ASSESSMENT OF WOOD CHIPS AND AGRICULTURAL RESIDUES AS DENITRIFYING BIOREACTOR FEEDSTOCKS FOR USE IN THE CANADIAN PRAIRIES

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HIGHLIGHTS

• Performance of denitrifying bioreactors in Alberta was evaluated.
• Barley straw was more effective in reducing nitrate compared to wood chips.
• Hydraulic retention time, feedstock, and season are the primary factors affecting nitrate removal.

ABSTRACT. This study evaluated the performance of pilot-scale denitrifying bioreactors (LWD: 6 × 0.6 × 1m) filled with different carbon substrates, including barley straw, hemp straw, and woodchips, for removing dissolved nitrogen from simulated subsurface drainage at two representative geographic locations in Alberta. In this study, the bioreactors were tested under varying hydraulic retention times (4, 8, and 12 h) in the spring, summer, and fall of one year. Tracer studies were conducted to evaluate flow and dispersion characteristics. The mean of nitrate removal efficiency ranged from 19% to 87% during the spring, 44% to 95% during the summer, and 21% to 68% during the fall. We found that barley straw was more effective in reducing nitrate (45% to 95%) compared to wood chips (19% to 54%). This study is the first testing of the effect of different biomass types and hydraulic residence times on bioreactor performance in the Canadian prairies (Alberta) and will allow agricultural producers and regulators to assess the suitability of these systems within the region.

Keywords. Bioreactor, Denitrification, Water quality, Wood chips, Agricultural residues, Subsurface Drainage.

Land and drainage for agricultural production originated at least 2,500 years ago in Egypt (Pavelis, 1987). It is the practice of removing excess water from the soil, which lowers the water table and creates a well-aerated environment in the root zone that enhances the availability and uptake of crop nutrients. In North America, Europe, and throughout the world, land drainage and water management for agriculture have become common practices. However, such practices have significantly altered the hydrology and nutrient balance of wetland, stream, river, floodplain, and riparian ecosystems (Blann et al., 2009; Christianson et al., 2016; Moore, 2016).

Subsurface drainage involves the use of buried perforated pipes or tiles that transport excess water away from the root zone of crops for discharge to downslope waterbodies. A consequence of subsurface drainage is increased loss of mobile nutrients (e.g., nitrate) from agricultural lands. Both surface and subsurface drainage result in substantial losses of soluble forms of nitrogen, phosphorous, and other soil or agricultural chemicals to surface water and groundwater (Blann et al., 2009; Moore, 2016). Subsurface drainage is becoming widely adopted in North America and is contributing to the increasing trend in nitrate-nitrogen loads observed in many rural streams (Hudson et al., 2018), which can lead to eutrophication and deterioration of water quality (Villeneuve, 2017). The problem of excessive nutrient loss from agricultural landscapes has been recognized, and various mitigation practices have been developed, particularly for nitrate (Christianson, 2011; Addy et al., 2016; Hudson et al., 2018). Christianson et al. (2016) described ten promising practices to reduce nitrate load and improve water quality – the installation of passive denitrifying bioreactors being one of them. A denitrifying bioreactor is a buried trench filled with carbon substrates (often fragmented wood products) that act as a carbon and energy source to facilitate the biochemical process of denitrification – the microbial-driven conversion of nitrate (NO3−N) to nitrogen gases (Schipper et al., 2010). One of the benefits of bioreactors is that they fit well in edge-of-field grassed buffer areas and typically...
require little or no land to be removed from agricultural production (Christianson et al., 2016).

Low temperatures in cold climate regions, such as Alberta and elsewhere on the Canadian Prairies, as defined by the Köppen-Geiger climate classification (Peel et al., 2007), limit the performance of passive bioreactors. This is due to the temperature dependency of microbial denitrification (Addy et al., 2016; Hassanpour et al., 2017; Povilaitis et al., 2018; Ghane et al., 2019) and the relation of cooler air temperatures to cooler water temperatures. To enhance nitrate removal performance in cold climates, some studies have explored the use of alternative carbon-rich feedstock sources that emit more labile carbon than fragmented woodchips. These alternative carbon-rich feedstock sources could be composted woodchips (Kouanda and Hua, 2021), fly ash pellets (Kiani et al., 2022), bottle sedge, barley straw (Hellman et al., 2021), and wheat straw (Saliling et al., 2007).

Promising performance of agricultural residue media has also been found in the laboratory. Warneke et al. (2011) performed a study within experimental barrels and showed that maize cobs, wheat straw, and green waste in these barrels removed more nitrate than wood substrates over 2.5 years. Feyereisen et al. (2016) explored the performance of agriculturally-derived substrates (rather than wood chips) at warm and cold temperatures in laboratory columns. They found that the nitrate removal rate was significantly lower for the cold temperature experiment compared to the warm temperature experiment for the agricultural residues but not for wood chips. Grießmeier and Gescher (2018) compared the nitrate removal performance of wood pellets, wheat straw, and wood chips in laboratory denitrification bioreactors and found that the bioreactors with straw showed the best nitrate removal rates for moderate nitrate concentrations.

This study compares the effects of different carbon-rich feedstocks on bioreactor performance in the Canadian prairies, which are characterized by cold climate conditions. According to Christianson and Shipper (2016), it is particularly important to test the performance of bioreactors under a wide range of climates around the world.

The goal of this study was to assess the performance of denitrifying bioreactors by evaluating nitrate removal and flow dynamics of bioreactors operating at hydraulic retention times (HRTs) of 4, 8, and 12 h and filled with different carbon-rich feedstocks: agricultural residues (barley straw and hemp straw) and wood chips. Agricultural residues are readily available on the Canadian prairies due to extensive agricultural crop production and ease of procurement of hemp straw in our study area (irrigation allows for production of specialty crops).

Tracer tests are a common method for assessing bioreactor performance and internal bioreactor hydraulics. A tracer test follows the movement of an injected substance through the bioreactor. In this study, sodium chloride was used. Results of the tracer tests allow for the characterization of hydraulic efficiency, short-circuiting, and dispersion (Christianson et al., 2013; Ghane et al., 2019). Assessment of these flow hydraulics is useful for diagnosing poorly performing bioreactors (Hoover et al., 2017), or more specifically, for the detection of poor flow distribution and mixing or re-circulation zones (Persson et al., 1999).

It was hypothesized that the performance of denitrifying bioreactors could be improved by using agricultural residues such as barley straw and hemp straw as fill media instead of wood. The longer retention time was also expected to enhance the overall nitrate removal capacity. The results from this study will contribute to the scientific community's understanding of bioreactor applications, enabling farmers and regulators to assess the technology's suitability in their local context.

**Materials and Methods**

The two sites in this study were located at the Crop Diversification Centre North (CDCN; Central Alberta) and the Taber Irrigation District (TID; Southern Alberta). These locations represent different climate conditions common to Alberta’s agricultural regions, and although they are both defined by Köppen-Geiger climate classification as cold, their subregional climates differ. The climates were humid continental in central Alberta and semi-arid in southern Alberta. During the growing season (April 1 to September 30), the sites differ in average air temperature (Air Temp. Avg.), precipitations patterns (Precip. Accumulated) and number of frost free days. The values for these parameters were observed at the two closest weather stations, Edmonton Namao AWOS A (central) and Fincastle IMCIN (south) (https://agriculture.alberta.ca/acis/weather-data-viewer.jsp), and are presented in table 1 for 2020.

Nine pilot-scale bioreactors (three replicates of three substrate types) were installed at each site in the fall of 2019. A trench-style bioreactor design was used in this study, as it represents a simple and practical way to intercept and treat subsurface drainage water. Each trench was excavated to approximate dimensions of 6 m length, 0.6 m width, and 1.3 m depth. These dimensions were considered suitable for pilot-scale bioreactors to test treatment performance and system hydraulics under varying HRTs and feedstocks. Field-scale application would require estimation of the typical rate of flow through a tile drain network outlet, and the system would have to be sized to achieve the desired HRT in the bioreactor as a function of the flow rate.

Prefabricated liners (30 mil linear low-density polyethylene to minimize damage from equipment used in the installation) were then fixed within the trenches to line the bottom and sides, with extra to fold over the top after filling with carbon feedstock. Field staff filled the trenches with one of three types of carbon-rich organic substrates: wood chips, hemp straw, and barley straw (fig. 1), which were obtained from local producers proximal to each site. The feedstocks were packed in the trenches as tightly as possible and filled until the material reached beyond the top of the trench. The filling procedure was done at both sites by different field staff.

<table>
<thead>
<tr>
<th>Station (Study Site)</th>
<th>2020 Growing Season Air Temp. Avg. (°C)</th>
<th>2020 Growing Season Precip. Accumulated (mm)</th>
<th>2020 Frost Free Days (0°C) (# days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Edmonton Namao AWOS A (CDCN)</td>
<td>11.7</td>
<td>369.0</td>
<td>125</td>
</tr>
<tr>
<td>Fincastle IMCIN (TID)</td>
<td>13.9</td>
<td>256.6</td>
<td>152</td>
</tr>
</tbody>
</table>

Table 1. Weather data calculated from observations at the weather stations closest to the bioreactor’s locations.
staff (fig. 2). Figure 3 shows the completed bioreactors with the wells.

A large polyethylene plastic cylindrical solution storage tank (550 gallon) was installed at the head of the bioreactors for storing and mixing the nitrate solution. Intake water was pumped from an adjacent stream for the CDCN site and from an irrigation canal for the TID site, which was then dosed inline with the nitrate solution using a fertigation-grade dosing pump (Dema MixRite TF-10) located in the pump shed (fig. 4).

Inflow and outflow pipes were placed at each end of the bioreactors. Four wells made of 10.2 cm (4 in.) polyvinyl chloride (PVC) tubing were installed vertically within the bioreactors: one each at the start (inlet) and end (outlet) positions, and one each at the two middle positions located at 1.8 m and 3.6 m from the first well (fig. 5). Pressure transducers (Solinst Levelogger Edge) were installed at the third (3.6 m) well to continually monitor water levels and water temperature within the bioreactors. This allowed for the calculation of the depth of the saturated zone. The wells also allowed for the collection of water samples from the bioreactor interior and for determination of saturated hydraulic conductivity of the feedstock material.

Three seasonal assessments of bioreactor performance for removing dissolved nitrogen were conducted on a seasonal basis throughout the growing season, focusing on the spring (May–June), summer (July–August), and fall (September–October) seasons. During each seasonal assessment, water was pumped from the stream or canal, filtered to <100 µm using an automated self-cleaning filter (Amiad Mini Sigma), and dosed to approximately 20 mg L⁻¹ of nitrate using a MixRite fertigation-grade dosing pump (Dema MixRite TF-10) located in the pump shed (fig. 4).

Figure 1. Feedstock used in this study: barley straw (left), woodchips (center), and hemp straw (right). The PVC pipe in the figure was 15.24 cm (6”) in diameter, for reference.

Figure 2. Installation of the bioreactor trenches and carbon substrates at (a) CDCN and (b) TID.

Figure 3. Buried bioreactors showing the vertical wells at (a) CDCN and (b) TID.
Flow control was required to achieve the desired (theoretical) HRT in order to compare the effect of different HRTs on nutrient removal performance. Three HRTs (4, 8, and 12 h) were targeted in triplicate at each site (table 2). These HRTs were targeted because they are consistent with several of the reported HRTs in the literature. For example, in Chun et al. (2009), laboratory-scale bioreactors filled with woodchips were reported to reduce NO$_3$-N concentrations by 10% to 40% at HRTs < 5 h and 100% at HRTs of 15.6 h and 19.2 h. In Christianson (2011), a pilot-scale bioreactor drainage study was performed at a location in Iowa. The bioreactors were packed with woodchips, and 30% to 70% NO$_3$-N removal within a 4–8 h HRT range was reported. Addy et al. (2016) compiled a spreadsheet for nitrate removal that included different HRTs and other parameters; lessons from their analysis suggest extending the HRT to manage nitrate removal under low temperatures and high flows.

Tracer tests were conducted on every bioreactor during each season at each site to characterize each bioreactor in terms of its physical and hydraulic properties. One kilogram of sodium chloride (NaCl) (4 L of 250 mg L$^{-1}$ solution) was added to the inlet of each bioreactor during the test, and the change in specific conductance was monitored at the outlet well using deployable conductivity sensors (Onset HOBO U24) capable of continuous monitoring. Calibration curves were established from each test to calculate solute mass transport from conductivity measurements. These measurements enabled the calculation of the actual hydraulic...
retention time as well as additional hydraulic properties for each bioreactor, such as hydraulic efficiency ($\lambda$; eq. 1), solute dispersion (using the Morrill Dispersion Index [MDI]; eq. 2), and preferential flow (using the short-circuiting index [S]; eq. 3). Equations are as follows:

$$\lambda = \frac{t_p}{\text{HRT}}$$  \hspace{1cm} (1)

$$\text{MDI} = \frac{t_{90}}{t_{10}}$$  \hspace{1cm} (2)

$$S = \frac{t_{16}}{t_{50}}$$  \hspace{1cm} (3)

with $t_p$ as the time to reach peak outflow concentration to the theoretical, targeted, or estimated HRT (Persson et al., 1999), and $t_{90}$, $t_{50}$, $t_{10}$, and $t_{16}$ representing the time for 90%, 50%, 16%, and 10% of the tracer to pass through the bioreactor, respectively (USEPA, 1986; Ta and Brignal, 1998; Hoover et al., 2017). According to Christianson et al. (2013), parameter values of $\lambda > 0.75$, $S = 1$, and MDI < 2 are classified as ideal hydraulic conditions for bioreactor performance.

Hydraulic efficiency ($\lambda$) was calculated as the ratio of mean solute HRT to the time of peak concentration (Persson et al., 1999), and it indicates the departure of the average HRT of solutes from the target HRT and the presence of dead zones (where fluid flows very slowly or not at all) in the interior of the bioreactor. Hydraulic efficiency values fall between 0.0 and 1.0, with 1.0 being the most ideal as it represents ideal flow and the greatest hydraulic efficiency. However, values above 0.5 indicate conditions that still allow for some effective flow and are considered satisfactory for a working bioreactor (Persson et al., 1999).

The Morrill Dispersion Index (MDI) is an indicator of dispersion and mixing of the tracer throughout the bioreactor, where values from 1.0 – 2.0 indicate plug flow (i.e., no mixing or back flow). Higher MDI values indicate that the tracer spread out within the bioreactor and the resulting tracer curve will have a wide peak rather than a sharp one (Dougherty, 2018). A spike response implies that every element of the pulse resides in the bioreactor for an equal amount of time (USEPA, 1986). The typical MDI for a completely mixed bioreactor is around 22 (Hoover et al., 2016).

The short-circuiting index (S) indicates the degree of preferential flow paths occurring in the bioreactors; an S value of 1.0 indicates uniform flow across the bioreactor, which is most effective for nitrate removal. S values less than 1.0 indicate that preferential flow or short-circuiting is occurring, which means a portion of the water flows quickly through the feedstock with little opportunity for nitrate removal (Hoover et al., 2017).

Saturated hydraulic conductivity along the flow path was calculated using a slug test in which a 9 cm diameter bailer (~5 L volume) was lowered into one of the internal wells in the bioreactor to remove a volume, or ‘slug’ of water (Hvorslev, 1951). The recovery of the water level was measured using a pressure transducer (Solinst Levelogger Edge) set to record water levels every 0.5 seconds to account for the rapid recovery of the water level in the substrates. Slug tests were performed at each bioreactor at the end of each season.

Bioreactor performance was assessed using the difference in concentrations from the inlet to the outlet well positions. During each of the three 4-week seasonal assessments, weekly water samples were collected from the outlet well of each bioreactor using a bailer. Source water samples from the stream (CDCN) and the irrigation canal (TID) were also collected and analyzed in order to provide background concentrations prior to mixing the source water with nitrate fertilizer. Sample bottles were triple rinsed with sample water, then filled with as little headspace as possible. Sample bottles were placed in coolers with ice packs and shipped to the laboratory. They were analyzed for pH, electric conductivity (EC), ammonium nitrogen (NH₄-N), nitrate-nitrogen (NO₃-N), nitrite-nitrogen (NO₂-N), and alkalinity content. The laboratory analysis for this project was conducted at the Government of laboratories in Lethbridge, Alberta.

The statistical analyses were performed using Microsoft Excel (Microsoft Corporation, 2016) and SigmaPlot (2011). The Mann-Whitney Rank Sum test was done to compare the hydraulic properties among the feedstocks at each site. Boxplots and scatterplots were created using the ‘ggplot2’ package in RStudio Team (2020) to provide visual displays of the water parameter concentrations.

### RESULTS AND DISCUSSION

#### HYDRAULIC PERFORMANCE OF THE BIOREACTORS AND FEEDSTOCK MATERIAL

Tracer and slug tests were successfully performed in all bioreactors. A compilation of the results of the slug tests (saturated hydraulic conductivity) and the tracer tests (hydraulic efficiency, dispersion, and short-circuiting) for all
Saturated hydraulic conductivity was higher at the CDCN site; however, there was a consistent trend between the agricultural residues, with barley straw exhibiting the lowest conductivity and hemp straw having higher conductivity. Feyereisen (2018) also observed higher hydraulic conductivities for wood chips than barley straw (0.048 and 0.028 m s⁻¹, respectively). Other studies have documented woodchip hydraulic conductivities ranging from 0.03 m s⁻¹ (Christianson et al., 2020) to 0.05 m s⁻¹ (Feyereisen et al., 2016), which is greater than the values observed at either site in this study. The hydraulic conductivity values were greater at the CDCN sites for all feedstock types. This could be due to several factors, including subtle differences in the way the material was packed by different field teams when the bioreactors were installed or differences in freeze-thaw events from the installation (fall 2019) and operation (spring 2020) in the different climatic zones.

Based on the classification regime developed by Persson et al. (1999), the bioreactors were operating at good (λ > 0.75) and satisfactory (0.5 < λ ≤ 0.75) hydraulic efficiency levels. The wood-filled bioreactors showed better hydraulic efficiency values than other feedstock types at both sites, while hydraulic efficiency values for hemp and wood were greater at the CDCN site than the TID site.

The MDI values, or degree of dispersion and mixing within the bioreactors at CDCN, were greater than 2 in all cases (outside the range of “effective plug flow”) and appeared to be lower in the hemp and wood bioreactors than bioreactors filled with barley straw. Conversely, the degree of dispersion was greater in the hemp straw bioreactors at TID. Though MDI values were outside the range of “effective plug flow” in this study, they were within the range of MDIs for other pilot-scale bioreactor testing (Christianson et al., 2013).

When short-circuiting exists (S values less than 1.0), a portion of the flow exits the bioreactor sooner than expected. The CDCN site had more ideal flow (i.e., higher S values; less short-circuiting), with S values in the order of wood>hemp>barley, whereas at the TID site, barley straw had less short-circuiting than either hemp or wood, in the order of barley=wood>hemp.

Similar studies for bioreactors filled with wood chips have been performed. Research conducted by Hoover et al. (2017) reported values around 2.8, 0.78, and 0.73 for λ, MDI, and S, respectively, while Schaefer et al. (2021) reported

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**Figure 6.** Hydraulic properties of the bioreactors as measured by (a) hydraulic conductivity (m s⁻¹), (b) hydraulic efficiency (unitless), (c) Morrill Dispersion index (unitless), and (d) Short-circuiting index (unitless). Results are differentiated by feedstock type (barley, hemp, wood chips) and sites (CDCN and TID). In these plots, the bottom of the box is the first quartile (25th percentile), and the top of the box is the third quartile (75th percentile). The line in the middle of the box is the median (50th percentile). The lines, also known as whiskers, extend to the lowest and highest values that are not outliers. Outliers are symbolized using circles.
values of 0.70, 3.3, and 0.66 for the same parameters, respectively. Gosch et al. (2020) also found values of 0.45, 5.8, and 0.56 for λ, MDI, and S, respectively. They also suggested that the parameters that represent preferential flow (e.g., S or λ) are better indicators of hydraulic performance than the parameters that represent dispersion (e.g., MDI), thus more consideration should be given to preferential flow parameters when evaluating hydraulic performance.

There were statistically significant differences in the four hydraulic properties between the two sites according to the results of the Mann-Whitney Rank Sum Test (P < 0.05). At the CDCN site, there was a statistically significant difference (P<0.05) in median values of λ, MDI, and S of barley straw compared to wood and hemp, but there were no statistically significant differences in median values of hydraulic conductivities among the different feedstocks. In contrast, there were no statistically significant differences in median values of the λ, MDI, and S among the three feedstocks at the TID site, but there was a statistically significant difference (P<0.05) in median values of hydraulic conductivities of barley straw compared to wood and hemp.

Collectively, our study results indicate that the physical and hydraulic properties of the bioreactors seemed to be influenced by site (e.g., installation and/or operation) and by feedstock.

EVALUATION OF DIFFERENT CARBON SOURCES FOR NO₃-N REMOVAL

The capacity for bioreactors to remove NO₃-N under varying HRT conditions and feedstock materials was assessed through weekly sampling during the three seasonal assessments (spring, summer, and fall).

At both sites, the source water from the stream (CDCN) and canal (TID) had NO₃-N values below 10 mg L⁻¹, and the pH values were within the range known to be ideal for denitrification (pH = 7.5–9.5); denitrification rates have been shown to decrease outside this pH range (Albina et al., 2019).

Our results show that substantive differences in overall nitrate removal performance between feedstock types were evident during the spring, summer, and fall assessment periods at both sites (fig. 7). The agricultural residues (hemp

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**Figure 7.** Overall percentage of NO₃-N removed during the spring, summer, and fall assessment periods according to the theoretical hydraulic retention time (4, 8, or 12 h) and feedstock material in 2020 for both sites. In these plots, the bottom of the box is the first quartile (25th percentile), and the top of the box is the third quartile (75th percentile). The line in the middle of the box is the median (50th percentile). The lines, also known as whiskers, extend to the lowest and highest values that are not outliers. Outliers are symbolized using circles.
straw, barley straw) tended to exhibit greater denitrification, or nitrate removal, than wood chips under all design HRTs. The denitrification rates during the fall assessment period were observed to be lower, which may have been due to the cooler temperatures during this season at the CDCN site and/or a reduction in labile carbon at both sites as a result of previous bioreactor operations. This is consistent with findings in the literature. Specifically, Feyereisen et al. (2016) found that denitrification was limited by carbon (C) availability at low temperatures, and Hoover et al. (2016) reported a stepped increase of nitrate removal with temperature. Further, Feyereisen (2018) found that cold temperatures tended to reduce microbial activity and negatively affect bioreactor efficiency. Jéglot et al. (2021) also reported that the efficiency of nitrate removal could be limited at cold temperatures because the kinetics of denitrification and fermentation (which supplies labile C) are temperature dependent. Schipper et al. (2010) report a positive relationship with available carbon and temperature on nitrate removal, where they observed reductions in nitrate removal over time with decreasing available C and higher nitrate removal with increasing average annual temperature. Hua et al. (2018) reported that dissolved organic carbon leaching potential followed the order of barley straw>corn stover>corn cobs>woodchips, which may explain in part the higher nitrate removal observed with barley straw in this study given that denitrification is a carbon-dependent biological process. In this study, hemp straw showed greater nitrate removal at 8 h and 12 h HRT at both sites, but it declined throughout the year at the TID site. Barley straw showed the greatest nitrate reduction during the summer season at both sites, but was optimized at 8 h and 12 h HRT, specifically at the TID site. Nitrate removal by bioreactors filled with wood chips varied between sites, showing the greatest nitrate reduction during the spring season at the CDCN site and during the summer season at the TID site. In general, the design of the 4 h HRT showed the lowest performance, suggesting that longer HRTs result in more nitrate removal.

$\text{NO}_3^-$ removal performance (i.e., the difference in $\text{NO}_3^-$ concentration between inlet and outlet wells) and internal water temperature for all bioreactors at both sites are shown in figure 8. In this figure, the three outflow samples (three triangles) for each inflow sample (black circle) are the three replicates, and they represent all the HRTs according to the schedule in table 2. From May to October 2020, the inlet concentrations of $\text{NO}_3^-$ averaged 22.4 ± 4.1 mg L$^{-1}$, which were significantly greater than those at the outlet; 8.9 ± 6.6 mg L$^{-1}$ (Mann-Whitney Rank Sum Test, $P<0.05$). Outlet $\text{NO}_3^-$ concentrations showed an inverse trend as concentrations decreased with increasing temperatures (summer) and increased with decreasing temperatures (fall).

For both sites, $\text{NO}_3^-$ concentrations were significantly lower (Kruskal-Wallis One Way Analysis of Variance on Ranks, $P<0.05$) at the outlets of bioreactors filled with agricultural residues (average concentrations of 5.8 ± 5.9 mg L$^{-1}$ and 7.6 ± 5.9 mg L$^{-1}$ for barley and hemp, respectively) than concentrations at the outlets of bioreactors filled with wood chips (average concentrations of 13.3 ± 5.6 mg L$^{-1}$). However, nitrate concentrations from the outlets of bioreactors filled with barley and hemp straw were not significantly different ($P<0.05$) from each other. This was true when examining each site individually, and when examining the data as a whole.

Figure 8. Measured concentration of $\text{NO}_3^-$ and water temperature during the spring, summer, and fall assessment periods at the inflow and outflow wells of the bioreactors.
Overall, barley straw was more effective (mean: 45% to 95%) than hemp straw (mean: 34% to 83%) and wood chips (mean: 21% to 54%) at removing nitrate. These findings are consistent with values reported in the literature. Feyereisen et al. (2016) found that populations of microbial denitrifiers were higher in agricultural residues (which include barley straw) than in wood chips. This could also partly explain why barley straw was more successful for removing nitrate in this study. Also, Hellman et al. (2021) reported that nitrate removal rates were highest in bottle sedge and barley straw bioreactors, which shared similar taxa within their bacterial communities than in woodchip bioreactors, which had different microbial community assemblages and lower nitrate removal rates. According to Kouanda (2021), agricultural residue media (corn cobs, corn stover, and barley straw) have shown greater nitrate removal than wood due to the more labile carbon content; however, they also observed that nitrate removal capacity declined after 13 months of bioreactor operation in bioreactors with agricultural residues. Several studies have documented NO$_3$-N removal efficiencies of about 50% for wood chip-filled bioreactors (Hassapour et al., 2017; Faramarzmanesh et al., 2021; Wrightwood et al., 2022), although ranges from 8% to 99% nitrate removal have been reported (Hoover et al., 2016; Rivas et al., 2019; Christianson et al., 2020; Díaz-García et al., 2021).

Comparatively, Jeyakumar et al. (2021) conducted a bioreactor study in Eastern Canada (Newfoundland and Labrador) from March to September 2017. In this study, the performance of the wood chip bioreactors resulted in 62% to 66% nitrate removal, which was considered very effective in this boreal forest environment.

Lastly, much research has been conducted in laboratory settings as it represents a step prior to pilot or full-scale trials (Tikhomirova et al., 2018). Hashemi et al. (2010) showed a NO$_3$-N reduction rate of 60% to 70% for laboratory bioreactors filled with barley straw. Similarly, Kouanda and Hua (2021) reported nitrate reductions of 15% for barley straw and 11% for wood in the laboratory, while Hellman et al. (2021) reported NO$_3$-N reductions of 42% for barley and 44% for wood in their laboratory study.

The observed accumulated mass of NO$_3$-N removed can be compared against the total mass of NO$_3$-N added during each assessment period (fig. 9). Higher flows associated with shorter HRTs result in more NO$_3$-N mass added during the approximate 4-week seasonal assessment periods, with longer HRTs (lower flows) never reaching the same cumulative additions.

**CONCLUSIONS**

This study, which aimed to evaluate the performance of pilot-scale denitrifying bioreactors in removing NO$_3$-N under varying agricultural field and climatic conditions in Alberta, was conducted at two different sites in 2020 and provides valuable insights into the effectiveness of this technology for managing nitrate pollution in agricultural settings.

Results show that agricultural residues of barley straw and hemp straw not only had the capacity to remove nitrate from drainage water, but when compared to wood chips, barley straw showed the best nitrate removal performance while the wood chips showed the poorest. The performance of barley straw was optimized in summer, which suggests that warm weather played a key role. When comparing the two sites, the bioreactors at CDCN showed greater mean values of nitrate reduction during almost all assessment periods and within all feedstocks.

The tracer test results indicated significant differences in the hydraulic properties (λ, MDI, and S) for different feedstocks at the CDCN site, but not at the TID site. This suggests that the hydraulic properties of the bioreactors may have been more influenced by the degree of packing during bioreactor construction and/or subsequent settling rather than the geographic location in the province. One way to mitigate the effect of construction methods could be to use a

![Figure 9. Cumulative mass of NO$_3$-N removed as function of the mass of NO$_3$-N added to each bioreactor according to the target hydraulic retention time (4 h, 8 h, or 12 h) and feedstock material for all the sampling dates in 2020.](image-url)
pre-measured volume for each bioreactor to ensure the same amount of measured feedstock is used and the same placement techniques are performed. These observations suggest that bioreactor hydraulics may experience variability if individual landowners or producers install the bioreactors rather than experienced technicians.

In summary, this study identified hydraulic retention time, carbon source material, and temperature as the primary factors affecting nitrate removal. It was found that nitrate removal was highly related to the season; higher rates of removal were observed during the summer season, which had the warmest temperatures.

The observed results are promising, given that hemp and barley straw agricultural residues are readily available in agricultural landscapes throughout the Canadian Prairies. However, a limitation of this study is that the results reflect just one year of bioreactor operation, so the nitrate removal performance of agricultural residues under longer-term operation cannot be inferred from this study, nor are we able to understand the durability of agricultural residues under longer-term operation, which can affect hydraulic properties and subsequently nitrate removal in successive years. The longevity of bioreactor function is an important consideration for future research, as the replacement of feedstocks is likely to be similar in cost to that of the original installation. The replacement cost of feedstocks would factor in the costs of labour and rental of equipment for the removal of soil caps, the excavation and disposal of spent feedstocks, and the purchase and re-installation of new feedstock material. New liners may also be required if compromised during the replacement. In their study, Lepine et al. (2018) found that excavation costs for feedstock replacement differed slightly from the original installation costs due to reduced excavation for plumbing installation. Feyereisen (2018) presents a cost analysis of feedstock replacement using assumptions with respect to the dimensions of the bioreactor, the cost of new media, and the media replacement interval. Estimating the replacement interval and costs depend on key unknowns, such as bioreactor performance, lifespan, and the actual producer cost of the agricultural residues.

The use of agricultural residues instead of wood chips provides an attractive option for the agricultural industry, at least in the short-term, and an incentive to further explore this technology.

This project is a valuable contribution to the development of commercial applications of bioreactor technologies for drainage water management in Alberta to help the agricultural industry minimize its impact on the environment and protect downstream water bodies. However, additional research is necessary prior to widespread implementation of this technology.

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REFERENCES


