2000/60/EC; Groundwater Directive, 2006/118/EC; Surface Water Directive, 75/440/EEC). If a simultaneous

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Nomenclature

AOB	Ammonia oxidising bacteria
BOD_5	5-Day biochemical oxygen demand
COD	Chemical oxygen demand
COD_f	Filtered COD
DO	Dissolved oxygen
FISH	Fluorescent *in situ* hybridization
HFBR	Horizontal flow biofilm reactor
HRT	Hydraulic retention time
MLSS	Mixed liquor suspended solids
N	Nitrogen
NH_4-N	Ammonium-nitrogen
NH_4-N_f	Filtered NH_4-N
NOB	Nitrite oxidising bacteria
NO_2-N	Nitrite-nitrogen
NO_2-N_f	Filtered NO_2-N
NO_3-N	Nitrate-nitrogen
NO_3-N_f	Filtered NO_3-N
NO_X	Oxidised nitrogen
ORP	Oxidation–reduction potential
PE	Persons equivalent
SND	Simultaneous nitrification and denitrification
SS	Suspended solids
SRT	Solids retention time (days)
STE	Septic tank effluent
SWW	Synthetic wastewater
TN	Total nitrogen
TN_f	Filtered TN
TS	Total solids
TPA	Total plan area (m^2)
TSPA	Top surface plan area (m^2)
VSS	Volatile suspended solids
WWTP	Wastewater treatment plant

reduction in NH_4-N and NO_3-N is required, the establishment of suitable conditions to facilitate both nitrification and denitrification is necessary. This represents a challenge to engineers when designing on-site wastewater treatment systems, because the two processes are catalyzed by physiologically distinct groups of micro-organisms i.e., autotrophic nitrifiers and heterotrophic denitrifiers, which have fundamentally different metabolic requirements (Lowe et al., 2008).

Nitrogen removal is normally realized by sequentially alternating between oxic and anoxic conditions or by the creation of separated zones with suitable conditions for nitrification and denitrification, respectively. Alternatively, high rates of simultaneous nitrification and denitrification (SND) can be achieved, in activated sludge and biofilm type systems alike, at operational conditions where both oxic and anoxic micro-environments are present (Randall, 1992; Henze et al., 1997). Nitrification can occur at the liquid/biomass interface, while denitrification of nitrate (or nitrite) may be found in deeper sub-surface biomass zones (Von Münch et al., 1996; Helmer and Kunst, 1998).

Combined carbonaceous oxidation, nitrification and denitrification systems, based on complex and high flow systems, can require frequent and costly maintenance (Ferguson et al., 2003; EPA, 2007). The horizontal flow biofilm reactor (HFBR) is a simple technology with a flexible design that provides a new effective technology for carbon and nitrogen removal from domestic wastewaters (Rodgers et al., 2004; Rodgers and Clifford, 2009). In contrast to conventional trickling filters, sand filters and other media filters, the HFBR technology enables easy access to the different reactor regions, hence allowing for the examination of contaminant and biomass distributions, microbial community structures and process transformation rates in various regions of the reactor. Such information can help scientists and engineers to understand the factors affecting treatment performance and lead to more efficient system design (Lydmark et al., 2006).

In this study an HFBR was monitored for its efficacy in removing carbon and nitrogen from a domestic strength synthetic wastewater (SWW). The spatial arrangement of microbial populations in an HFBR, with a particular focus on nitrogen dynamics, was investigated. To obtain detailed information on system performance, traditional methodologies for characterisation of wastewater parameters were combined with advanced bio-sensing technology and molecular tools. This approach provided data that can be used by engineers and scientists to design HFBR systems and optimise nitrogen removal.

2. Materials and methods

2.1. Design and operation

The HFBR comprised a vertical stack of 60 horizontal polystyrene sheets (Terram Ltd.) that were arranged in sets of 10 sheets, on polypropylene shelves positioned one above another and supported on a simple frame (Fig. 1). Each sheet measured 340 mm × 310 mm in plan and had 10-mm deep frustums, giving a potential volume of 1.24 l/sheet. Three sides of each sheet were turned up to a height of 10 mm in order to direct the flow along the sheets to its exit end. The top surface plan area (TSPA) of each sheet was 0.1054 m^2 (0.34 m × 0.31 m). The total plan surface area (TPA) of the media was 6.324 m^2 (TSPA × 60).

SWW was pumped from a feed tank using a Masterflex L/S economy peristaltic pump. The SWW was applied intermittently for 10 min every hour onto the top sheet at 29.4 l/day (Sheet 1) and at a step-feed point at 14.7 l/day (Sheet 38). This equated to a TSPA hydraulic load of 418.4 l/m^2 day on the unit. Wastewater flowed along one sheet, dropped to a sheet underneath, and then flowed in the opposite direction on that sheet, and so on down through the reactor. The pump was calibrated, the tubing cleaned, and the feed tank cleaned and refilled every second day. The SWW (Table 1) was based on a mix by Odegaard and Rusten (1980). The unit, seeded on Day 0, with activated sludge taken from a municipal activated sludge treatment plant (WWTP), was located in a temperature controlled room at 11 °C and the system was operated for a total of 450 days. The STU was seeded with 30 l of SWW mixed with 15 l of nitrifying activated sludge taken from the