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Investigation on the performance of sugarcane bagasse as a new carbon source in two hydraulic dimensions of denitrification beds

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Abstract

Hydraulic modeling of denitrification beds is very useful for improving the performance of substrates. In this work, a column study was conducted for 98 days on two types of substrates using two different column lengths and at varying loading rates to determine the best hydraulic dimensions of the substrates. One substrate consisted of soil alone and the other substrate consisted of the same soil along with sugarcane bagasse (acting as an additional carbon source). The substrate with 0.7 h actual hydraulic retention time and 5.84 cm h\(^{-1}\) hydraulic loading rate was chosen as the best model for simulation of denitrification substrate with an optimum nitrate removal efficiency (85%) and a maximum removal rate (50 mg L\(^{-1}\) h\(^{-1}\)). The Fourier Transform Infrared analysis confirmed the degradation of sugarcane bagasse during the denitrification process.

Key words: Denitrification bed; Sugarcane bagasse; Nitrate removal; Hydraulic loading rate; Carbon source.

1. Introduction

Nitrate is one of the most common groundwater contaminants (Schipper and McGill, 2008). Available technologies for reducing nitrate leaching include plant or crop harvesting (Cameron, 1997); nitrate immobilization into the organic matter (Degens et al., 2000) and denitrification (Ghane et al., 2015). Denitrification is the process by which nitrate is reduced to N\(_2\) gas by microbes, completing the nitrogen cycle (Schipper and McGill, 2008). This technology has been developed to remove/reduce the nitrate concentrations from the aquatic environment (Xiao et al., 2013). Denitrification walls
can consist of 100% woodchips or sawdust mixed with soil or sand (Robertson and Cherry, 1995). The performance of four carbon sources (wood, barley straw, rice husks, and date palm leaf) as denitrification substrates has been previously studied (Hashemi et al., 2011). Hydraulic loading rate has been reported as an important factor influencing the performance of a soil remediation system (Li et al., 2011). Recently, different types of bed reactors using heterotrophic microorganisms and solar energy-powered floating media have been examined for the removal of nitrate-nitrogen (Chang et al., 2016; Mohanty et al., 2016). Sugarcane industries produce different types of solid and liquid wastes which cause serious environmental pollution due to the lack of sustainable solutions for their waste management (Bhatnagar et al., 2016). Sugarcane bagasse is one of the by-products generated in sugar industries. Many developing countries produce enormous quantities of sugarcane bagasse and destroy or burn them inadequately causing pollution of the environment. However, many studies have shown the beneficial uses of sugarcane bagasse for different purposes (Makul and Sua-iem, 2016; Renouf et al., 2013).

To date, a variety of solid carbon sources (e.g., fresh chips, kinloch, karaka, dargaville, maize cobs, wood chips, hardwood, green waste, wheat straw, softwood, barley straw and palm leaf) have been investigated for nitrate removal in denitrification beds (Cameron et al., 2011; Robertson, 2010; Schipper et al., 2010). Nevertheless, it is still necessary to find a cost-effective and more economical carbon source. Therefore, the main objectives of this study were to evaluate the performance of two substrates (i) soil alone and (ii) mixture of soil and sugarcane bagasse (as a new denitrification substrate).
in the denitrification process and to determine the optimal hydraulic parameters to improve the performance of substrates containing sugarcane bagasse.

2. Materials and methods

2.1. Preparation of substrates and laboratory model

The soil was collected from a depth of 40 to 50 cm in an agricultural field placed in the research station of Shahid Chamran University, Ahvaz, Iran. Some of the important properties of substrates or biofilters are listed in Table 1. In each column, 70% of its volume consisted of soil and 30% consisted of sugarcane bagasse (Saccharum hybrid cultivar, CP69-1062). Fig. 1 shows the schematic representation of experimental columns set-up and simulation of hydraulic loading rates. Columns with lengths of 35 and 65 cm consisted of a mixture of soil and sugarcane bagasse and were named CT\textsubscript{1}SB and CT\textsubscript{2}SB, respectively. Columns with lengths of 35 and 65 cm consisted of only soil were named CT\textsubscript{1}S and CT\textsubscript{2}S, respectively. In order to properly simulate the denitrification process with saturated conditions, an upward flow was used. The input nitrate concentration of 45 mg L\textsuperscript{-1} was prepared with potassium nitrate (KNO\textsubscript{3}). The approximate temperature of the study was 35±5°C.

2.2. Monitoring process

After the preparation of the columns and before the beginning of sampling, leaching of the columns was performed with urban treated water for one month. After determining the approximate outflow rate, drainage water with a known concentration of nitrate was injected into the columns. An upward flow was used to ensure that entire pore volumes
of the columns were filled. During the experiments, flow was continuous, and the average influent nitrate concentration was 45 mg L\(^{-1}\). The daily amount of drainage water was simulated in a large reservoir. The influents were supplied from a 80 L reservoir, which was placed at a height to ensure a constant entrance head. During sampling, nitrate concentrations of outlet and inlet were measured on the same day. Sampling of drainage water from the columns was additionally performed at the same time.

2.3. Sampling and water quality analysis

Sampling of influent and effluent was performed in the beginning of the experiments, daily for one week. After one week, sampling was limited to once weekly and finally bi-weekly. The nitrate concentration was analyzed immediately in the samples by using a spectrophotometer (DR5000, Hach, USA) at a wavelength of 220 nm. The pH of the samples was measured using a pH meter (Inolab model). For all samples, the outflow discharge rates were approximated through the collection of a given volume of water in a specific time (Hashemi et al., 2011).

2.4. Statistical analyses

All statistical analyses were performed using SPSS 21 software. All significance testing was at the 95% confidence level.

2.5. Estimation of nitrate removal rate
Nitrate removal rate (mg L\(^{-1}\) h\(^{-1}\)) was calculated using the following equation (Ghanie et al., 2015):

\[
r_{Nitrate} = -\Delta C / AHRT
\]  
(1)

where \(-\Delta C\) and AHRT are the loss of input nitrate concentration (mg L\(^{-1}\)) and actual hydraulic retention time (h), respectively.

AHRT was calculated using the following equation (Ghanie et al., 2015):

\[
AHRT = (L \times n_e) / HLR
\]  
(2)

where L, \(n_e\) and HLR are the column length (m), effective porosity (dimensionless) and hydraulic loading rate (m h\(^{-1}\)), respectively. Estimation of effective porosity was calculated using the equation described by Franzmeier (1991):

\[
K_S = (1.95 \times 10^{-3}) \times (\Theta_e^{2.67})
\]  
(3)

where \(K_s\) and \(\Theta_e\) are the saturated hydraulic conductivity and effective porosity, respectively.

Hydraulic loading rate and saturated hydraulic conductivity were estimated by the equations (4-6):

\[
HLR = Q / A
\]  
(4)

\[
K_S = Q / (i \times A)
\]  
(5)

\[
i = \Delta h / L
\]  
(6)

where Q, A, i, \(\Delta h\) and L are the outflow discharge rate (m\(^3\) h\(^{-1}\)), inflow cross-section (m\(^2\)), hydraulic gradient slope (m m\(^{-1}\)), constant head (m) and column length (m), respectively. In this study, the head constant was 102 cm throughout all the experiments. Therefore, the hydraulic gradient slope was equivalent to 2.91 and 1.56 m m\(^{-1}\) for the 35 and 65 cm beds, respectively.
Nitrate removal efficiency was estimated from the following equation (Zhu et al., 2015):

\[
R\% = \frac{C_i - C_{ef}}{C_i} \times 100
\]  

(7)

where \( C_i \) and \( C_{ef} \) are the nitrate concentrations of the influent and effluent (mg L\(^{-1}\)), respectively.

3. Results and discussion

3.1. Effect of adding new carbon source and column length on substrate performance

As seen in Fig. 2, nitrate removal efficiency in CT\(_1\)SB, CT\(_2\)SB and CT\(_2\)S columns was higher (80%) in all the experiments, while in the CT\(_1\)S column, it was lower than 40% (except in the beginning of experiments). Schipper and Vojvodic-Vukovic (1998) reported a removal efficiency of over 90% for the groundwater velocities (generally < 0.1 m day\(^{-1}\)), while in this study, a removal efficiency of over 90% occurred in the entrance flow rate of over 0.73 m day\(^{-1}\). By comparing the results of present study with the study of Schipper and Vojvodic-Vukovic (1998), it can be stated that different carbon sources have different effects on hydraulic parameters and performance of beds. Schipper and Vojvodic-Vukovic (1998) investigated the performance of sawdust as a denitrification wall and the position of denitrification wall had different effects on the nitrate removal efficiency.

In the present study, addition of a new carbon source (sugarcane bagasse) caused a decrease in HLR and an increase in AHRT in the shorter column and improved the nitrate removal efficiency considerably. Severe decrease in HLR and subsequently hydraulic conductivity (during the addition of organic matter to the soil) has also been
observed by other researchers (Schipper et al., 2010). It was attributed to clogging to bubble formation and accumulation of microbial biomass in the columns (Soares and Abeliovich., 1998). These results are consistent with the previous findings, reported by Ghane et al. (2015), who suggested that increasing bed length is important to create a longer hydraulic retention time and, finally, to create a lower outflow nitrate concentration.

Table 1 shows that the effective porosity in CT$_1$SB column is lower than CT$_2$SB column. Therefore, it can be deduced that in the beginning of the experiments, when the new carbon source was added, soil particles moved and finally led to the blocking of soil pores in the shorter column (CT$_1$SB) with a higher gradient slope. The results of this study suggest that improving the AHRT and decreasing the HLR are not alone effective on substrate performance and the presence of a new carbon source is also important.

3.2. Optimization of hydraulic parameters

HLR has been reported as one of the important parameters in wetland design (Lin et al., 2008). With increasing HLR, organic content in the effluent could be lower than that in the influent. Lin et al. (2008) have observed this trend in the HLRs of more than 0.04 m day$^{-1}$. Researchers have found that nitrate removal rate was increased with increasing HLR until a maximum HLR value; and after that, further increase in HLR led to a considerable decrease in nitrate removal rate (Lin et al., 2008). In this study, the optimal AHRT and HLR were chosen as 0.7 h and 1.4 m day$^{-1}$, respectively. An increase in HLR (>5.84 cm h$^{-1}$) led to a considerable decrease in nitrate removal rate in shorter
columns without sugarcane bagasse (Fig. 3(a)), while the nitrate removal rate was increased in the T_2 columns, with an increasing HLR until 4.5 cm h^{-1} (Fig. 3(b)). These results suggest that achieving desirable amounts of r_{NO_3} and nitrate removal efficiency might be possible through optimizing the column length and adding a new carbon source. The results of this study have shown that increasing AHRT (more than 1.9 h) does not have any significant effect on improving the nitrate removal efficiency (Fig. 4(a)) and therefore, an AHRT of ca. 1.9 h was found to be the best for removing more than 90% of input nitrate in the longer columns. However, in the shorter columns, nitrate removal efficiency increased from 85% to 95% by increasing the AHRT from 0.7 h to 1.5 h (Fig. 4(b)). The results of this study reveal that CT_1SB and CT_2S columns exhibit the same performance. Therefore, CT_1SB column with 0.7 h AHRT and 5.84 cm h^{-1} HLR was chosen as the best model for the simulation of denitrification with an optimum nitrate removal efficiency (85%) and a higher removal rate (50 mg L h^{-1}) with 45 mg L^{-1} input nitrate concentration.

3.3. Fourier Transform Infrared (FT-IR) analysis
The results of FT-IR analysis are presented in Fig. 5 (a) and (b). The considerable differences were observed between functional groups of fresh and used sugarcane bagasse, as can be seen in the FT-IR spectra. For example, the bands at 1328 and 1728.82 cm^{-1} were observed in fresh sugarcane bagasse, while these bands disappeared from the used sugarcane bagasse confirming the degradation of sugarcane bagasse during the denitrification process.
4. Conclusions

The results of hydraulic modeling of denitrification substrates have demonstrated that different parameters such as HLR and AHRT can influence the design of biofilters or beds and therefore, an optimum range for these parameters should be first examined to improve the nitrate removal rate and removal efficiency to achieve a desirable level. CT$_1$SB column with 0.7 h AHRT and 5.84 cm h$^{-1}$ HLR was selected as the best model for the simulation of denitrification with an optimum nitrate removal efficiency (85%) and a maximum removal rate (50 mg L h$^{-1}$) with 45 mg L$^{-1}$ input nitrate concentration. The results of this study also suggest that adding a new and ideal carbon source to the environment might help to improve the nitrate removal efficiency during the denitrification process and decrease the amount of nitrate leaching from the system. The study also concluded that sugarcane bagasse offered a more favorable condition to the denitrification process than did the initial carbon source present in the soil. Sugarcane bagasse helped to improve the AHRT and decreased nitrate leaching from substrates. Effect of HLR was found greater than the effect of AHRT on substrate performance.

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References


**Table 1.** Important properties of the biofilters used in this study.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Type of substrate or biofilter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Soil</td>
</tr>
<tr>
<td>Organic material (%)</td>
<td>1.4</td>
</tr>
<tr>
<td>Organic carbon (%)</td>
<td>0.82</td>
</tr>
<tr>
<td>Total nitrogen (%)</td>
<td>0.075</td>
</tr>
<tr>
<td>C:N</td>
<td>10.93</td>
</tr>
<tr>
<td>ρ (g cm$^{-3}$)</td>
<td>(1.55$^a$, 1.63$^b$)</td>
</tr>
<tr>
<td>Total porosity (%)</td>
<td>(41.5$^a$, 38.5$^b$)</td>
</tr>
<tr>
<td>Effective porosity (%)</td>
<td>(12$^a$, 11$^b$)</td>
</tr>
<tr>
<td>Clay (%)</td>
<td>12</td>
</tr>
<tr>
<td>Sand (%)</td>
<td>44.6</td>
</tr>
<tr>
<td>Silt (%)</td>
<td>43.4</td>
</tr>
<tr>
<td>Soil texture</td>
<td>Loam</td>
</tr>
</tbody>
</table>

$a$: biofilter with length of 35 cm and $b$: biofilter with length of 65 cm.
**Figure captions**

**Figure 1.** Schematic representation of the laboratory columns used for the simulation of two different hydraulic loading rates.

**Figure 2.** Trends of nitrate removal rate and nitrate removal efficiency during experiments in the columns with 35 cm and 65 cm lengths (○: CT₁S-Removal rate; ●: CT₁S-Removal efficiency; ◊: CT₂S-Removal rate; △: CT₂S-Removal efficiency; □: CT₁SB-Removal rate; ■: CT₁SB-Removal efficiency; ⋆: CT₂SB-Removal rate; ▲: CT₂SB-Removal efficiency).

**Figure 3.** Correlation between HLR, nitrate removal efficiency and nitrate removal rate in the columns divided based on the length and substrate type (a) with 35 cm bed length (●: CT₁S-Removal rate; ▲: CT₁SB-Removal rate; ○: CT₁S-Removal efficiency; △: CT₁SB-Removal efficiency) and (b) with 65 cm bed length (●: CT₂S-Removal rate; ⋆: CT₂SB-Removal rate; ○: CT₂S-Removal efficiency; ◊: CT₂SB-Removal efficiency).

**Figure 4.** Correlation between AHRT, nitrate removal rate and nitrate removal efficiency in the columns divided based on the length and substrate type: (a) with 65 cm bed length (●: CT₂S-Removal rate; □: CT₂SB-Removal rate; ○: CT₂S-Removal efficiency; ■: CT₂SB-Removal efficiency) and (b) with 35 cm bed length (○: CT₁S-Removal rate; △: CT₁SB-Removal rate; ●: CT₁S-Removal efficiency; ▲: CT₁SB-Removal efficiency).
Figure 5. FT-IR spectra: (a) fresh sugarcane bagasse and (b) sugarcane bagasse after use.
Figure 1. (for online publication of this article).
Figure 2.

Nitrate removal rate (mg L\(^{-1}\) h\(^{-1}\)) vs. Time (days)

Nitrate removal efficiency (%) vs. Time (days)
Figure 3.
Figure 4.
Figure 5.
Highlights:

• Performance of two substrates in the denitrification process is evaluated.
• Sugarcane bagasse as a new carbon source in denitrification beds is studied.
• Hydraulic dimensions of beds are optimized to improve the nitrate removal rate.