Treatment of hydroponic wastewater using a Denitrification Filter System (DFS) - Summer trial

NIWA Client Report: HAM2009-084
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Jason Park
Rupert Craggs

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Horticulture N.Z. Ltd

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National Institute of Water & Atmospheric Research Ltd
Gate 10, Silverdale Road, Hamilton
P O Box 11115, Hamilton, New Zealand
Phone +64-7-856 7026, Fax +64-7-856 0151
www.niwa.co.nz

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Reviewed by:

Approved for release by:

James Sukias

Neale Hudson

Formatting checked

A. Bartley

Executive Summary

Horticulture NZ Ltd contracted NIWA to investigate nitrogen and phosphorus removal in a full-scale Denitrification Filter System (DFS) over an 8-week period during the summer (February to April 2009). Information from this summer trial would be combined with results from earlier studies of the full-scale DFS, undertaken during the previous autumn and winter (May to July 2008). The earlier studies demonstrated that the DFS could consistently remove >95% of nitrate-N and ~70% of phosphorus from the wastewater of a hydroponic glasshouse operation. This study aimed to: (1) investigate if similar nitrate-N and phosphorus removal could be achieved during the summer, (2) determine key operation parameters for summer conditions, and (3) establish general DFS design and operation parameters for year-round DFS operation.

Daily wastewater inflow rates in this monitoring period (3.5 and 6.8 m^3/d) were similar to those during the winter monitoring period (3.0 to 7.6 m^3/d). Waste plant material from the Yearbury glasshouse operation was added to the anaerobic digester and mixed with hydroponic wastewater (at an approximate ratio of 2 m^3 plant material per m^3 of hydroponic wastewater) to produce the organic liquor necessary for heterotrophic denitrification.

During the first 7 days of operation (without organic liquor addition), the hydroponic wastewater nitrate-N concentration was reduced by 35% (from ~150 to ~90 mg/L). This indicated that endogenous metabolism of bacteria in the DFS can provide some organic carbon for the denitrifying bacteria. From day 7, organic liquor was added to the DFS with ~300% effluent recirculation to achieve nitrate-N removal (>92% reduction, from ~200 mg N/L to <15 mg N/L). However, since this organic liquor had been digested for less than 7 days (rather than the 14 day minimum identified in the winter trial), a high volumetric dose (260 L/m^3) of the low $sBOD_5$ concentration (1500 mg/L) organic liquor was required to provide the ~2C:N ratio for efficient denitrification. A consequence of using the higher volumetric dose was an elevation in the effluent organic-N concentration (to ~40 mg/L).

The second plant material digestion was conducted over 14 days with effluent recirculation and like the winter study, produced a concentrated organic liquor ($sBOD_5$ of 3500 mg/L). Using a lower dose (95 L/m^3) of this concentrated organic liquor with ~300% effluent recirculation achieved high levels of nitrate-N removal (>92% reduction, from ~230 mg N/L to <20 mg N/L) without increasing effluent organic-N and $sBOD_5$ levels.

The summer monitoring results indicate that a consistent and reliable organic carbon supply (anaerobic digester organic liquor with a high $sBOD_5$ concentration) are critical to achieve a high level of nitrogen removal by the DFS, as well as minimize residual organic-N and $sBOD_5$ in the DFS effluent.

The DFS also reduced the total phosphorus (TP) and DRP in the hydroponic wastewater by 53% (from 42 mg/L down to 20 mg/L) and 51% (from 40 mg/L down to 19 mg/L) respectively. Despite a higher phosphorus concentration in the hydroponic wastewater than in the winter period (42 mg/L compared with 25 mg/L) the phosphorus removal rates were very similar (~5 $g/m^3/d$). This indicates that phosphorus removal via the DFS may be unaffected by seasonal variation in ambient temperature. Furthermore, there was no indication of saturation of the filter media by phosphorus accumulated by the anaerobic bacteria after 2 ½ years of operation.

Given the success of this demonstration project, general DFS design specifications and operation parameters are suggested based on both summer and winter studies.

NIWA would be pleased to assist Horticulture NZ in disseminating information on the DFS to the horticulture industry and to provide specific designs for particular horticulture operations.

1. Introduction

Initial experiments conducted using laboratory-scale and full-scale Denitrification Filter System (DFS) are described in previous NIWA client reports (Park et al. 2004; 2005; 2008). The previous full-scale DFS trial from May to July 2008 (late autumn to early winter) demonstrated that consistently high levels of nitrate-N (>95%) and phosphorus removal (~70%) were achieved by the DFS (Park and Craggs 2008). However, key summer operation parameters (such as organic liquor dose rate, effluent recirculation rate, organic liquor production and daily wastewater flow) still needed to be determined to enable general design specifications and operation parameters for the DFS to be established.

Therefore, this study aimed to: (1) investigate nitrate-N and phosphorus removal in the full-scale DFS over an 8-week summer period, (2) determine key operation parameters for summer conditions, and (3) establish general DFS design and operation parameters for year-round operation.

2. Methodology

2.1 Yearbury glasshouse operation during the summer monitoring period

The characteristics of the hydroponic wastewater taken from the Yearbury glasshouse operation on the 19th January 2009 are shown in Table 1. The nitrate-N concentration of the hydroponic wastewater was high (200 mg/L), although lower than that found in previous studies (~300 mg/L). The ammoniacal-N concentration was negligible (0.2 mg/L).

NIWA has developed the DFS to treat the high nitrate-N concentration of hydroponic wastewater by denitrification (reducing nitrate-N to nitrogen (N_2) gas). Denitrification requires organic carbon to reduce nitrate-N under anoxic conditions, however, the organic carbon (measured as $sBOD_5$) concentration in hydroponic wastewater is very low (~1.0 mg/L). Therefore, an external organic carbon source is required to enhance nitrogen removal by denitrification. Anaerobic digestion of waste plant material from the glass house operation can provide suitable organic carbon source.

Table 1: Concentrations of key water quality parameters in the hydroponic wastewater from the Yearbury glasshouse operation measured on the 19th January 2009.

Parameter	Unit	Value
Total Suspended Solids (TSS)	mg/L	35
Volatile Suspended Solids (VSS)	mg/L	25
Soluble BOD_5 ($sBOD_5$)	mg/L	1.1
Total-N	mg/L	200
Nitrate-N (NO_3^--N)	mg/L	200
Ammoniacal-N (NH_4^+-N)	mg/L	0.2
Total-P	mg/L	44
Dissolved Reactive Phosphorus (DRP)	mg/L	42
pH	units	5.9

2.2 Operation of the full-scale Denitrification Filter System in summer

The design specifications and key operation parameters of the DFS and the plant material anaerobic digester constructed at the Yearbury glasshouse operation were described previously (Park and Craggs, 2005; 2008).

While daily wastewater inflow rates during the summer period were highly variable (3.5 - 6.8 m^3/d) and dependent on the specific glasshouse operation at the time (Figure

1), they were similar to those measured during the winter monitoring period (3.0 to 7.6 m^3/d).

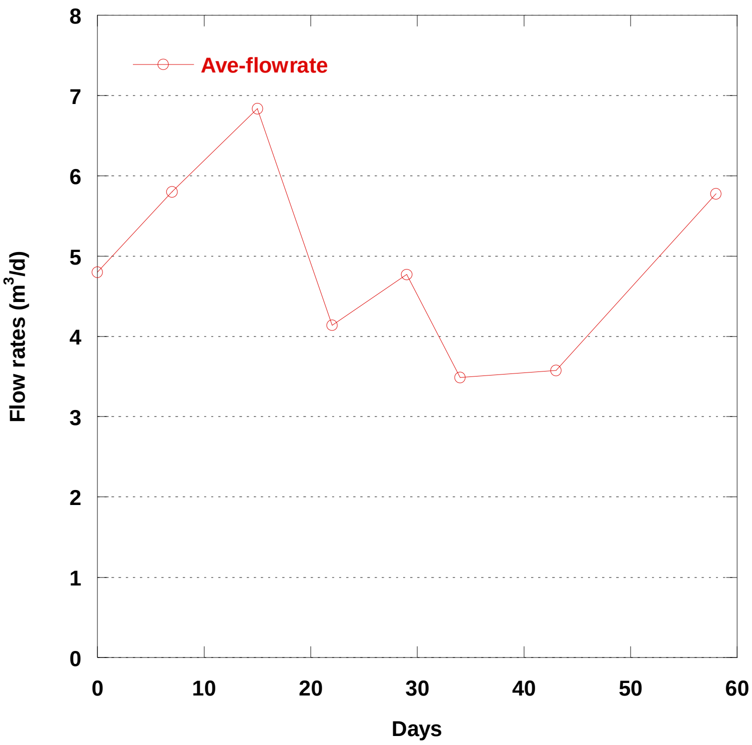

Figure 1: Daily wastewater inflow rates to the DFS during the summer monitoring period

2.3 Production and addition of organic carbon to the DFS

The main innovation of the DFS is the use of organic liquor derived from anaerobic digestion of waste plant material as the supplementary organic carbon source for denitrification. The organic liquor replaces expensive methanol (a widely used supplementary organic carbon source) with a freely available "waste" material produced by the glasshouse operation, thereby enabling more sustainable and cost-effective operation of the DFS (Park and Craggs, 2008).

Waste plant material (~20 m^3 mainly consisting of cucumber leaves and stems) from the Yearbury glasshouse operation was added to the anaerobic digester every two weeks during the summer monitoring period (12/02, 26/02, 12/03, and 26/03). During the winter plant material was added on a monthly basis due to lower plant growth.

Following addition of the waste plant material, the hydroponic wastewater flow was diverted to the digester for ~2 days until the digester was full (~10 m^3, 0.5 m^3 to 1 m^3

of plant biomass). To improve the degradation of the plant material and increase the concentration of the organic liquor (measured as $sBOD_5$), the plant digester liquor was recirculated (pumped) from the collection tank back to the top of the digester for at least 14 days (Figure 2).

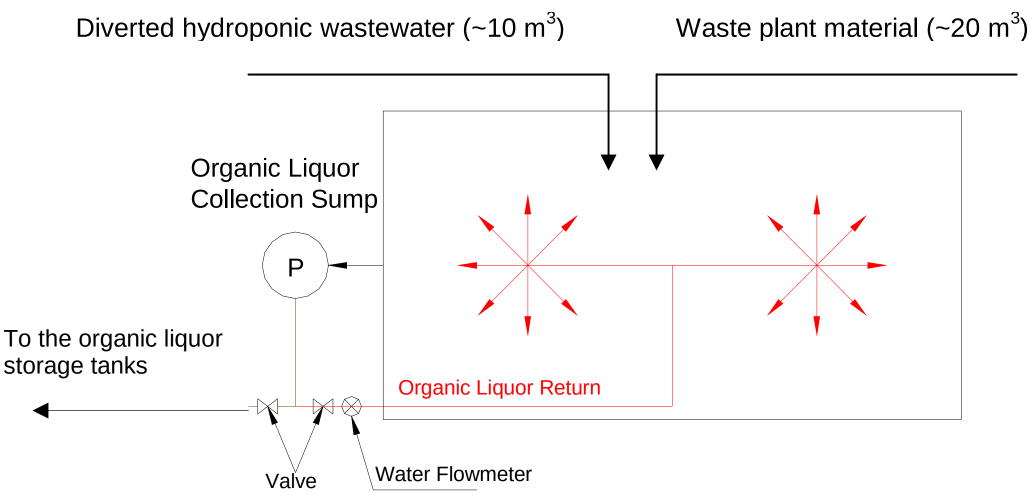

Figure 2: Schematic diagram showing the operation of the anaerobic plant material digester

While the $sBOD_5$ concentration of organic liquor gradually increased to 3,500 mg/L over 14 days of anaerobic digestion, it was lower than that measured in the winter period (4500 mg/L) and only a third of that produced in previous laboratory-scale studies (~12,000 mg/L, Park et al. 2005). This suggested that excess hydroponic wastewater may have been added to the digester, diluting the organic carbon content. This highlighted the need for simple but effective measurement of the volumes of both plant material and added water.

The organic liquor produced by the anaerobic plant material digester was temporarily stored in two 10 m^3 storage tanks until used. A chemical dosing pump (Grundfos DMS Digital Dosing™ pump) was used to add the organic liquor to the DFS. The procedure describing organic liquor addition and photos were shown in the previous NIWA client report (Park and Craggs, 2008).

The dose of organic liquor was adjusted according to the $sBOD_5$ concentration of the organic liquor, the nitrate-N concentration of the hydroponic wastewater and the average daily inflow rate, based on a 2:1 C:N ratio for efficient denitrification (Park, 2005) using Equation 1.

Equation 1: Organic liquor dose rate

$$Organic\ \ liquor\ \ dose\ rate(L/d) = \frac{NO_3^{\,-} - N\ conc\ (g/m^3) \times Daily\ \ flow\ rate\ (m^3/d) \times C:N\ ratio^{*}}{sBOD_5\ conc\ (g/m^3)} \times 1000$$

* Optimal C:N ratio of 2: 1 for this trial

Therefore, for an organic liquor $sBOD_5$ concentration of 3,500 mg/L and hydroponic wastewater nitrate-N concentration of 200 mg N/L, a volume of 114.3 L of organic liquor would be required per cubic metre of hydroponic wastewater (see below):

$$114.3\,(L/d) = \frac{200\ (g/m^3) \times 1\,(m^3/d) \times 2}{3500\ (g/m^3)} \times 1000$$

2.3 Monitoring and operation of the full-scale DFS

System operation and *in-situ* monitoring were conducted on a weekly basis by NIWA over the eight week period (5th February to 4th April 2009). Influent and effluent samples were taken twice a week (mostly Monday and Thursday) for nitrate-N analysis (using a HACH 2800 portable spectro-analyser) and a leachate sample was taken once a week for $sBOD_5$ analysis. Influent and effluent samples (total 4 data sets) were taken every two weeks and analysed by Hill Laboratories in Hamilton for the following water quality variables: pH, DRP, TP, NO_3^--N, TKN, and $sBOD_5$.

3. Results and discussion

3.1 Nitrate-N removal

The DFS summer monitoring period commenced on the 5th February 2009. Hydroponic wastewater was added to the DFS at an average daily flow rate of ~5 m^3/d and the treated effluent was recirculated back to the DFS at 300 to 400% of the inflow application rate. Effluent recirculation increases the biological contact time between the denitrifying bacteria and hydroponic wastewater and improves the stability of the DFS operation especially when the daily inflow is highly variable, as in this case (3.5 - 6.8 m^3/d in the summer, and 3.0 - 7.6 m^3/d in the winter).

Influent and effluent nitrate-N concentrations and effluent $sBOD_5$ concentrations are presented in Figure 3. During the initial operation period (days 0 - 7), prior to addition of organic liquor, nitrate-N in the hydroponic wastewater was reduced by 35% (from ~150 mg/L to ~90 mg/L). This indicated that endogenous metabolism of bacteria under anaerobic conditions can provide some of the organic carbon needed by the denitrifying bacteria.

The organic liquor initially used in the experiment was digested for ~7 days prior to transfer to the storage tanks, rather than the minimum 14 day digestion period identified in the winter trial. It was thought that the plant material might have digested at a faster rate at the higher summer temperatures. However, this did not occur and the $sBOD_5$ concentration of this organic liquor was low (only 1500 mg/L compared to that of the liquor used during the winter trial; 4500 mg/L). Therefore, a relatively high volumetric dose of 260 L organic liquor per m^3 of hydroponic wastewater (based on ~2:1 C:N ratio, and influent nitrate-N concentration of 200 mg N/L) was required to add sufficient carbon for denitrification compared with the 100 -170 L/m^3 dose used in the winter trial.

Efficient nitrate-N removal (>92% reduction, from ~200 mg N/L to <15 mg N/L) was still achieved using this higher volumetric dose of organic liquor; however, organic matter from the liquor increased the DFS final effluent organic-N concentration to ~40 mg/L. This highlighted the need to produce a high-strength organic liquor (in terms of $sBOD_5$) in the anaerobic digester before transfer to the storage tanks to reduce organic-N addition to the DFS.

The second plant material digestion was conducted over 14 days with 300% effluent recirculation and, like the winter study produced a high-strength organic liquor ($sBOD_5$ concentration of 3500 mg/L).

By using this high-strength organic liquor, the dose to the DFS was reduced to 95 L/m^3 and with ~300% effluent recirculation both high levels of nitrate-N removal (>92% reduction, from ~230 mg N/L to <20 mg N/L) and low levels of effluent residual organic-N and $sBOD_5$ were achieved (Figure 3). From day 43, failure of the organic liquor dosing pump resulted in an inconsistent supply of organic liquor and nitrate-N removal decreased to ~60% (from 230 mg/L to 92 mg/L).

These summer-monitoring results indicate that a consistent and reliable organic carbon supply (anaerobic digester organic liquor with a high $sBOD_5$ concentration) are critical to achieving a high level of nitrogen removal by the DFS and minimizing residual organic-N and $sBOD_5$ in the DFS effluent.

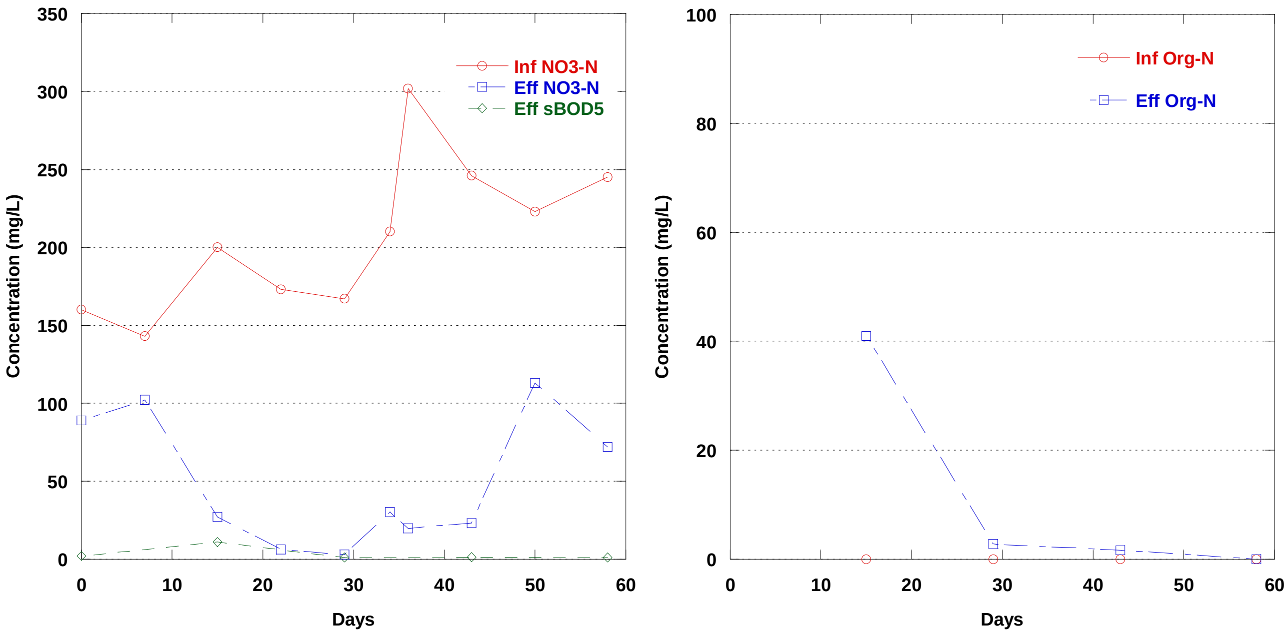

Figure 3: Influent and effluent nitrate-N concentrations and effluent $sBOD_5$ concentrations (left) and influent and effluent organic-N concentrations (right) monitored during the eight week summer monitoring period.

3.2 Phosphorus removal

The DFS also reduced the TP and DRP in the hydroponic wastewater by 53% (from 42 mg/L down to 20 mg/L) and 51% (from 40 mg/L down to 19 mg/L) respectively. Despite a higher phosphorus concentration in the hydroponic wastewater than in the winter period (42 mg/L compared with 25 mg/L), the phosphorus removal rates were very similar (~5 $g/m^3/d$). This indicates that phosphorus removal via the DFS may be unaffected by seasonal variation in ambient temperature. Furthermore, there was no indication of saturation of the filter media by phosphorus accumulated by the anaerobic bacteria after 2 ½ years of operation.

4. Conclusions

Nitrate-N and phosphorus removal in a full-scale DFS was monitored over an 8-week summer period from 5th February to 4th April 2009 and key operation parameters for hydroponic wastewater treatment were investigated.

The major conclusions of this study were:

1. High levels of nitrate-N removal (>92% reduction, from ~230 mg N/L to <20 mg N/L) were achieved using an organic liquor dose of ~2C:N with effluent recirculation of ~300% of daily flow. These similar results to the winter trial indicate that seasonal variation in temperature has little effect on nitrate-N removal by the DFS.

2. A consistent organic carbon supply (organic liquor with a high $sBOD_5$ concentration) is critical to achieve a high level of nitrogen removal by the DFS as well as minimal residual organic-N and $sBOD_5$ in the DFS effluent.

3. A digestion period of at least 14 days with recirculation is required throughout the year to produce a high-strength organic liquor from waste plant material.

4. Phosphorus removal (~50%) also appeared to be unaffected by seasonal temperature variation, and after 2 ½ years of operation, there was no indication of saturation of the filter media by phosphorus accumulation.

5. Endogenous metabolism of bacteria in the DFS enabled ~35% nitrate-N removal. This may explain how the DFS has operated with a relatively low C:N ratio (2C:N) while still achieving high levels of nitrate-N removal (>90%) compared with literature C:N values (e.g., 3C:N; Metcalf & Eddy, 1991).

This summer full-scale demonstration trial has confirmed that the DFS will effectively remove nitrogen and phosphorus from hydroponic wastewater using organic liquor digested from glasshouse waste plant material throughout the year as long as sufficient soluble organic carbon is supplied.

Given the success of this demonstration project, dissemination of the potential benefits of the DFS to glasshouse operations is warranted. NIWA would be pleased to assist

Horticulture NZ in providing information regarding the design and operation of the DFS to the horticulture industry.

5. General DFS specifications and operation parameters

Based on these full-scale DFS demonstration results general DFS specifications and key operational parameters for the management of hydroponic wastewater from glasshouse operations in New Zealand have been determined, assuming a hydroponic wastewater flow of 10 m^3/d with a nitrate-N concentration of 300 mg/L (Table 2; Figures 4, 5 & 6).

The DFS requires a total volume of 45 m^3 (working volume of 20 m^3 assuming a media porosity of 45%) to give a ~2 d Hydraulic Retention Time (HRT). Consistent addition of organic plant liquor to the DFS at the 2C:N ratio is critical for effective nitrate removal.

An anaerobic plant material digester (with a hydroponic wastewater addition rate of 0.5 m^3/m^3 waste plant biomass) can produce organic liquor with a $sBOD_5$ concentration of ~5000 mg/L after ~14 days digestion with recirculation. To provide sufficient organic carbon for the DFS, approximately 0.1 m^3/d of waste plant material would need to be generated in the glasshouse operation. Ideally this would be added to the anaerobic digester every two weeks. The plant material digester should not need to be desludged for at least 5 years (based on an annual non-volatile solids accumulation rate of 1.8 m^3/y (Park and Craggs, 2008)).

The Yearbury's DFS was constructed from concrete blocks (Interbloc™), and a 20 ft shipping container was used for the anaerobic digester. However, a range of materials or containers may be suitable for construction of the DFS and the anaerobic digester. The tanks must be structurally sound and be made water and air-tight.

A total of 3 pumps (influent, effluent recirculation and organic liquor recirculation/drain pump) are required for the DFS and the anaerobic digester operation. One chemical dosing pump (e.g., Grundfos DMS Digital Dosing™ pump) is required for organic liquor addition.

Predicted effluent characteristics from the DFS are given in Table 3. Total-N removal of ~87% (from 300 to 40 mg/L) and nitrate-N removal of ~90% (from 300 to 30 mg/L) are achievable year-round. In addition, Total-P and DRP removal of ~50% are achievable throughout the year.

Table 2: DFS specifications and key operation parameters based on a daily hydroponic wastewater flow of 10 m^3/d.

Design parameters	**General DFS**
Hydroponic wastewater flow (m^3/d)	10
Nitrate concentration (g N/m^3)	300[1]
Total daily nitrogen load (kg/d)	3
Optimal DFS Hydraulic Retention Time (d)	2
External Carbon Source	digested organic liquor
Effluent Recirculation Rate	300% of daily flow rate
(1) Denitrification Filter System (DFS)	
DFS working volume (m^3)	20
Type of growth media	Pumice/Gravel
Porosity of growth media (%, assumed)	45
DFS reactor volume (m^3)	45
Total volume of media required (m^3)	45
Total volume of pumice (m^3)	35
Total volume of gravel for drainage (m^3)	10
(2) Anaerobic plant material digester	
$sBOD_5$ released by 1 kg waste plant material (g) (Park et al. 2005)	12.0
Practical ratio of Carbon to Nitrate (Park et al. 2005, 2008)	2 :1[2]
Total mass of $sBOD_5$ required (kg $sBOD_5$/d, to treat 1 m^3 wastewater)	0.6
Digested organic liquor $sBOD_5$ conc. (mg/L)	~5000
Organic liquor dose (L/d)	1200
Total mass of waste plant material required (kg/d)	500
Approximate daily volume of waste plant required (m^3/d)	1.0
Water addition rate (L/m^3 waste plant biomass)	500
Total volume of the anaerobic plant material digester (m^3) (20 ft open shipping container)	21
Approximate desludging interval (year)[3]	5

[1] will be varied depending on wastewater characteristics

[2] needs to be adjusted to achieve both high nitrate removal and low $sBOD_5$ concentration in the final effluent

[3] or more frequently if blockages occur

Table 3: Typical DFS effluent characteristics

Parameters	Concentrations (mg/L)	Comments
Total-N	<40	Total-N removal of ~90% (300 → 40 mg/L)[1]
NH_4^+-N	<2	-
NO_3^--N	<30	NO_3^--N removal of 90% (300 → <30 mg/L)[2]
Total-P	<15	Total-P removal of 50% (30 → 15 mg/L)
DRP	<15	Total-N removal of 50% (30 → 15 mg/L)[3]

[1] An additional ~10 mg/L organic-N removal could be achieved by using a higher-strength organic liquor (less organic N addition due to lower volume added)

[2] Optimal operation could reduce nitrate to <30 mg/L (up to 90% removal based on 95 percentile effluent concentrations).

[3] Optimal operation could reduce DRP to <15 mg/L (up to 70% removal based on 95 percentile effluent concentrations)

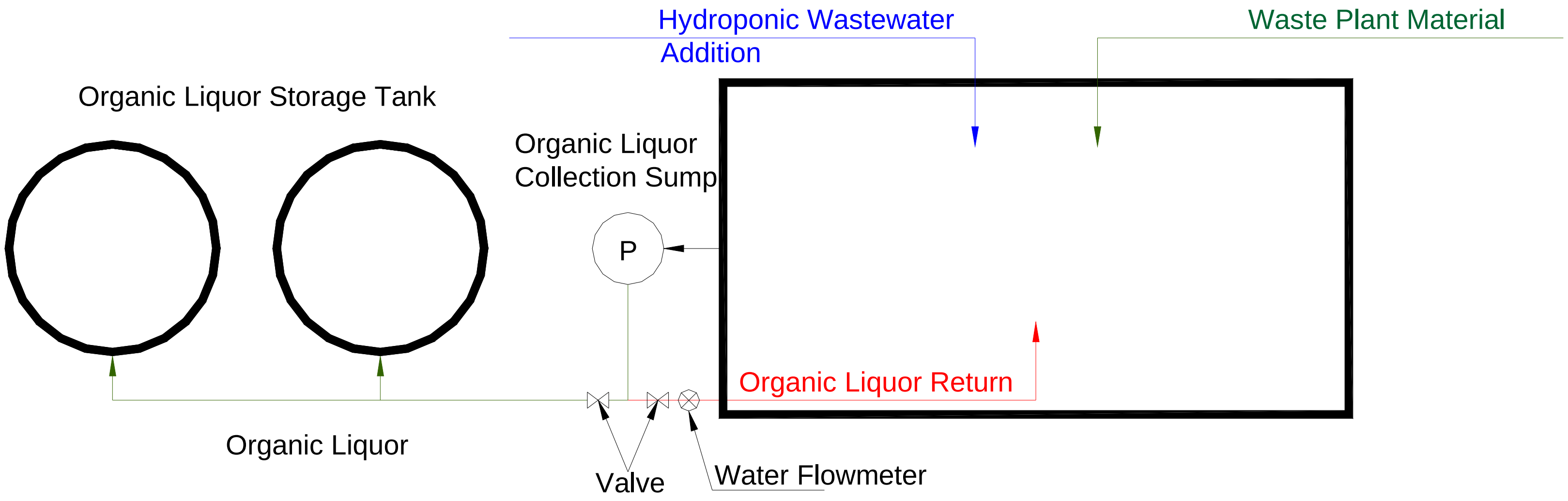

Figure 4: **Plan view of** waste plant material anaerobic digester for organic liquor production.

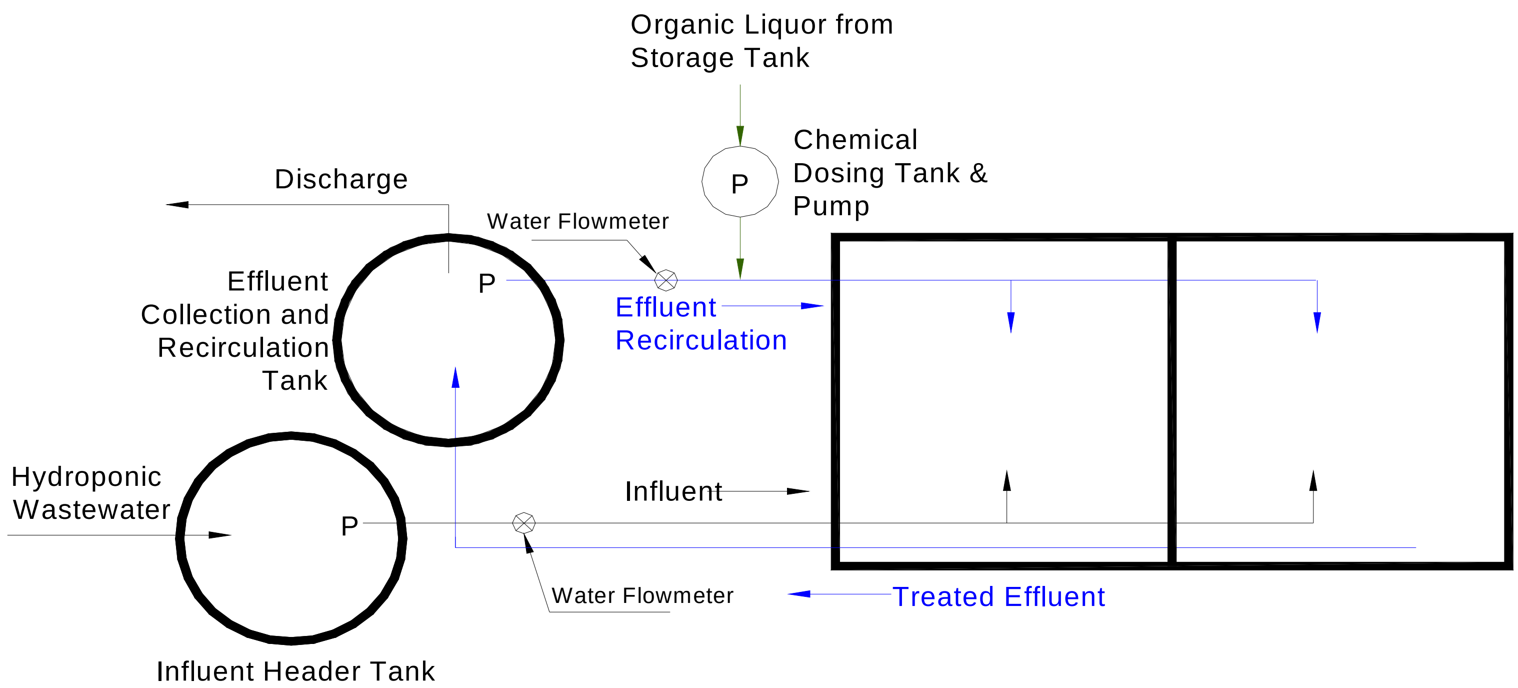

Figure 5: Plan view of a Denitrification Filter System (DFS)

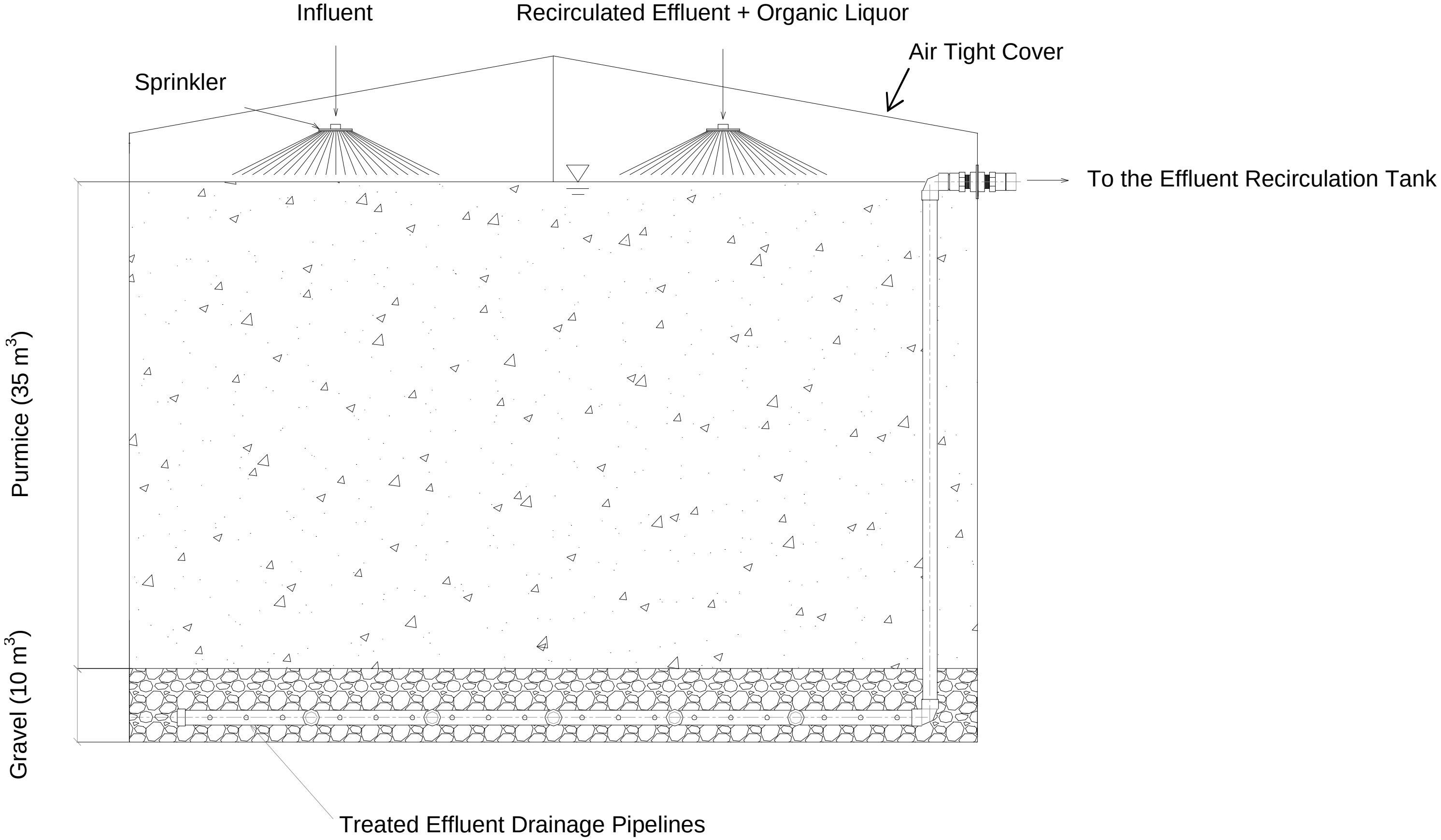

Figure 6: Side view of a Denitrification Filter System (DFS)

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