Using denitrifying bioreactors as a beneficial management practice for agricultural drainage waters in Alberta

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Executive Summary

In Alberta, sub-surface drainage is a common agricultural water management practice that removes excess water from the soil profile to improve soil moisture conditions for seeding and crop growth. However, sub-surface drainage systems provide direct conduits for transporting nutrients from agricultural fields to surrounding water bodies such as irrigation canals, reservoirs and streams. Elevated concentrations of dissolved nutrients, such as nitrogen (N) and phosphorus (P), in drainage water can lead to water quality impairments including eutrophication of rivers and lakes, toxic algal blooms and potential damage to, and delayed water conveyance in, irrigation infrastructure due to buildup of weeds and algae. Simple, low cost technologies are needed to reduce nutrient export from agricultural sub-surface drainage to sensitive aquatic ecosystems. A potential solution is the use of denitrifying bioreactors– a passive treatment approach where drainage water is routed through solid carbon substrates to remove dissolved nutrients through physicochemical and biological processes. This edge-of-field water treatment technology is gaining popularity in the mid-western United States and eastern Canada, but has not gained widespread acceptance in the Canadian Prairies. Consequently, there remains uncertainty as to whether these technologies are appropriate for the Canadian Prairies considering agricultural drainage is greatest during spring snowmelt and the bioreactors are driven by biological processes, which may be inhibited by cooler spring temperatures.

This study evaluated the performance of pilot-scale denitrifying bioreactors for removing dissolved nutrients under Alberta agricultural field conditions at two representative geographic locations. Substrates were sourced from local materials and included wood chips, hemp straw and barley straw. The substrates were tested under varying hydraulic retention times (flow rates) and temperatures from the beginning of the growing season in the spring to the end of irrigation season in fall for nutrient removal potential. Results from this study identified temperature, flow rate, carbon source material and bioreactor age as primary factors affecting nitrate removal. The flow design demonstrated that the lowest flow rate maximized nitrate removal efficiency and was further optimized in the warmer summer season. There appears to be a possible decline of nitrate removal capacity over time.

Overall, the average nitrate-N load reduction as a percentage of inlet load for the various treatments was 45%, 59% and 36% for spring, summer and fall, respectively. The load reductions were significantly lower for the wood chips (32%) compared to the agricultural residues (hemp at 50%, barley at 58%). Denitrifying bioreactor performance appears to be improved with the use of agricultural residues (barley straw and hemp straw) as fill media as compared to wood, although the retention time also influenced the overall nitrate removal capacity.

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1 Introduction

In Alberta, sub-surface drainage is an agricultural water management practice that facilitates crop growth improvements by reducing excess soil water in the rooting zone. This practice is gaining popularity in Alberta's agricultural sector in response to increasing land values and a desire to maximize yield and achieve product consistency under variable topography, soil texture and precipitation patterns. This practice can also increase the soil absorption capacity between rain events and reduce overland sediment and contaminant transport in areas prone to surface runoff. By managing soil saturation, sub-surface drainage can result in a net reduction of non-point source pollution to receiving water bodies occurring through surface runoff. However, this results in sub-surface transport of soluble nutrients with a point source discharge at a central outlet. The accumulation of nutrients discharged from several outlets can have wide-ranging consequences to receiving water bodies including rivers, reservoirs, irrigation canals and return flow channels.

Recent research and development efforts in the Midwestern United States have demonstrated the applicability of denitrifying bioreactors as an end-of-pipe treatment method for mitigating impacts from agricultural drainage waters. However, unlike the Midwestern United States, the highest drainage rates in Alberta generally occur during snowmelt in early spring under cool temperature periods in which biological activity may be substantively reduced. Consequently, uncertainty exists in applying denitrifying bioreactors to Alberta's agricultural landscape as design parameters have not been tested or optimized for the Canadian Prairies. This project evaluated bioreactor performance based on Alberta climate conditions and will allow stakeholders such as farmers, irrigation districts and regulators to assess the suitability of these systems within their local context.

2 Objectives

The goal of this study was to evaluate the feasibility and optimize the design criteria of denitrifying bioreactors as an edge-of-field beneficial management practice (BMP) for mitigating environmental effects of agricultural drainage in Alberta. Project objectives outline the need for comparisons to be made between bioreactor performance in different geographic locations and with different design parameters to better understand such influences on bioreactor nutrient removal in Alberta.

Objective 1: Construct nine replicated pilot-scale bioreactors at each of the central (Edmonton) and southern (Taber) Alberta locations.

> To account for interprovincial climatic variation, nine pilot-scale bioreactors were installed at each of two sites: one set was located in central Alberta at the Crop Diversification Centre North (CDCN) and one set was located in southern Alberta within the Taber Irrigation District (TID). These locations represent different climate conditions common to Alberta's primary agricultural region and, as such, differ in their relative temperatures, precipitation patterns, day lengths, growing degree days, growing season lengths and soil types. These climates were humid continental in central Alberta and semi-arid in the south. At the CDCN site, the soil was a Black Chernozem and at the TID site, the soil was a Brown Chernozem.

Objective 2: Assess the efficacy of local carbon feedstocks for reducing annual nutrient loading under climatic conditions common to Alberta.

> Much of the field-based research completed on denitrifying bioreactors focuses on the use of wood chips as a carbon-based feedstock to stimulate biological denitrification (Dougherty, 2018). Wood-based substrates are recommended for their physical durability, but laboratory studies have shown that denitrification rates in wood-based bioreactors are hampered under cold temperatures due to lower emission of labile carbon (Cameron and Schipper, 2010). Agricultural residues such as straw, have demonstrated greater success at stimulating denitrification in cold temperatures (Feyereisen et al., 2016), but have not been subject to field-performance testing to any significant

> degree that could inform their suitability as a bioreactor feedstock in Alberta. In this study, hemp straw and barley straw were compared with wood chips as a bioreactor feedstock at each site.

Objective 3: Evaluate the effect of hydraulic retention time on nutrient load reductions by changing the retention times from the beginning of the spring to the end of the fall.

> Cool temperatures reduce the rate of biological processes, such as denitrification, increasing the time required to achieve equivalent levels of biological activity under warmer temperatures. Much of the literature on field applications for denitrifying bioreactors describe studies that have been completed in warmer climates where agricultural drainage is primarily driven through growing-season rainfall events (Feyereisen et al., 2016). As a result, the recommended hydraulic retention times reported in the literature may be unsuitable for conditions in Alberta, where agricultural drainage is primarily snowmelt-driven and occurs in the spring when temperatures are cool. Hydraulic retention times (HRT) of 4, 8 and 12 hours were compared at both sites to evaluate the relative effectiveness of increasing retention time on nutrient removal.

3 Methodology

3.1 Site Selection

Two sites that represent different climatic areas of Alberta were selected to install replicated pilot-scale bioreactors. The CDCN site was located just outside of Edmonton and represented a humid continental climate (Figure 1) and the TID site was located just outside of Taber and represented a semi-arid climate (Figure 2). Alberta's primary agriculture region spans both these climates.

3.2 Bioreactor Design and Construction

Nine replicated pilot-scale bioreactors were installed at each site in the fall of 2019. A trench-style bioreactor design was used, as it represents a simple and practical way for producers to use bioreactor technology to intercept and treat subsurface drainage water. Each trench was excavated to approximate dimensions of 6 m length × 0.6 m width × 1.3 m depth. Prefabricated liners (30 mil Linear Low Density Polyethylene) were then fixed within the trenches to cover the bottom and sides, with extra to fold over the top after filling. The trenches were filled with one of three types of carbon-rich organic substrates. Wood chips, hemp straw and barley straw were used at both sites; the wood chips (a by-product of power pole manufacturing) were obtained from a common source and hemp straw and barley straw were procured from a local producer proximal to each site. Each bioreactor was filled with organic substrate. The hemp and barley straw came in the form of large square bales; staff cut the tying strings and then broke off slices from the bale. Slices were then placed in the trench and around the test pipes/wells. Each layer of straw was packed down as tightly as possible and the trench was filled until it reached beyond the top of the bioreactor. The wood chips were in a loose form, so were shoveled into the trenches, and then packed down as tightly as possible. Once trenches were full of either straw or wood chips, the plastic liner was then folded over the top of the material and covered with soil. Inflow and outflow pipes were placed at either ends of the bioreactors. Four wells made of 10.2 cm (4 in.) polyvinyl chloride (PVC) tubing were installed at the start and end positions of the bioreactors and at two middle positions located at 1.8 m and 3.6 m from the first well. Water levels and water temperature within the bioreactors were continually monitored throughout the study using pressure transducers to calculate the depth of the saturated zone (Figure 3). The wells allowed for collection of water samples from within the bioreactor. The inlet water was fed from the top of the inlet well, and the outlet port was positioned to maintain a saturated depth of approximately 1 m within the bioreactors (Figure 4).

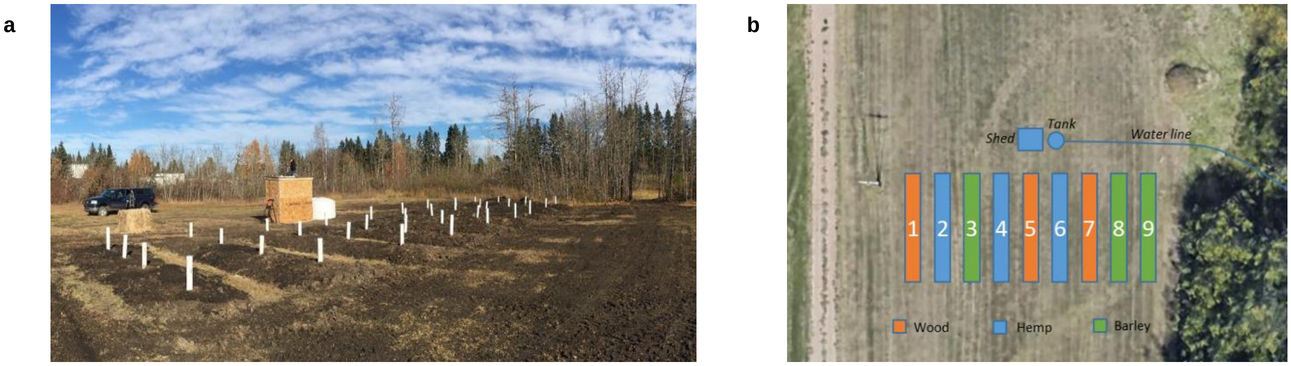

Figure 1. (a) Bioreactors at CDCN (b) CDCN Bioreactor identification and feedstock schematic.

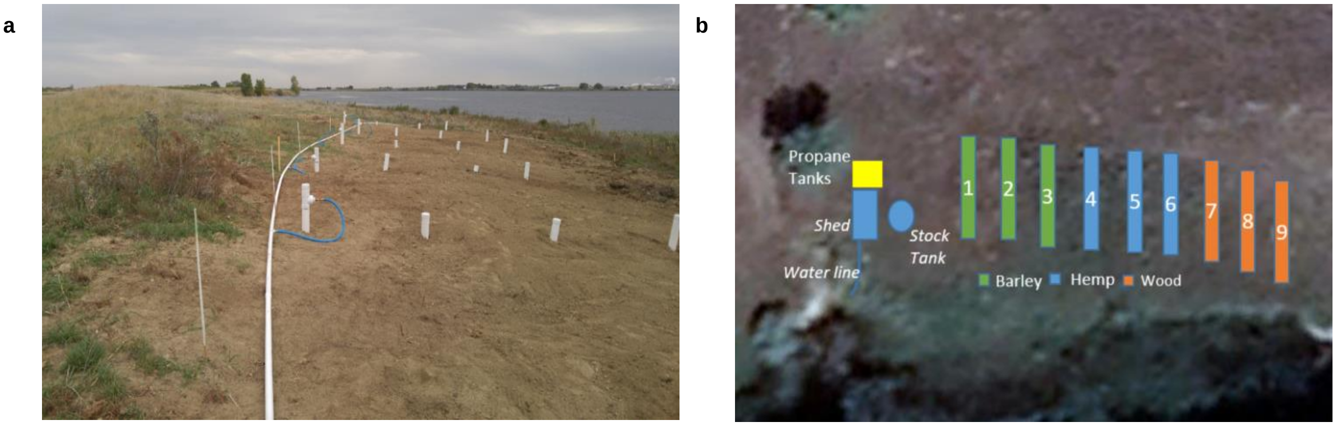

Figure 2. (a) Bioreactors at TID (b) TID Bioreactor identification and feedstock schematic

Figure 3. Sampling well with pressure transducer removed and resting on cap awaiting download.

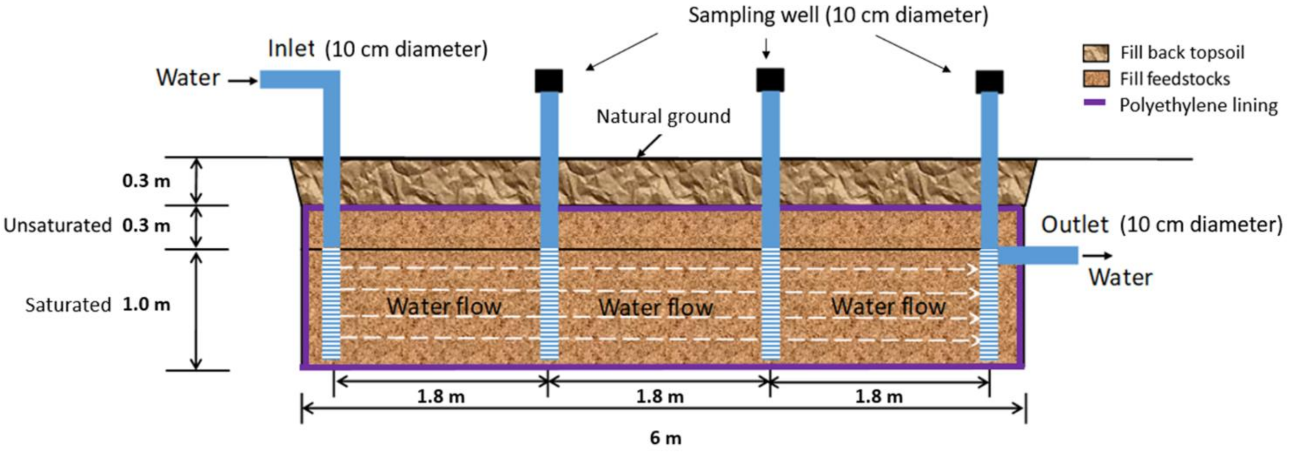

Figure 4. Dimensional schematic of pilot-scale bioreactors in longitudinal cross-section.

Water was diverted from an adjacent stream for the CDCN site and from an irrigation canal at the TID site to supply water to the bioreactors. Water was pumped from the stream or canal, filtered to <100 µm using an automated self-cleaning filter and dosed to approximately 20 mg/L of nitrate using a dosing pump attached to a large stock tank. Stock solutions of nitrate were prepared weekly using filtered stream/canal water and potassium nitrate fertilizer. Flow into each bioreactor was controlled with valves and flow meters attached to each inlet pump. Flow control was required to achieve the desired (theoretical) HRT in order to compare the effect of different HRTs on nutrient removal performance.

3.3 Physical and Hydraulic Properties

Tracer tests were conducted in order to characterize each bioreactor in terms of physical and hydraulic properties. One kilogram of sodium chloride (NaCl) (4 L of 250 mg/L solution) was added to each bioreactor and the change in specific conductance (SpC) was monitored at the outlet well using deployable conductivity sensors capable of continuous monitoring. Calibration curves were established from each event 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 substrate under different flow conditions, such as hydraulic efficiency, solute dispersion– using the Morrill Dispersion Index (MDI) and preferential flow – using the short-circuiting index (S). These hydraulic properties were used to determine the flow rates needed to achieve the various retention times for each type of feedstock bioreactor.

Hydraulic efficiency was calculated as the ratio of mean solute retention time to the time of peak concentration (Persson et al., 1999) and it indicates the departure of the average retention time of solutes from the target HRT. Hydraulic efficiency values fall within 0.0 – 1.0, with 1.0 being the most ideal as it represents unimpeded flow or greatest hydraulic efficiency. However, values above 0.5 indicate conditions that allow for effective flow and are considered satisfactory for a working bioreactor. The MDI is an indicator of dispersion and mixing of the tracer throughout the bioreactor, where lower values (i.e. near zero) indicate less mixing and less contact with the feedstock material and MDI values from 1.0- 2.0 indicate plugged flow, or more opportunity for mixing. A high MDI indicates the tracer was widely distributed throughout the bioreactor and the resulting tracer curve typically shows a wide peak rather than a sharp one (Dougherty, 2018). 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 the water quickly flows through the feedstock with little opportunity for nitrate removal (Hoover et al., 2017).

Saturated hydraulic conductivity (Ksat) 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. The recovery of the water level was measured using a pressure transducer set to record water levels every 0.5 seconds to account for the rapid recovery of the water level in the substrates. The slug tests were performed at each site at the end of each season.

3.4 Experimental Design

3.4.1 2020 Field Season (CDCN and TID)

In 2020, the study was designed in a way that at each site (CDCN and TID) and each feedstock material (three bioreactors each of wood, hemp and barley) would be combined with each HRT treatment (4, 8 and 12 h), to test the interactive effect between the treatments. As a result, these target HRTs were cycled between seasons throughout 2020 and the tracer tests were conducted at the start and end of the seasonal assessment. The flow rates in each bioreactor were adjusted to a different HRT level in each seasonal assessment (spring, summer and fall). Slug tests were also performed in order to characterize the physical stability of the feedstocks.

3.4.2 2021 Field Season (TID)

In 2021, Government of Alberta (GOA) staff were unable to operate the bioreactors at CDCN and each bioreactor at TID was run through the same flow-recession design each season, which allowed for a direct comparison of treatment performance between feedstocks during each assessment period. This flow-recession design mimicked natural conditions of high- to low-flow conditions during a runoff event. The bioreactors started at a flow rate of 2 GPM (US gallons per minute) (~5 h HRT), followed by successive declines to 1.5 GPM (~7.5 h HRT) and 1 GPM (~10 h) each season. The duration of each flow rate was approximately one week. Three seasonal assessment periods were conducted (spring, summer and fall) to account for seasonal differences in treatment performance. Corresponding tracer studies were conducted at the start of each seasonal assessment at a flow rate of 2 GPM only with slug tests performed at the end.

3.5 Bioreactor Assessment

Assessment of bioreactor performance for removing dissolved nitrogen was conducted on a seasonal basis throughout the growing period, focusing on spring (May–June), summer (July–August) and fall (September–October) seasons. During each seasonal assessment, nitrate-dosed water was pumped through the bioreactors continuously for approximately four weeks with a three- to four-week shutdown period in between seasons during which no water flowed in the bioreactors.

Bioreactor performance was assessed using the difference in concentrations from the inlet to the outlet well positions. Cumulative nitrate-N mass loads entering and exiting the bioreactor were calculated by multiplying the incremental flow volume (measured at the inlet wells using continuous loggers) by the nitrate concentration (from the inlet and outlet positions), and then summing those incremental loads over each monitoring period or season (spring, summer and fall), expressed as mass per unit of time. During each seasonal assessment, weekly water samples were collected from the outlet well using a bailer. Source water samples from the stream (CDCN) and the 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 (NH_4-N), nitrate nitrogen (NO_3-N), nitrite nitrogen (NO_2-N) and alkalinity content. Mass loading of NO_3-N into and out of the bioreactors was calculated using cumulative flow (measured at the inlet wells using continuous loggers) and nitrate concentrations. The laboratory analysis for this project was conducted at Government of Alberta laboratories in Lethbridge for the first year of operation (2020) and at the ALS laboratory in Calgary for the second year (2021).

3.6 Statistical Analyses

In this study, three feedstock treatments were repeated in triplicate, with three HRT treatments within the feedstocks and repetition of HRT treatments within the bioreactors. Therefore, a crossover repeated measures design was used to determine nutrient removal performance and to account for within-bioreactor variability and potential carry-over between HRT treatments. The analysis was performed using Microsoft® Excel® (2016) and RStudio (2020). Cumulative load reductions were also calculated in both trial years to assess the temporal resilience in load reductions after overwintering. The Mann-Whitney Rank Sum test (using SigmaPlot (2011); $P < 0.05$) was also carried out to compare the hydraulic proprieties at TID for both years of operation. Boxplots and scatterplots were created in RStudio to provide visual displays of the water parameter concentrations.

4 Results

4.1 Physical and Hydraulic Properties

4.1.1 2020 Field Season (CDCN and TID)

Tracer tests were run at different targeted (theoretical) HRTs (4, 8 and 12 h) prior to each of the three seasonal assessment periods (spring, summer and fall) to collect information on the hydraulic properties of each bioreactor. At CDCN, all the peaks occurred in less than 15 hours after the injection (time 0) while at TID, all the peaks occurred in less than 10 hours (Figure 5). Overall, the time required for the salt wave to pass varied from one hour to over 15 hours. The change in specific conductance during the salt wave passage depended on the mixing characteristics of the bioreactors, how the bioreactors were constructed, and how the feedstocks were packed. The type of feedstock did not appear to affect specific conductance because the bioreactors filled with the same feedstock showed different curves (Figure 5).

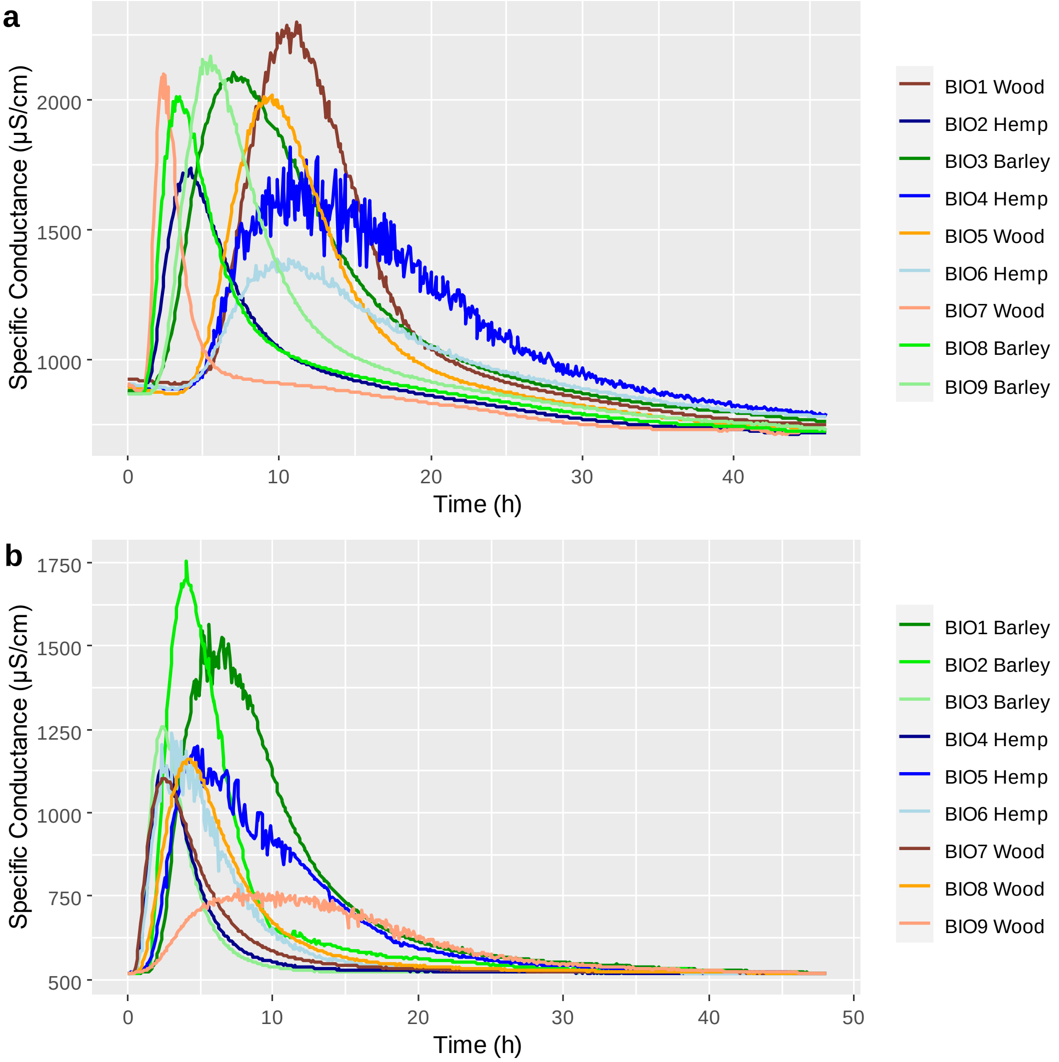

Figure 5. Time series of specific conductance (µS/cm) of bioreactors after the tracer tests at (a) CDCN (July 2020) and (b) TID (June 2020). Results are differentiated by feedstock type (barley, hemp and wood).

The physical and hydraulic properties measured in the bioreactors through slug and tracer tests were hydraulic conductivity, hydraulic efficiency, dispersion and short-circuiting. These properties, according to the feedstock and HRT for the first year of operation, are presented in Figure 6.

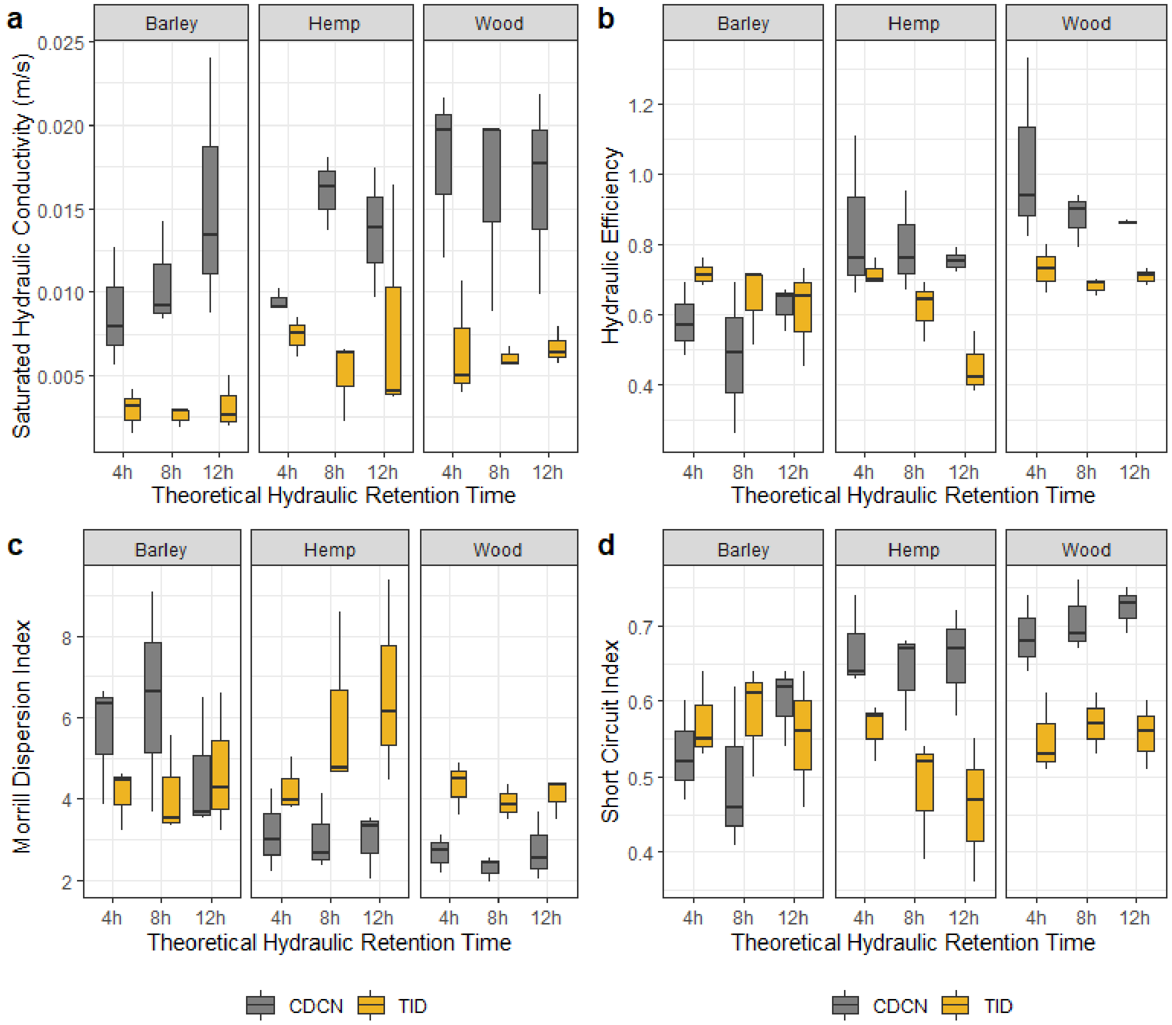

Figure 6. Hydraulic properties of the bioreactors as measured by (a) saturated hydraulic conductivity (m/s), (b) hydraulic efficiency (unitless), (c) Morrill Dispersion Index (unitless) and (d) Short-circuiting index (unitless) in 2020. Results are differentiated by feedstock type (barley, hemp and wood), theoretical hydraulic retention time (4, 8 and 12 h) and sites (CDCN and TID).

For the first year of operation, clear differences can be observed between sites. Saturated hydraulic conductivity (Ksat) demonstrated a consistent trend between feedstock types at both sites, where wood and hemp straw demonstrated greater conductivity than barley straw. Similarly, Feyereisen (2018) found higher hydraulic conductivities for wood chips than barley straw (0.048 and 0.028 m s^{-1}, respectively). The Ksat values were substantially greater at the CDCN site for all feedstock types, perhaps due to differences in the way the feedstock material was packed or the freeze-thaw event between the installation (fall 2019) and the operation (spring 2020). Other studies have documented wood chip hydraulic conductivities ranging from 0.03 m s^{-1} (Christianson et al., 2020) to 0.05 m s^{-1} (Feyereisen et al., 2016).

The wood bioreactors showed greater hydraulic efficiency values than other feedstock types at both sites with hydraulic efficiency values being greater at the CDCN site for hemp and wood than the TID site. However, all the values (except for hemp at TID for 12 h HRT) were greater than 0.5, which is considered satisfactory.

The MDI, or degree of dispersion or mixing, within the bioreactors at CDCN appeared to be greater in the barley straw bioreactors. In fact, the MDI was consistently lower in the hemp and wood bioreactors, as indicated by lower hydraulic efficiency and greater MDI values for barley straw. Conversely, the degree of dispersion was relatively consistent among the barley and wood bioreactors at the TID site, but was greater in the hemp straw bioreactors.

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 hemp=wood>barley.

Collectively, these first year results indicate that the physical and hydraulic properties of the bioreactors seemed to be more influenced by site than by either feedstock or hydraulic retention time.

Comparatively, for bioreactors filled with wood chips, Hoover et al. (2017) reported values around 2.8, 0.78 and 0.73 for MDI, hydraulic efficiency and short circuiting, respectively, while Schaefer et al. (2021) reported values of 3.3, 0.70 and 0.66 for the same parameters, respectively. Gosh et al. (2020) also found values of 5.8, 0.45 and 0.56 for MDI, hydraulic efficiency and short circuiting respectively.

4.1.2 2021 Field Season (TID)

For the second year of operation, the experiment could only be conducted at the TID site. The tracer tests were run at a fixed flow rate of 2 GPM (~5 h HRT). Like in 2020, all the peaks occurred within 10 hours after the injection and the time required for the salt wave to pass varied from one hour to over 10 hours (Figure 7). The presence of multiple peaks (BIO5, BIO 6 and BIO8) may mean that a short circuiting stream or preferential flow existed in the bioreactor, producing different flow channels from the inlet to the outlet (Wang et al., 2015).

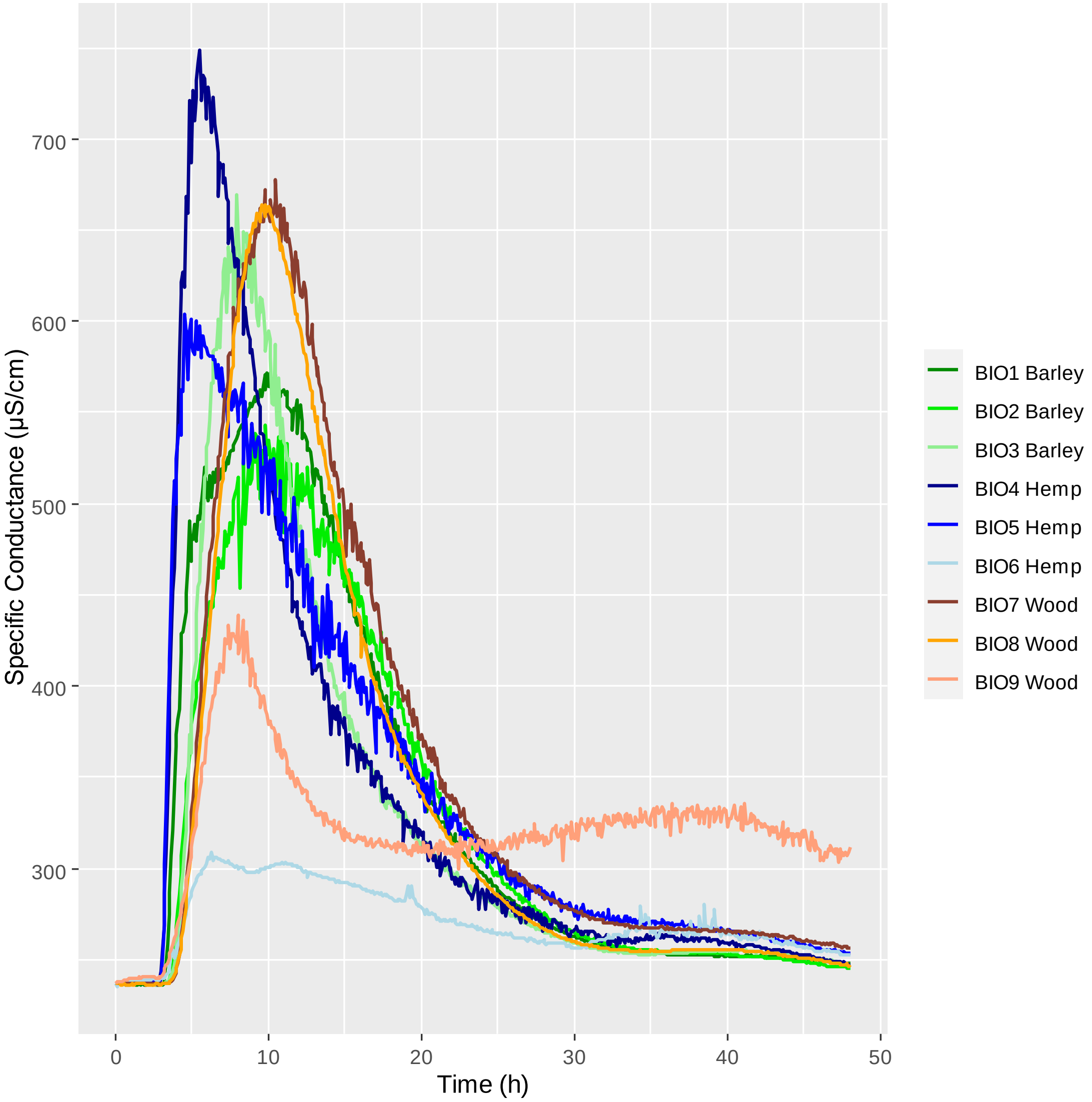

Figure 7. Time series of specific conductance after tracer tests for nine pilot-scale denitrifying bioreactors at TID after the summer 2021 seasonal test. Results are differentiated by feedstock type.

Physical and hydraulic properties (hydraulic conductivity, hydraulic efficiency, dispersion and short-circuiting) are presented in Figure 8. Wood chips demonstrated greater Ksat than hemp and barley straw. The wood and barley bioreactors showed hydraulic efficiency values greater than 0.5, while the hemp bioreactor showed lower values as in the first year of operation. The MDI was relatively consistent among all the bioreactors at the TID site, but was slightly greater in the hemp bioreactors. Like the first year of operation, barley straw showed a lower degree of short-circuiting (lower S values) than either hemp straw or wood chips at the TID site.

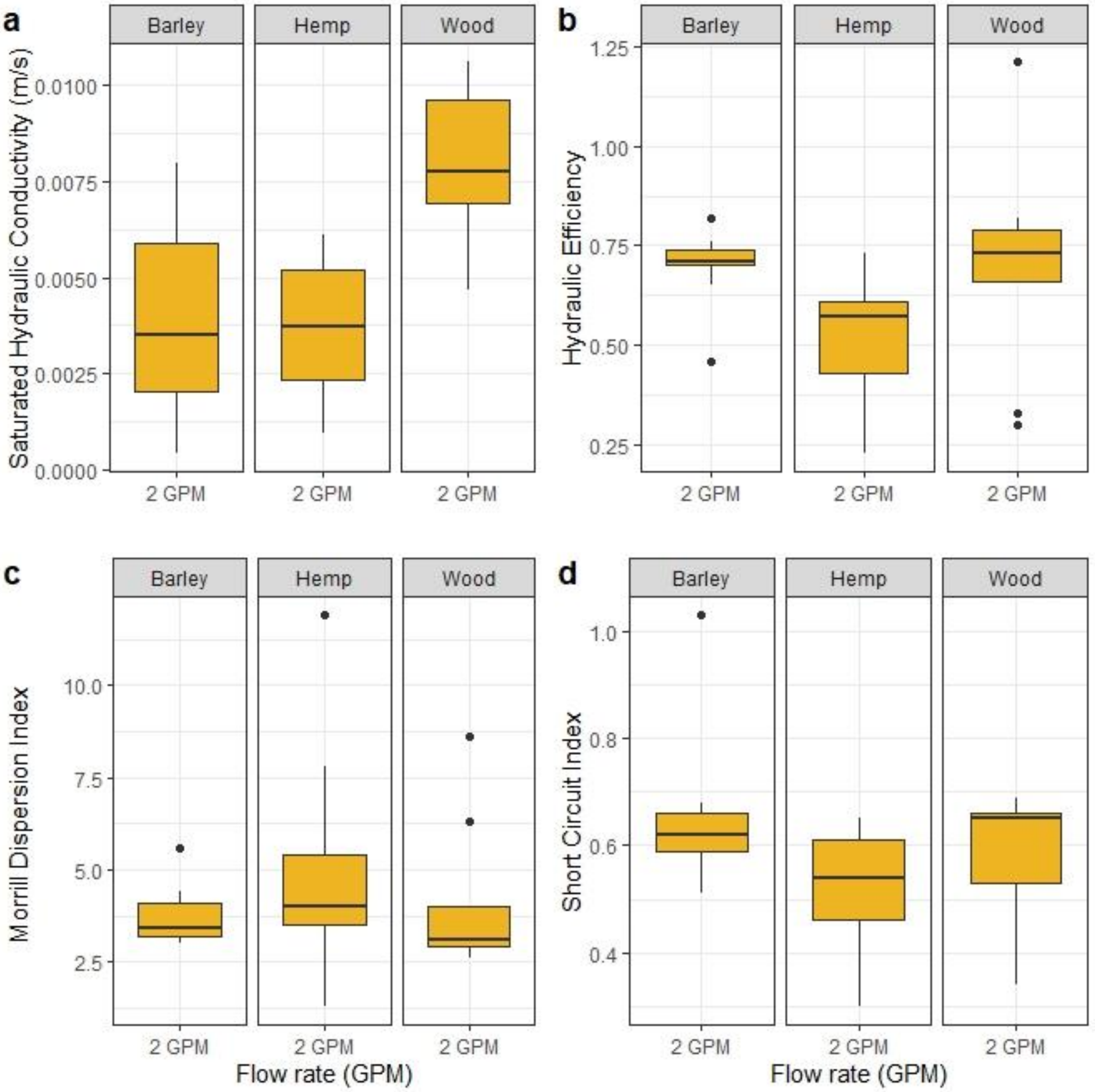

Figure 8. Hydraulic properties of the TID bioreactors as measured by (a) saturated hydraulic conductivity (m/s), (b) hydraulic efficiency (unitless), (c) Morrill Dispersion Index (unitless) and (d) Short-circuiting index (unitless) in 2021. Results were collected at 2 GPM (~5 h HRT) and are differentiated by feedstock type (barley, hemp, wood). Dots denote outliers.

4.1.3 Overall Assessment (TID)

After two years of operation, the hydraulic properties at TID were compared. Table 1 and Table 2 report the mean and median values, respectively.

TABLE 1. MEAN VALUES FOR THE ASSESSMENT PERIODS FOR 2020 AND 2021 ACCORDING TO THE FEEDSTOCK MATERIAL

	2020			2021		
Feedstock	**Barley**	**Hemp**	**Wood**	**Barley**	**Hemp**	**Wood**
Hydraulic Conductivity (m/s)	0.003	0.007	0.006	0.004	0.004	0.008
Hydraulic Efficiency (unitless)	0.66	0.59	0.71	0.70	0.51	0.70
Morrill Dispersion Index (unitless)	4.32	5.64	4.10	3.79	5.01	4.06
Short Circuiting (unitless)	0.57	0.50	0.56	0.65	0.52	0.58

TABLE 2. MEDIAN VALUES FOR THE ASSESSMENT PERIODS FOR 2020 AND 2021 ACCORDING TO THE FEEDSTOCK MATERIAL

	2020			2021		
Feedstock	**Barley**	**Hemp**	**Wood**	**Barley**	**Hemp**	**Wood**
Hydraulic Conductivity (m/s)	0.003	0.006	0.006	0.004	0.004	0.008
Hydraulic Efficiency (unitless)	0.71	0.64	0.70	0.71	0.57	0.73
Morrill Dispersion Index (unitless)	4.26	4.77	4.35	3.40	4.00	3.10
Short Circuiting (unitless)	0.56	0.52	0.56	0.62	0.54	0.65

There was a statistically significant difference in the median Ksat values for hemp in 2020 compared to 2021 (Mann-Whitney Rank Sum Test, $P < 0.05$). This might explain the differences in performance of the bioreactors. There were no statistically significant differences between median values for the other feedstocks and parameters.

The range of the hydraulic efficiency remained the same for both years with no statistically significant difference between their median values.

The mean MDI values for 2020 (4.10 to 5.64) were greater than the 2021 MDI values for all bioreactors (3.79 to 5.01). This suggests a slightly greater flow dispersion in the first year of operation; however, there were no statistically significant differences in the median values between years. Calculated MDIs in this study are similar to other reported MDI values for wood feedstock (Christianson et al., 2011).

Average short-circuiting values increased in all the bioreactors in 2021: the mean S values for 2020 (0.5 to 0.57) were lower than the mean 2021 S values for all bioreactors (0.52 to 0.65). This suggests that less short-circuiting occurred in 2021, which means potential for denitrification increased because the water flowed through the bioreactor closer to the intended treatment time (Dougherty, 2018); however, there were no statistically significant differences in the median S values between years.

4.2 Nitrate Removal Performance of Bioreactors

4.2.1 2020 Field Season (CDCN and TID)

The capacity of bioreactors to remove nitrate under varying HRT conditions and feedstock materials was assessed through weekly sampling during the target seasons. The observed percentages of nitrate removal were determined as a function of the ratio of the concentration of nitrate at the inlet and outlet positions, compared against the total mass of nitrogen added during the assessment periods for 2020 (Figure 9). In general, the nitrate removal performance of bioreactors filled with agricultural residues (hemp and barley straw) tended to fluctuate around a mean value and did not exhibit positive or negative trends as nitrate was cumulatively added to the systems in 2020. However, the wood chips, particularly at 8 h and 12 h retention times, showed increased nitrate removal performance as the cumulative mass of nitrate increased in the system. This may reflect a difference in the capacity of the materials to harbour populations of denitrifying bacteria, or it may be a function of assimilatory nitrate uptake given the greater carbon-to-nitrogen ratio present in woody biomass compared to agricultural residues. Thus, it appears that in the first year of operation, agricultural residues demonstrate a stable and relatively consistent capacity to remove nitrate. However, the retention time and material type have a clear influence on overall nitrate removal capacity.

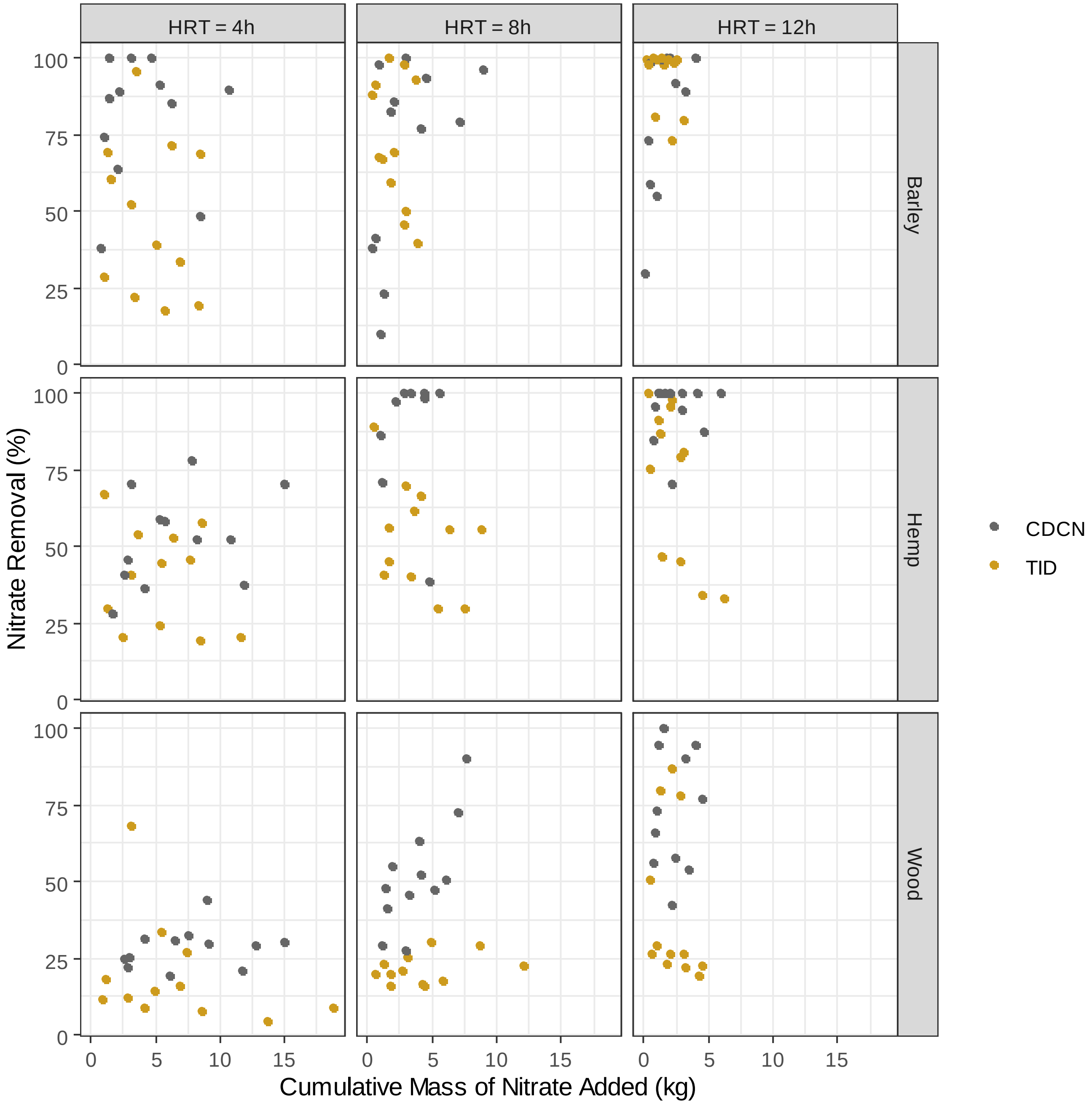

Figure 9. Percentage of nitrate removal between inlet and outlets of bioreactors versus the cumulative mass of nitrate added (kg) according to the target hydraulic retention time (4, 8, or 12 h) and feedstock material for all the sampling dates in 2020.

As mentioned, nitrate removal performance was defined as the percentage of nitrate mass removed as water flowed from the inlet to outlet well positions. Substantive differences in overall nitrate removal performance between feedstock types were evident during the spring, summer and fall assessment periods, for both sites, in the 1,544 samples collected (Figure 10). The agricultural residues tended to exhibit greater denitrification, or nitrate removal, than wood chips under all design HRTs. The cooler temperatures during the fall assessment period seemingly decreased the denitrification rates observed in all bioreactors.

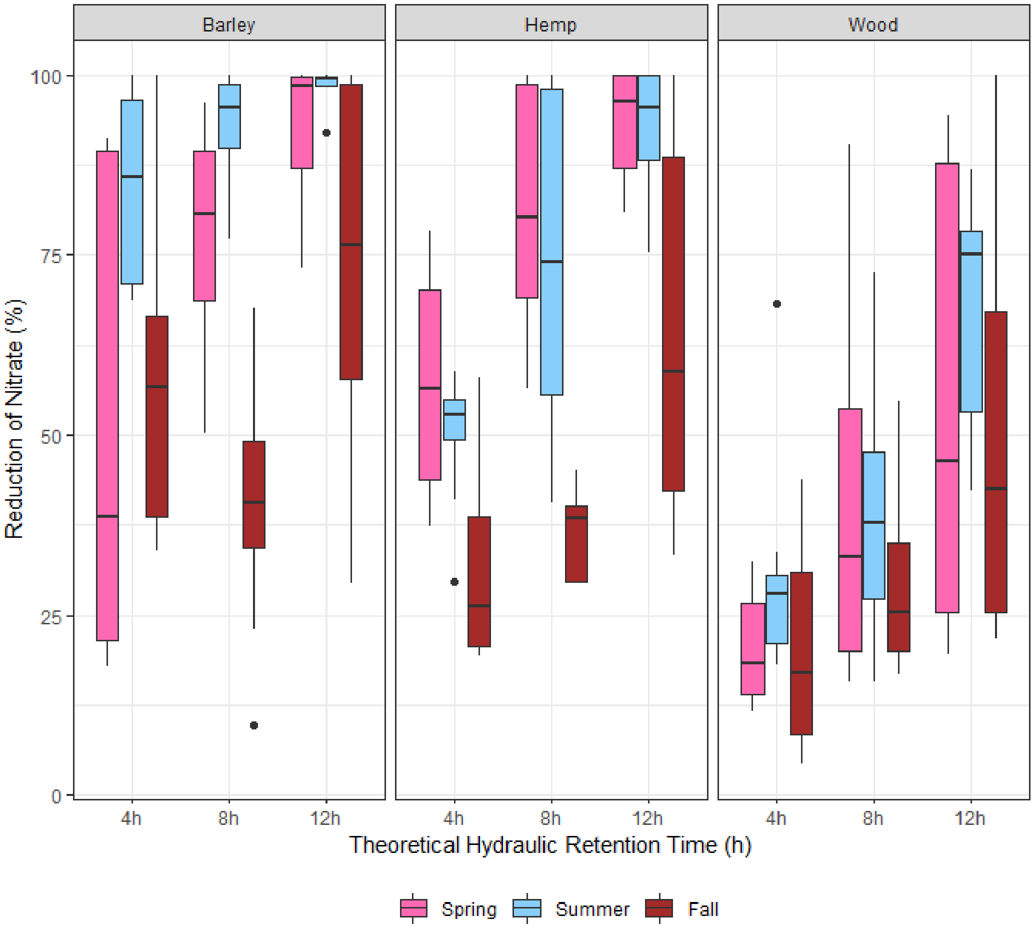

Figure 10. Overall percentage of nitrate removed during the spring, summer and fall assessment periods according to the theoretical hydraulic retention time (4, 8, or 12 h) and feedstock material for 2020 (TID and CDCN combined, N=1,544 samples).

Table 3 shows the mean values per assessment period and feedstock. Wood chips showed the lowest mean value during each season at the TID site and during spring and summer at the CDCN site. During the summer, barley straw showed the greatest overall mean nitrate reduction for both sites.

At both sites, hemp straw showed the greatest nitrate reduction in the spring then declined though the year (first year of operation). Barley straw showed the greatest nitrate reduction in the summer. Wood chips varied between sites, showing the greatest nitrate reduction in the spring at CDCN site and during the summer at the TID site.

TABLE 3. MEAN VALUES OF NITRATE REDUCTION (%) IN EACH ASSESSMENT PERIOD FOR 2020 AND FEEDSTOCK MATERIAL AT THE CDCN AND TID SITE

	CDCN			TID		
Feedstock	**Barley**	**Hemp**	**Wood**	**Barley**	**Hemp**	**Wood**
Spring	87	83	54	59	70	19
Summer	95	81	44	91	62	46
Fall	45	55	45	68	34	21

Collectively, barley straw was more effective (58%) than wood chips (32%) for nutrient removal while hemp straw showed a nitrate reduction of 50%. These findings were consistent with values reported in the literature. Several studies have documented nitrate reduction for wood bioreactors, which was commonly about 50% (Faramarzmanesh et al., 2021; Hassapour et al., 2017; Wrightwood et al., 2022), although they range from 51 to 90% (Gosh et al., 2020), from 40 to 90% (Diaz-Garcia et al., 2021), from 46 to 68% (Christianson et al., 2020), from 8 to 55% as HRT increased (Hoover et al., 2016) and from 45 to 99% (Rivas et al., 2019).

Research conducted by Hashemi et al. (2010) showed a nitrate reduction for laboratory denitrification bioreactors from 60.22 to 69.87% for barley straw while Kouanda (2021) reported a nitrate reduction of 15.25% for barley straw and 11.01% for wood, Hellman et al. (2021) reported a nitrate reduction of 42% for barley and 44% for wood.

At both sites, the source water (i.e. prior to mixing with fertilizer) had nitrate values below 10 mg L^{-1} and pH values within the range known to be ideal for denitrification (pH = 7.5–9.5) – outside this range, denitrification rates have been shown to decrease (Albina et al., 2019).

To provide a visualization of nitrate removal, measured nitrate concentrations in the inlet well of CDCN 1-1 (Inflow) and outlet well CDCN 1-4 (Outflow) from May through October 2020 from one of the wood-filled bioreactors at the CDCN site (bioreactor 1) are shown in Figure 11. The closer the inlet concentrations are to the outlet concentrations, the less nitrogen is being removed. Through this period, inlet Nitrate-N averaged 24.9 mg L^{-1}. Outlet nitrate-N concentrations were elevated in spring, coinciding with low temperatures and snow melt runoff; they decreased with increasing temperatures and increased at the beginning of fall.

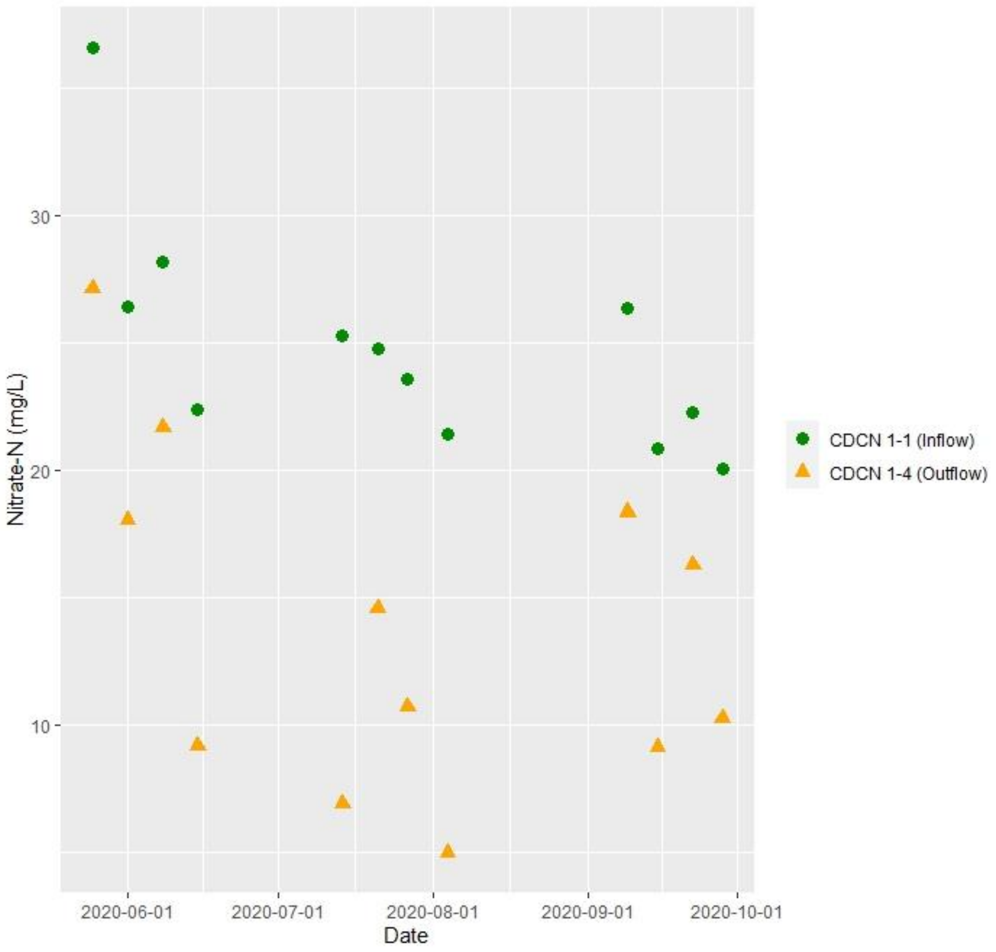

Figure 11. Measured concentration of nitrate during the spring, summer and fall assessment periods at the inlet well (CDCN 1-1) and monitoring well (CDCN 1-4) at the first bioreactor (wood chips).

4.2.2 2021 Field Season (TID)

As mentioned, in 2021, only the TID bioreactors were operational. All nine bioreactors operated on the same flow schedule, which allowed for a direct comparison of treatment performance between feedstocks during the assessment period. As the total mass of nitrate injected into the system increased with time, the flow rate was decreased to evaluate the effect of HRT on nitrate removal.

The observed percentages of nitrate removal, as a function of the ratio of the concentration of nitrate at the inlet and outlet positions, compared against the total mass of nitrogen added during the assessment periods for 2021 are presented in Figure 12.

Nitrate Removal percentage as function of the cumulative mass of nitrate added has the highest removal in summer, remaining almost constant during the fall. The bioreactors were run only two weeks in the spring due technical problems, explaining the decreased mass added to the system during this time.

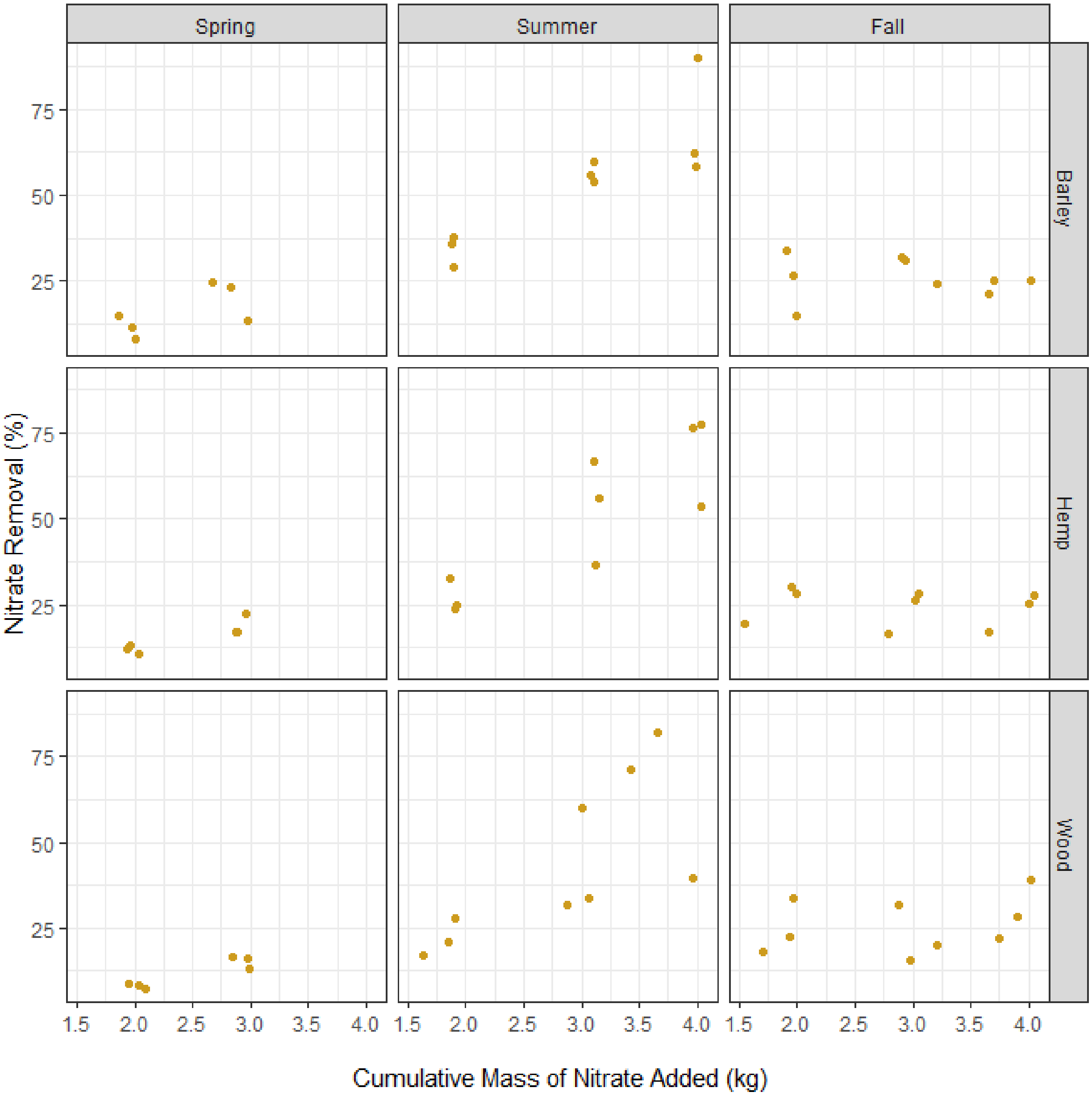

Figure 12. Percentage of nitrate removal between the inlets and outlets of TID bioreactors as a function of cumulative mass of nitrate added (kg) for each feedstock material during the three assessment periods: spring, summer and fall.

As in 2020, nitrate removal performance in 2021 was determined by the percentage of nitrate mass removed as water flowed from the inlet to outlet well positions. Substantive differences in overall nitrate removal performance among the feedstock types was evident during the spring, summer and fall assessment periods (Figure 13). The bioreactors tended to exhibit greater denitrification under lower flow rates during the summer season. The warmer temperatures during the summer assessment period likely increased the denitrification rates in all bioreactors.

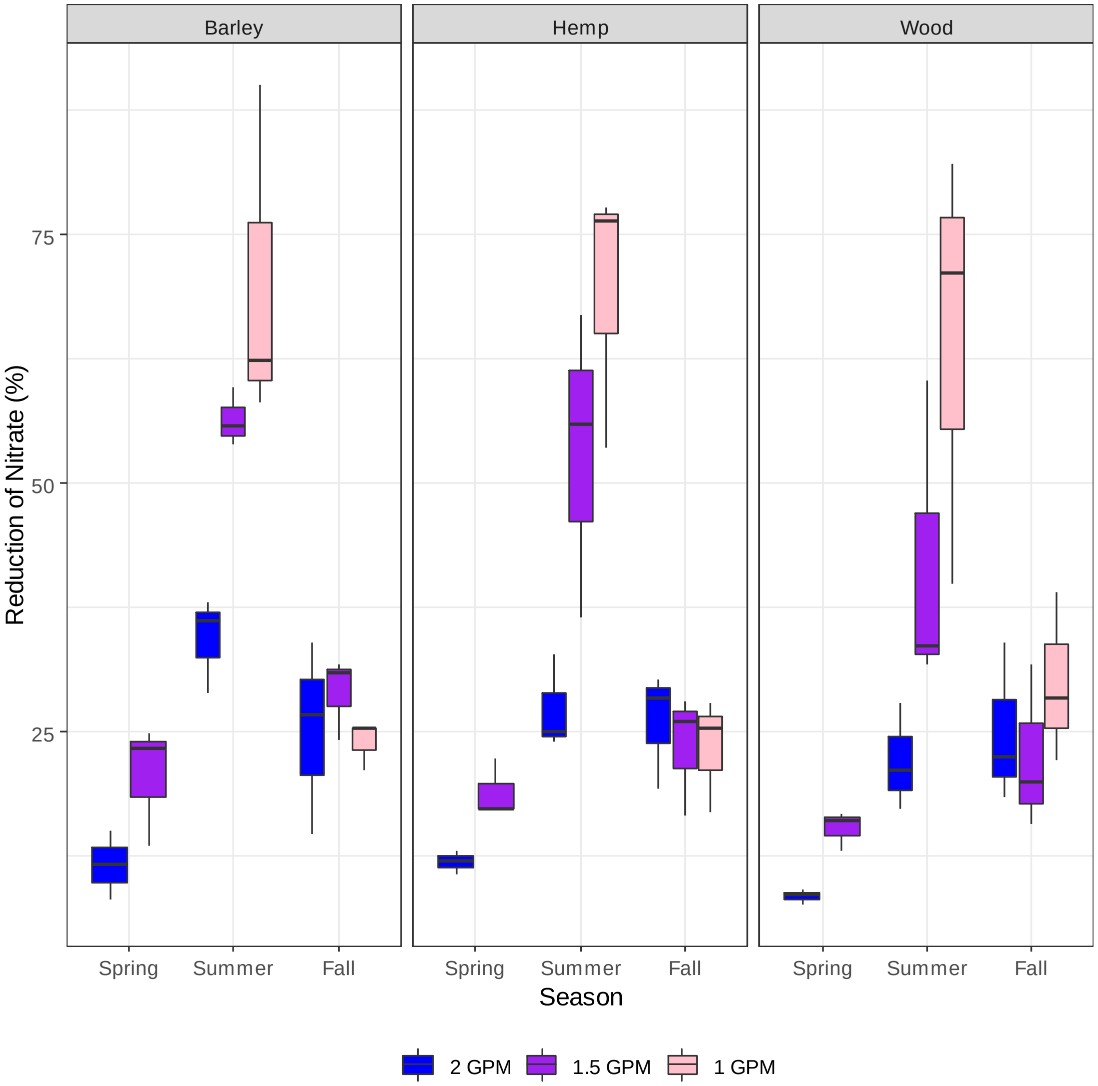

Figure 13. Overall percentage of nitrate removed during the spring, summer and fall assessment periods according to the flow rate (2 GPM, 1.5 GPM, or 1 GPM) and feedstock material for the TID site in 2021.

4.2.3 Overall Assessment

For the bioreactors at the TID site in the first year of operation, there was a greater rate of nitrate removal while the overall performance during the second year decreased, especially for the spring and fall periods. Overall, barley showed the best performance while wood showed the poorest (Figure 14).

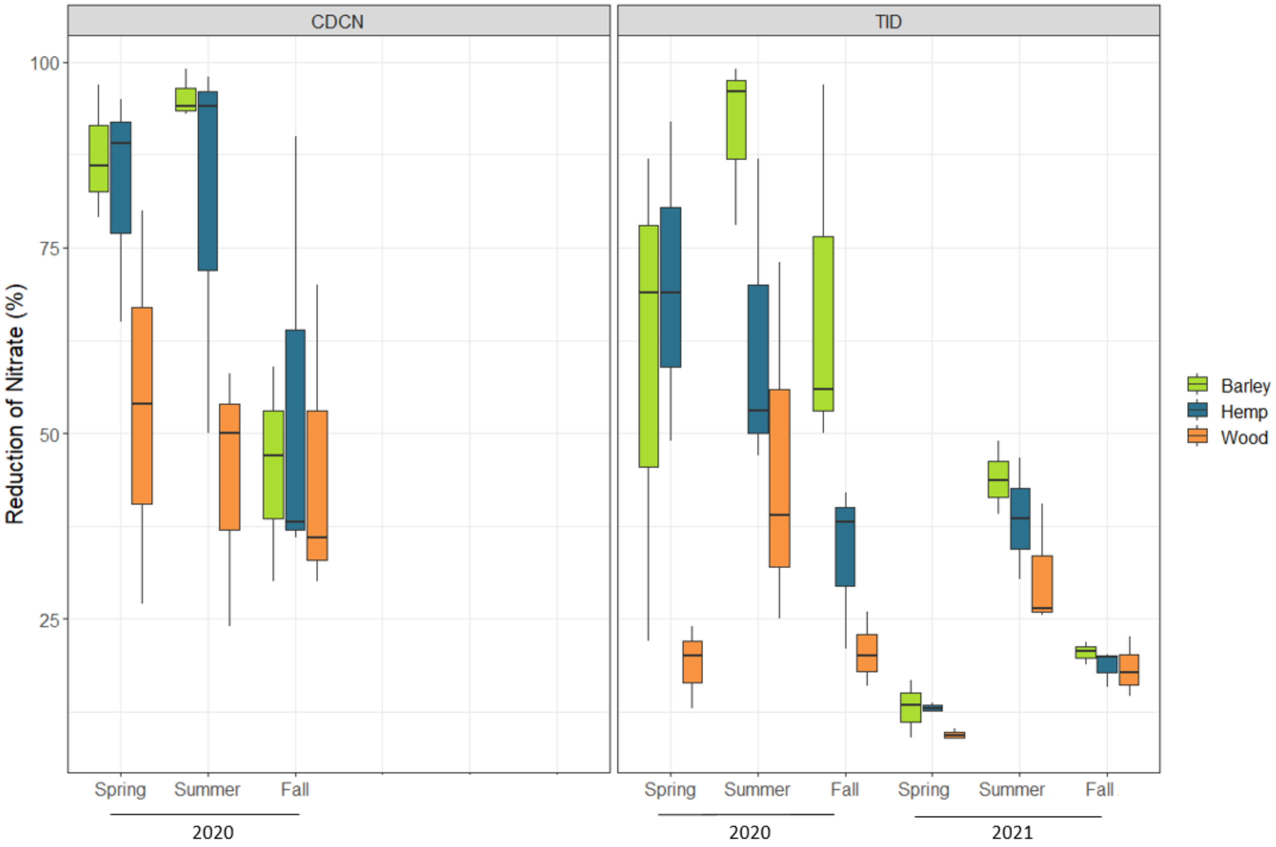

Figure 14. Overall percentage of nitrate removed during the six assessment periods according to the feedstock material for CDCN and TID. CDCN only operated in 2020, while TID operated in 2020 and 2021.

After two years of operation at TID, the nitrate removal performance of all feedstocks combined in 2020 were compared to that of all feedstocks combined in 2021. It was found that nitrate removal performance in 2021 was significantly less than in 2020 (p= 0.002) according to results of a Mann-Whitney Rank Sum Test (Table 4). Wood chips showed the lowest mean nitrate reduction during each season.

With the exception of hemp straw in 2020, all other bioreactors at the TID site showed peak performance during the summer seasons, indicating that temperatures were a crucial factor in the performance as highlighted by Hoover et al. (2016). Greatest year-on-year declines occurred in spring for all feedstocks. Barley straw saw the greatest overall reduction in the second year of operation.

Some studies have documented a decrease in nitrate reduction after the first year of operation. Rivas et al. (2019) reported a decrease from 99% to 48% for wood bioreactors within two years of operation while Gosh et al. (2020) reported a decrease from 90.2 to 51.0% from the first year to the second, but an increase to 84.9% in the third year of operation of wood chip bioreactors.

TABLE 4. MEAN VALUES OF NITRATE REDUCTION (%) IN EACH ASSESSMENT PERIOD FOR 2020 AND 2021 AND FEEDSTOCK MATERIAL AT THE TID SITE

	2020			2021		
Feedstock	**Barley**	**Hemp**	**Wood**	**Barley**	**Hemp**	**Wood**
Spring	59	70	19	13	13	9
Summer	91	62	46	44	39	31
Fall	68	34	21	20	19	18

Nitrate concentrations in the inlet well TID 1-1 (Inflow) and outlet well TID 1-4 (Outflow) from May to Sept 2020 and May through October 2021 at the TID site are shown in Figure 15. The lowest nitrogen concentrations observed in the outflow monitoring well indicate high rates of nitrate removal and occurred during all three seasons during the first year of operation and during the summer season of the second year.

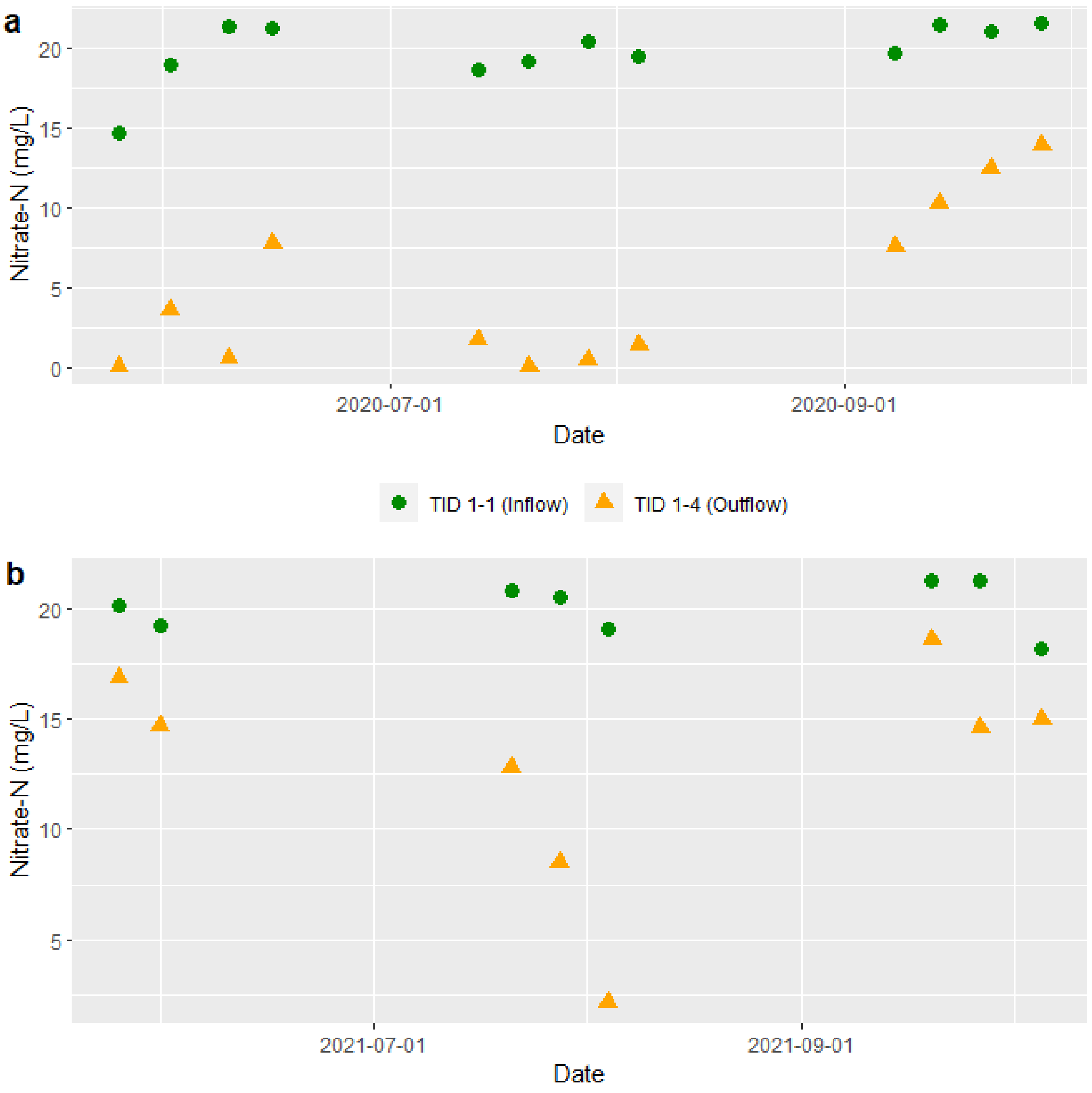

Figure 15. Concentration of nitrate removed during the spring, summer and fall assessment periods for (a) 2020 and (b) 2021 at the inlet well (TID 1-1) and monitoring well (TID 1-4) at the first bioreactor (barley) at the TID site.

5 Conclusions

5.1 Physical and Hydraulic Properties

Based on the physical and hydraulic properties measured by slug and tracer tests at both sites, agricultural residues (barley straw and hemp straw) performed at varying degrees. Hydraulic conductivity and efficiency, as well as optimal mixing and consistent flow patterns throughout the bioreactors were achieved and sometimes optimized by agricultural residues. Nevertheless, there were notable differences between locations and time of year, demonstrating the impacts that temperature and moisture conditions are known to have on denitrification. There were no consistent trends in properties among feedstocks or sites, which may indicate that the hydraulic properties of the bioreactors were more influenced by construction methods during bioreactor installation rather than the functional attributes of either feedstock material, hydraulic retention time or geographic location in the province. Construction methods that may affect physical or hydraulic properties of the bioreactors could be the method of packing or amount of feedstock used. One way to mitigate this could be to use a pre-measured volume for each bioreactor to ensure the same amount of measured feedstocks are used and that the same placement techniques are performed. It is recommended that slug and tracer tests be conducted upon installation of denitrifying bioreactors to ensure physical and hydraulic properties are conducive to effective operation.

5.2 Nitrate Removal Performance of Bioreactors

When compared to wood chips, the amount of nitrate removed by agricultural residue was consistent over the seasonal operation of the bioreactor (i.e., similar performance at beginning and end of month-long seasonal trials). In contrast, the removal of nitrate by the wood chips was maximized as the cumulative mass of nitrate increased with time. The differences in surface area or size of the feedstock pieces might have influenced the differences observed between the performance of wood chips and agricultural residues in that the feedstocks act as a filter and the ‘filter size’ is defined by the size of the feedstock pieces. However further research on this possibility is needed.

Nitrate removal was optimized by longer hydraulic retention times and warmer temperatures as evidenced by slowest flow rates and the highest nitrate removal during the warmer summer seasonal trials, respectively.

The nitrate reductions for the wood chips and barley straw were consistent with what other researchers have found with the first year of operation showing the greatest reduction.

Looking at performance over time, the bioreactors at the TID site showed the greatest rates of nitrate removal during the first year of operation, while the overall performance during the second year decreased, especially for the spring and fall periods. Overall, barley straw showed the best performance while the wood showed the poorest. The barley straw performance was optimized in summer, which suggests that warm weather played an important role. When comparing the two sites in 2020, the bioreactors at CDCN showed greater mean values of nitrate reduction during almost all assessment periods and within all feedstocks.

The observed results are promising given that agricultural residues are readily available in agricultural landscapes throughout Alberta. These results, however, only reflect one year of operation for the bioreactors located in central Alberta and two years for the bioreactors located in southern Alberta and so do not reflect the temporal stability and durability of agricultural residues under longer-term operation.

6 Summary and Recommendations

This project evaluated the performance of pilot-scale denitrifying bioreactors for removing dissolved nutrients under varying agricultural field and climatic conditions in Alberta. Two representative geographic locations were selected for the study (Objective 1). Local biomass materials (wood chips, hemp straw and barley straw) were tested for nutrient removal potential under varying retention times and ambient temperatures throughout the growing season (Objective 2). After installation of bioreactors at the two sites in fall 2019, sodium chloride tracer tests were conducted on each replicated bioreactor to determine physical characteristics and flow parameters (Objective 3). This information was used to determine the flow rates needed to achieve the various retention times for each type of feedstock bioreactor.

The tracer test results indicated that the hydraulic properties of the bioreactors seemed to be more influenced by the degree of packing during bioreactor construction and subsequent settling rather than the functional attributes of either feedstock or hydraulic retention time.

In summary, this study identified temperatures, flow rate (hydraulic retention time), carbon source material and age of the bioreactor as the primary factors affecting nitrate removal. The flow-recession design demonstrated that the lowest flow rate maximized the nitrate removal efficiency. However, it was highly related to the season as nitrate removal was greater in summer. In general, there appears to be a possible decline of nitrate removal capacity over time; however, the effective bioreactor lifespan is still unknown.

The use of readily-available/locally-sourced agricultural residues instead of wood chips provides an attractive option, at least in the short-term, and an incentive to further explore this technology. It appears that agricultural residues tended to exhibit greater denitrification than wood chips under all design HRTs. This may be a function of physical properties (size of individual wood chips relative to barley/hemp straw) or chemical properties.

This project is a valuable contribution to the development 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, prior to implementing the knowledge acquired, additional research is necessary. Recommendations for future research are:

1) Implementation and testing on a larger scale and for an extended time period (> 2 yr) prior to making recommendations for commercialization. A comparison with other comparable edge-of-field technologies for drainage water management such as wetlands, buffer strips and sediment control are warranted. There is also a need for testing these practices and verifying the performance in different ecoregions in Alberta.

2) Long-term effectiveness of different feedstocks. A longer-term study is necessary to make recommendations about how often the feedstock should be replaced. According to Lepine et al. (2018), only a bioreactor with fresh wood chips (i.e., one-year wood chip replacement schedule) is likely to demonstrate maximum removal rates due to ideal flow conditions and available labile carbon. They highlighted that while N removal rates will likely be inconsistent from year to year; they show a general trend of decreased performance after one year of operation, though years two and onward tend to be similar.

3) Tests for mixing wood chips with agricultural residues. Expecting better performance from mixing substrates is speculative, but it could be assumed that mixing a good performing substrate with a poorer performing substrate would result in a performance somewhere in the middle.

The agricultural industry, as well as drainage contractors, have demonstrated interest in assisting with field-scale bioreactor installations, project coordination and communication of learnings.

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