



# Removal of nitrate and phosphorus from hydroponic wastewater using a hybrid denitrification filter (HDF)

J.B.K. Park \*, R.J. Craggs, J.P.S. Sukias

National Institute of Water and Atmospheric Research Ltd. (NIWA), P.O. Box 11-115, Hamilton, New Zealand

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## ABSTRACT

A laboratory-scale hybrid-denitrification filter (HDF) was designed by combining a plant material digester and a denitrification filter into a single unit for the removal of nitrate and phosphorus from glasshouse hydroponic wastewater. The carbon to nitrate (C:N) ratio for efficient operation of the HDF was calculated to be 1.93:1 and the COD/BOD<sub>5</sub> ratio was 1.2:1. When the HDF was continuously operated with the plant material replaced every 2 days and 100% internal recirculation of the effluent, a high level of nitrate removal (320–5 mg N/L, >95% removal) combined with a low effluent sBOD<sub>5</sub> concentration (<5 mg/L) was consistently achieved. Moreover, phosphate concentrations in the effluent were maintained below 7.5 mg P/L (>81% reduction). This study demonstrates the potential to combine a digester and a denitrification filter in a single unit to efficiently remove nitrate and phosphate from hydroponic wastewater in a single unit.

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## 1. Introduction

Biological denitrification is an efficient process for nitrogen removal from wastewater in which heterotrophic bacteria in the absence of oxygen (anaerobic conditions) convert nitrate-N and nitrite-N to nitrogen gas (Prosnansky et al., 2002; van Rijn et al., 2006). The process requires sufficient organic carbon as an electron donor for complete nitrate removal (Cambardella et al., 1999; Greenan et al., 2006; Healy et al., 2006). Methanol, ethanol, and acetic acid are commonly used as organic carbon sources for denitrification processes to enhance denitrification activity in organic carbon-limited wastewaters (Grguric et al., 2000; Menasveta et al., 2001; Killingstad et al., 2002; Kim et al., 2002; Suzuki et al., 2003; Tal et al., 2003).

The optimum C/N ratio required for complete nitrate reduction to nitrogen gas by denitrifying bacteria depends on the nature of the carbon source and the bacterial species present (Chiu and Chung, 2003; van Rijn et al., 2006).

The availability of the organic carbon for denitrification is an important factor that controls the denitrification performance (Tan and Ng, 2008). A wide range of COD/NO<sub>3</sub><sup>-</sup>-N values have been reported in the literature (6–11) for complete denitrification (Carucci et al., 1996; Tseng et al., 1998). Tam et al. (1994) reported an optimal sBOD<sub>5</sub>:NO<sub>x</sub>-N ratio of 2.48 for denitrification using methanol and acetic acid as the carbon source. The cost of these carbon sources is a major part of total treatment cost. Thus, waste carbon

sources such as industrial effluents have been suggested as alternatives (Sage et al., 2006). However, low carbon availability in some industrial effluents has led to in-complete denitrification and accumulation of denitrification intermediates such as nitrite, nitric oxide and nitrous oxide (Chiu and Chung, 2003; Kim et al., 2002). Nitrate removal rates reported by researchers depend on operational parameters, such as system configuration, types of organic carbon source, reduction states of the reactors and the ambient nitrate concentration at which the various reactors were operated (Park et al., 2008; van Rijn et al., 2006). The wide range (0.043–3.984 kg N/m<sup>3</sup>/day) of nitrate removal rates is most likely due to differences in: system configurations, types of organic carbon, redox state of the reactors and the nitrate concentrations of the wastewaters being treated (van Rijn et al., 2006).

Greenan et al. (2006) evaluated the ability of organic materials (wood chips, wood chips amended with soybean oil, cornstalks, and cardboard fibers) to serve as carbon substrates for laboratory-scale denitrification biofilters. All of the C substrates stimulated denitrification and rates of denitrification ranged from 0.427 g N kg<sup>-1</sup> substrate day<sup>-1</sup> for the cornstalks to 0.066 g N kg<sup>-1</sup> substrate day<sup>-1</sup> for the wood chips (Greenan et al., 2006).

Some heterotrophic denitrifiers store phosphorus in excess of their metabolic requirements through poly-phosphate (poly-P) synthesis under either aerobic or anoxic conditions, without the need for alternating anaerobic/aerobic conditions (Barak and van Rijn, 2000b). Unlike poly-phosphate accumulating organisms (PAO), these denitrifiers are unable to use polyhydroxyalkanoates (PHA) as an energy source for poly-P synthesis and derive energy from oxidation of external carbon sources (van Rijn et al., 2006).

\* Corresponding author. Tel.: +64 7 856 1777; fax: +64 7 856 0151.

E-mail address: [j.park@niwa.co.nz](mailto:j.park@niwa.co.nz) (J.B.K. Park).

The feasibility of this type of phosphate removal has been previously demonstrated in both freshwater and marine recirculating treatment systems (Barak and van Rijn, 2000b,a; Gelfand et al., 2003; Shnel et al., 2002). In these systems, orthophosphate concentrations in the effluent were found to be very stable.

Shi and Lee (2006) isolated denitrifying P-removal bacteria (DPB) from wastewater sludge and investigated potential for phosphorus removal under anaerobic/anoxic and anaerobic/aerobic conditions. Most of the isolated DPBs had no obvious anaerobic P release, but significant P uptake was observed under anoxic conditions. Pure isolated DPB cultures achieved N- and P-removal efficiencies of 96% and 86%, respectively (Shi and Lee, 2006).

Waste plant material (including pruned leaves, stems and discarded fruit) is produced in large volumes at commercial glasshouse operations. At present, the plant material is a waste which needs to be disposed of; however, it may provide a convenient on-site carbon source for treating the nitrate-rich wastewater produced by the glasshouse operation. Park et al. (2008) demonstrated the feasibility of using organic-rich liquors from pre-treated waste plant material as an organic carbon source for the denitrification of hydroponic wastewater with high nitrate-N concentration (> 300 mg N/L). When an anaerobically digested plant liquor was added to a denitrification filter at the organic carbon:nitrogen ratio of 2C:N, nitrate removal efficiency was maintained at >85% (reduced from 300 mg N/L to 45 mg N/L) and final effluent sBOD<sub>5</sub> concentrations were consistently maintained <25 mg N/L.

In this paper we investigate the potential to reduce the footprint of the denitrification system using anaerobically digested plant material liquor as the organic carbon source by combining the digester and denitrification filter into a single unit, called a hybrid-denitrification filter (HDF).

## 2. Methods

### 2.1. Sample collection

Waste plant material, mainly tomato and cucumber leaves, and hydroponic wastewater were collected from a glasshouse operation (Under Glass NZ Ltd.) at Karaka, South Auckland, New Zealand. The waste plant material was stored in a 1 °C constant-temperature room until use. Typical composition and physical properties of the hydroponic wastewater are shown in Table 1.

The hydroponic growth media is recirculated 2–3 times and then discharged as wastewater to avoid pest or disease incursion such as Tomato/Potato Psyllid and *Candidatus liberibacter* sp.

### 2.2. Hybrid-denitrification filter (HDF) experiment

The hybrid denitrification filter (HDF) had two zones (a digester zone to provide organic carbon for denitrification and a denitrifica-

tion filter zone) and an external tank to recirculate treated effluent (recirculation tank).

The digester zone had a total volume of 10 L (3 L working volume, with a 7 L volume headspace). The denitrification filter zone (4.5 L total volume) was filled with gravel (10–30 mm size) creating a working volume of 2 L (~45% porosity). Hydroponic wastewater was added at the rate of 3 L/day and the hydraulic retention time of the HDF was 1.7 days (total working volume: 5 L). The volumetric nitrogen loading rate was 0.19 kg/m<sup>3</sup>/day (based on the influent concentration of 325 mg/L).

The effluent from the denitrification filter zone was collected in a recirculation tank (10 L), and recirculated back to the top of the digester zone by a peristaltic pump (Masterflex, Cole-Parmer, HV-07523-60) at daily rates between 100% and 300% of the influent flow to enhance plant material breakdown (releasing organic carbon) and increase the biological contact time between the denitrifying bacteria and hydroponic wastewater.

The experiment was divided into three periods based on the dose of plant material in the digester zone and effluent recirculation rate:

*Period 1: initial investigation with a single addition of plant material to the HDF*

Waste plant material (4 kg) was placed in the digester zone of the HDF. The hydroponic wastewater was added to the digester zone and then passed through to the denitrification bringing organic carbon released from the plant material. Treated effluent from the denitrification filter was collected and recirculated (300% of influent flow) back to the top of the digester zone of the HDF. Influent and effluent nitrate-N concentrations were analysed five times per week and phosphate was analysed on a weekly basis.

*Period 2: continuous operation of the HDF with addition of plant material every 6–7 days*

This experiment was conducted over 33 days with 1 Kg of waste plant material added to the digester zone every 6–7 days to provide a constant supply of organic carbon to the denitrification filter. All other operational parameters of the HDF were the same as in Period 1.

*Period 3: continuous operation of the HDF with addition of plant material every 2 days*

This experiment was conducted over 35 days with 1 kg of the waste plant material added to the digester zone every 2–3 days to provide a more consistent supply of organic carbon to the denitrification filter.

The HDF experiment was conducted in a 20 °C constant-temperature room, and the denitrification bacteria inoculum was taken from activated sludge from Pukete domestic wastewater treatment plant, Hamilton, New Zealand. Influent and effluent nitrate-N concentrations were analysed with a nitrate electrode (Orion Model 97-07 ionplus™ nitrate electrode with Thermo Orion Model 290A plus datalogger), calibrated using 5, 50 and 500 mg N/L of nitrate standard solutions (Orion Research Inc., USA, Cat. No.: 920707). Influent and effluent samples were analysed for nitrite-N nitrate-N and dissolved reactive phosphorus (DRP) on a weekly basis according to the Standard Methods (APHA, 2005). Nitrite-N in the influent and effluent was negligible (<0.5 mg N/L).

### 2.3. Organic carbon production using waste plant material

This experiment determined the total amount of organic carbon released by 1 kg of waste plant material digested with hydroponic wastewater to enable optimisation of the use of waste plant material as an organic carbon source. A 5 L tank containing 1 kg of waste plant material was continuously supplied with hydroponic wastewater (3 L/day) for 7 days. The soluble BOD<sub>5</sub> (sBOD<sub>5</sub>) of a composite sample of the effluent was measured daily. This experiment coincided with Days 13–20 of the HDF experiment (Period 2). Data

**Table 1**  
Composition and physical properties of hydroponic wastewater from the glasshouse operation.

Parameter	Concentration (mg/L)	Parameter	Concentration (mg/L)
Nitrate-N	325	Copper	0.07
Total phosphorus	38	Boron	0.71
Phosphate	29.4	Iron	1.5
Sodium	108	Manganese	0.8
Potassium	459	Chloride	80
Calcium	295.5	Sulphur	192
Magnesium	85	pH (unit)	5.45
Zinc	0.5	Conductivity (μmho/cm)	37.5

from both experiments were used to calculate the optimal interval for replacing the waste plant material and C:N ratio for the HDF.

### 3. Results and discussion

Experiments to investigate the potential to efficiently remove nitrate and phosphorus from hydroponic wastewater using digested plant material liquor as the organic carbon source were conducted using a HDF operated over three periods with different intervals between plant material addition and effluent recirculation rates to the digester zone.

#### 3.1. Nitrate removal

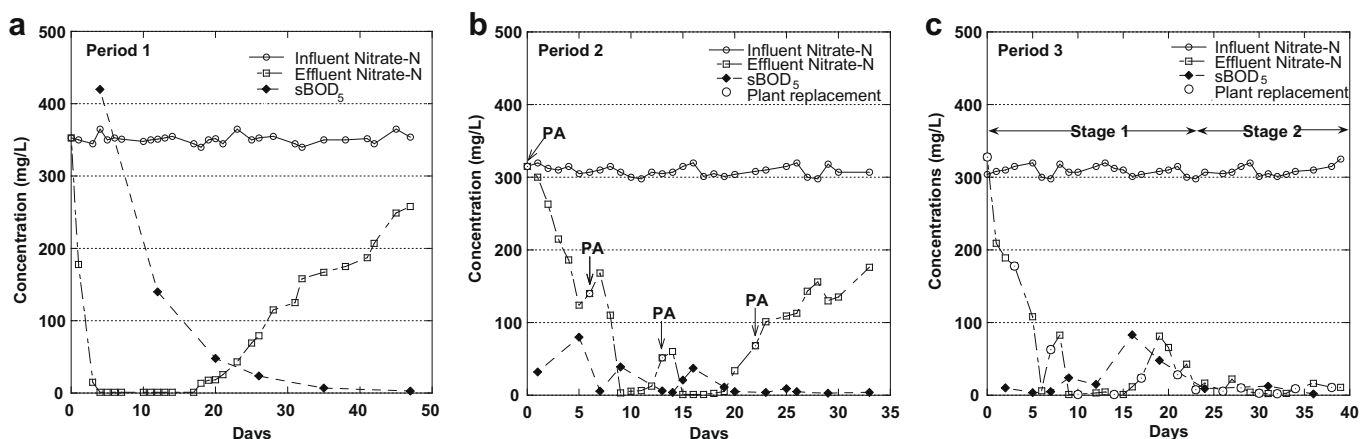
The HDF was initially operated for 47 days (Period 1) with 300% effluent recirculation and a single addition of 4 kg of waste plant material to the digester zone to release organic carbon into the hydroponic wastewater.  $sBOD_5$  and nitrate-N concentrations in the HDF influent and effluent during Period 1 are presented in Fig. 1a. The effluent nitrate-N concentration declined to less than 5 mg N/L (>95% removal) by Day 4 of the experiment, and was maintained at this level until Day 18 when it began to increase due to a lack of available organic carbon (measured as  $sBOD_5$ ) for the heterotrophic denitrifying bacteria. However, the organic carbon concentration in the effluent was initially very high (420 mg  $sBOD_5$ /L on Day 4) and then declined during the experiment, indicating that much of the organic carbon was released from the waste plant material during the first few days of the experiment and was in excess of that required by the HDF, and therefore washed out of the system without being used in spite of 300% effluent recirculation. This suggests that release of organic carbon from waste plant material does not occur at a steady rate, therefore, some optimisation of the amount and frequency of waste plant material addition would be necessary to maximise the availability of organic carbon released from waste plant material for nitrate removal as well as to minimise effluent  $sBOD_5$  concentrations.

The HDF process was then operated over 33 days (Period 2) with regular addition (every 6–7 days) of 1 kg of waste plant material to the digester zone to provide a more constant supply of organic carbon for the denitrification filter and to improve operational consistency in terms of nitrate removal and minimise effluent  $sBOD_5$  concentrations. All other operational parameters of the HDF were unchanged. The HDF influent and effluent ni-

trate-N and  $sBOD_5$  concentrations during Period 2 are compared in Fig. 1b. The effluent nitrate-N concentration from the HDF declined from 315 to 124 mg N/L by Day 5 but increased to 140 mg N/L on Day 6, associated with a decline in effluent  $sBOD_5$  (5.8 mg/L) concentration. Following replacement of the waste plant material (1 kg) on Day 6, the effluent nitrate-N concentration further increased to 168 mg N/L on Day 7. However, by Day 9 the nitrate-N concentration declined to less than 5 mg N/L and remained at this level for four days until Day 13 (>95% nitrate-N removal for 4 days), when it increased to 51.3 mg N/L. Following replacement of the waste plant material on Day 13, the nitrate-N concentration again initially further increased to 61 mg N/L on Day 14, but, then declined back to less than 5 mg N/L (by Day 15) and remained at this level for four days until Day 20 (>95% nitrate-N removal), when it increased to 33 mg N/L (Fig. 1b). The Period 2 results suggested that the organic carbon released from the waste plant material was exhausted in less than 6 days, and that the newly added waste plant material took up to 2 days to provide sufficient organic carbon to sustain rates of denitrification.

Complete nitrate removal is only achieved if sufficient organic carbon is available for the denitrifying bacteria (Olsson and Newell, 1999). The Period 2 results indicate that a 6-day plant material replacement interval did not maintain sufficient organic carbon for denitrification. On Day 22, the influent flow rate was increased from 3 to 6 L/day to determine if more efficient organic carbon use could be achieved at a lower hydraulic retention time (0.8 day). The effluent nitrate-N concentration increased to >100 mg N/L on Day 22, however, a very low effluent  $sBOD_5$  concentration (<5 mg  $sBOD_5$ /L) was maintained until the end of the experimental period (Fig. 1b). This indicated that the organic carbon was washed out of the system before being used by the denitrifying bacteria due to the short the hydraulic retention time and the remaining organic carbon was insufficient for complete denitrification in the HDF.

An experiment to determine the total amount of organic carbon released by 1 kg waste plant material with addition of hydroponic wastewater was conducted during Period 2 to enable optimisation of the use of waste plant material as an organic carbon source for denitrification. The effluent  $sBOD_5$  concentrations and cumulative mass of  $sBOD_5$  released over 7 days are shown in Fig. 2. The experiment indicated that >95% of total organic carbon produced from the digester zone was released in the first 2 days after waste plant material addition, and after 4 days, carbon release was negligible. This may explain why a low effluent nitrate-N concentration



**Fig. 1.** Influent and effluent nitrate-N and  $sBOD_5$  concentrations of the HDF during 3 experimental Periods: Period 1 over 47 days with a single waste plant material addition and 300% effluent recirculation (a), Period 2 over 33 days with waste plant material addition every 6–7 days and 300% effluent recirculation (b) and Period 3 over 39 days with 3-day waste plant material addition and 300% effluent recirculation until Day 22 (stage 1) and 2-day waste plant material addition and 100% internal recirculation from Days 23 to 39 (stage 2) (c).

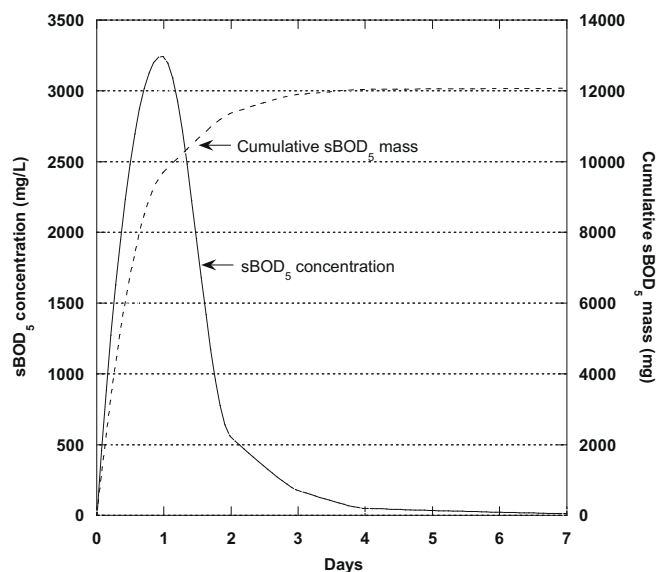


Fig. 2. sBOD<sub>5</sub> concentration released from waste plant material and cumulative mass of dissolved BOD<sub>5</sub> released over 7 days.

(<5 mg N/L) was only maintained for about 4 days after the addition of waste plant material during Period 2. These results indicate that waste plant material should be added every 2–3 days to maintain sufficient organic carbon levels to achieve high denitrification in the HDF.

The total amount of organic carbon as sBOD<sub>5</sub> released by 1 kg plant material measured in the experiment (Fig. 2) and the total amount of nitrate-N removed over the same period (measured in Period 2 (Fig. 1b; Days 13–20) were then used to calculate the C:N ratio to optimise HDF performance.

The total amount of organic carbon (sBOD<sub>5</sub>) released by 1 kg of the waste plant material was 12,075 mg, and total amount of organic carbon used for the removal of 6135 mg of nitrate-N during Days 13–20 was 11,841 mg. Therefore, the C:N ratio for the HDF using digested waste plant material liquor as an organic carbon source was 1.93:1. Literature values reported for optimal sBOD<sub>5</sub>:NO<sub>x</sub>-N ratios for denitrification using methanol and acetic acid as the carbon source are typically higher (~2.5) than that found for the HDF in this study (Tam et al., 1994; Carucci et al., 1996). Tseng et al. (1998) suggested COD/NO<sub>3</sub>-N (w/w) ratio of 6–11 for complete nitrate reduction to elemental nitrogen. The ratio of 1.93C:N found in the HDF study is lower than that of these reported values. A relative ratio between COD and BOD<sub>5</sub> of less than 2.5 or 3.0 indicates a wastewater contains a high biodegradable fraction (Sperling et al., 2005). The COD/BOD<sub>5</sub> ratio in the digested waste plant material liquor was 1.2 (14.5 g COD/12 g BOD<sub>5</sub>), suggesting that it is readily biodegradable, which could account for the relatively low amount of organic carbon (1.93C:N ratio) required for denitrification.

During Period 2 effective denitrification was maintained for 4 days (from Day 15–18) (effluent concentrations maintained below 5 mg N/L with >95% nitrate removal efficiency), even though >98% of the organic carbon was shown to be released in the first 2–3 days after addition of the waste plant material (Fig. 2). This suggested that denitrification was maintained by recirculation of the effluent (300% of influent flow) by recirculating sufficient organic carbon for denitrification in the system for 6 days after waste plant material addition, rather than it being washed out of the system after a single pass.

Based on these results the HDF was then operated for 23 days with a 3-day waste plant material addition interval and without internal recirculation. (Period 3: stage 1). From Day 24, the addi-

tion interval was reduced to 2 days with 100% internal recirculation to enhance nitrate removal and minimise effluent residual organic carbon (sBOD<sub>5</sub>) levels (Period 3: stage 2).

Influent and effluent nitrate-N and sBOD<sub>5</sub> concentrations of the HDF are shown in Fig. 1c. The nitrate-N concentration declined from 328 to 5.8 mg N/L by Day 6. However, between Days 7 and 23 (stage 1), when the waste plant material was added at 3-day intervals, a high level of nitrate removal combined with a low effluent sBOD<sub>5</sub> concentration was not consistently achieved. Thus, from Day 24 (stage 2) the plant material replacement interval was reduced to 2 days with 100% internal recirculation of effluent. During this period, over 95% of nitrate was removed (320 mg N/L down to less than 5 mg N/L) and effluent sBOD<sub>5</sub> concentrations also remained below 5 mg/L over 15 days. These results indicate that 100% internal recirculation associated with a 2 day plant addition interval provided additional consistency in treatment performance by extending the contact time of the denitrifying bacteria with the hydroponic wastewater. The average volumetric nitrate removal rate was 0.17 kg N/m<sup>3</sup>/day, which is in the middle range of other denitrification systems (0.043–3.984 kg N/m<sup>3</sup>/day) using organic carbon sources such as methanol/ethanol, glucose and starch (Grguric et al., 2000; Menasveta et al., 2001; Park et al., 2001; Tal et al., 2003). This study confirmed that digested waste plant material from a glasshouse operation was an excellent organic carbon source for denitrification, thus significantly reducing potential operating costs for glasshouse effluent treatment.

### 3.2. Phosphorus removal

Phosphorus removal from hydroponic wastewater using the HDF was investigated during the experimental periods reported above and influent and effluent DRP concentrations are presented in Fig. 3.

During Period 1, the effluent DRP concentration declined to less than 2 mg P/L by Day 6 of the experiment and remained below 4 mg P/L until Day 47 (89% removal). The HDF also reduced the phosphate level in the hydroponic wastewater by 86.9–93.2% during Period 2 (influent 36.8–38.9 mg P/L; effluent 2.1–4.9 mg P/L) and 76.6–88.2% during Period 3, (and Period 3: influent 30.5–33.1 mg P/L; effluent 3.8–7.6 mg P/L). This suggests that the denitrifying organisms in the HDF may accumulate phosphorus under the anoxic conditions and the process is independent of nitrate re-

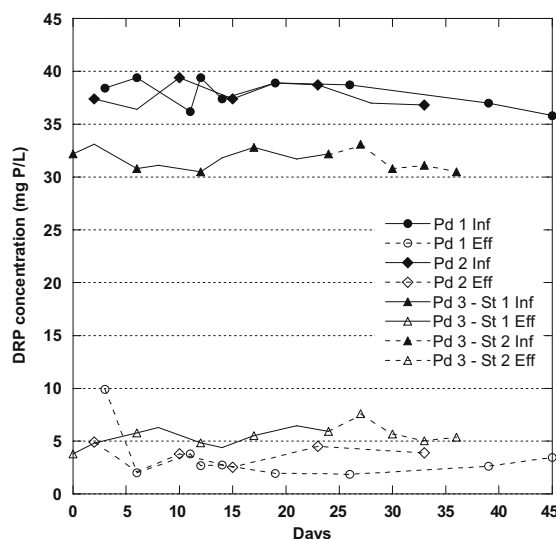


Fig. 3. Influent and effluent DRP concentrations of the HDF process during the experimental Periods 1–3.



moval. Barak and van Rijn (2000a) reported accumulation of phosphorus in excess of metabolic requirements by heterotrophic denitrifying bacteria through poly-P synthesis under anoxic conditions, where the denitrifiers derive energy from oxidation of external carbon sources (van Rijn et al., 2006). Phosphate removal in the HDF could be by a similar mechanism (Park et al., 2008; Shi and Lee, 2006). The phosphate removal rate during Periods 1 to 3 declined from 0.054 to 0.045 kg P/m<sup>3</sup>/day, indicating that such a high rate of phosphate removal may not be sustainable over the long term as phosphate cannot accumulate indefinitely within the denitrification filter (Park et al., 2008).

#### 4. Conclusions

The HDF combining a digester zone to release organic carbon from waste plant material and a denitrification filter zone into one single unit efficiently removed nitrate and phosphorus from hydroponic wastewater. Combining these processes in a single reactor also reduced the overall foot-print of the treatment system, which may be important on sites where space is limited. Waste plant material from the glasshouse operation was a suitable organic carbon source for the denitrification filter significantly reducing potential operating costs for denitrification of glasshouse effluent.

The optimal ratio of waste plant material organic carbon (measured as sBOD<sub>5</sub> mg/L) to hydroponic wastewater nitrate-N (mg/L) was found to be 1.93:1 and the organic liquor released was readily biodegradable (COD:BOD<sub>5</sub> ratio of 1.2).

A plant material addition interval of 2 days combined with 100% effluent recirculation maintained consistent organic carbon loading to the denitrification filter zone but minimised residual organic carbon concentrations in the HDF effluent. At a flow rate of 3 L/day (HRT 2.3 days), nitrate concentrations were reduced by >95% (nitrate removal rate 0.17 kg N/m<sup>3</sup>/day) and phosphate concentrations were reduced by >81% (phosphate removal rate 0.045 kg P/m<sup>3</sup>/day), while effluent residual BOD<sub>5</sub> concentrations were maintained below 5 mg/L.

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