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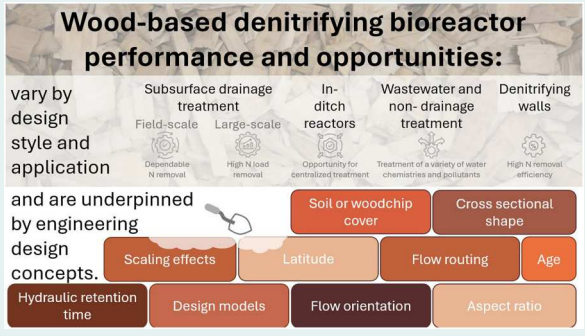
Global engineering design review of wood-based denitrifying bioreactors

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ABSTRACT

Denitrifying bioreactors that use wood-based fill media provide relatively simple and cost-effective nitrate (N) treatment for many waters and wastewaters around the world. The number of studies about this young technology has grown exponentially over the past decades, but there has been no comprehensive evaluation of the basic engineering design concepts that fundamentally underpin the effectiveness of any bioreactor operating in the field. This quantitative review of full-size wood-based denitrifying bioreactors novelly synthesizes the current state of bioreactor engineering to better position future research and development for improved N treatment across applications. A database was compiled to assess the design and annual performance of five bioreactor styles/applications: field- and catchment-scale subsurface drainage treatment; in-ditch reactors; wastewater treatment; and denitrifying walls ($n = 136$, 23, 13, 45, and 51 site-years, respectively). Specific assessments across the database showed bioreactors treat N in drainage water effectively across latitudes and that decreases in performance with increasing bioreactor age are most likely hydraulics-related. Bioreactor sizing models and engineering concepts (e.g. hydraulic retention time, reactor geometry, flow routing, bioreactor covers) were also reviewed. Looking forward, more long-term monitoring is recommended especially for evaluation of: aging bioreactors; treatment of larger drainage areas and high flows; designs with varying aspect ratios and features; and pairing bioreactors with other technologies (e.g. automation, water storage). This synthesis of the current state of bioreactor design science builds momentum for future engineering advances that will provide greater impact at the site level and greater implementation toward overall watershed goals.



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1. Introduction

Denitrifying woodchip bioreactors use carbon sourced from wood to enhance the denitrification of nitrate (N) in waters and wastewaters around the world [1]. The earliest studies of wood-based denitrification were performed in the 1990s, making this a relatively young concept [2–4]. Nevertheless, understanding of these simple and flexible treatment systems has now matured to where a comprehensive review of design concepts would position bioreactor research to accelerate in coming decades.

A number of recent reviews reiterate the robustness of denitrifying woodchip bioreactors for passive N

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treatment. These reviews have focused on bioreactor microbiology [5,6], bioreactor fill [7–9], or abiotic factors such as water chemistry and temperature that influence performance [10]. Other bioreactor reviews describe treatment of non-agricultural flows that face more regulatory pressure than subsurface drainage, the most common application of woodchip bioreactors to date [11,12]. Reviews by both Carstensen et al. [13] and Christianson et al. [14] reported an annual N removal efficiency of 40% for woodchip bioreactors treating drainage water but neither explicitly assessed engineering design aspects. An engineering review of bioreactor design features and concepts would progress beyond previous review articles to accelerate implementation of these treatment systems for a variety of N-laden waters.

Addy et al. [15] noted a steady increase in the number of bioreactor studies from 1994 to 2015, which is a trend that continued over the following decade (Figure S1). Many newer bioreactor studies seek to enhance N removal using novel techniques including liquid carbon dosing, heating, drying cycles, or bioaugmentation [16–21]. Other newer woodchip bioreactor studies have expanded beyond N treatment into additional pollutants [22–24]. Nevertheless, the performance of all bioreactors is underpinned by basic concepts of engineering design.

This quantitative review of full-size wood-based denitrifying bioreactors synthesizes the current state of bioreactor engineering. Compiling bioreactor design and performance information will better position future research and development work for more practical and cost effective N treatment in a variety of applications. This review specifically sought to compare different bioreactor design styles, applications, and engineering features. It was also timely to assess understanding of the current limits of bioreactor performance (e.g. latitude, age).

2. Review methods

2.1. Quantitative review and selection criteria

This review focuses on the design and application of denitrifying bioreactors that use wood media as the carbon source, with five design styles/applications evaluated (Figure 1). Treatment of subsurface drainage (tile drainage) was a major emphasis because this has been a primary application of bioreactors. Field-scale and catchment-scale bioreactors were distinguished from each other based on the drainage treatment area (i.e. < 60 ha vs 75–250 ha, respectively). The term 'field-scale' was used to refer to bioreactors that are designed to treat a given tile drainage outlet; such outlets drain one field or portions of several fields. This was differentiated from 'catchment-scale' bioreactors that treat drainage from much larger areas encompassing more than one field following terminology from [25]. Other bioreactor types reviewed included: bioreactors designed for in-ditch treatment; bioreactors treating wastewater or other non-agricultural drainage waters (municipal and aquacultural wastewater, on-site septic effluent, desalinization brine, waste rock leachate); and denitrifying walls (Figure 1). Lab- and pilot-scale bioreactor studies were excluded because the emphasis was on bioreactor design and management; however, pilot-scale studies were originally reviewed and compiled (Table S1: 15 studies, 85 site-years).

Data extraction and database compilation were performed between Aug 2023 and Jan 2024 [26], although studies published since then were used to further inform the discussion. Studies were initially identified using Google Scholar, and then by tracing references from appropriate field-scale bioreactor studies. Gray literature was included (e.g. reports, proceedings, factsheets).

A total of 120 bioreactor studies were reviewed. Of those, 78 studies contributed 353 bioreactor site-years to the full database (Table 1; Table S1). The U.S.A. represented 161 of the total compiled site-years, with Denmark, Canada, and New Zealand/Australia also notably contributing (66, 56, and 46, site-years, respectively; Figure S2). Because the focus was on annual performance (i.e. site-years), this review resulted in a smaller dataset than the review by Fan et al. [10] who reported over 10,000 data points sourced from 63 bioreactor studies.

2.2. Data extraction and statistical analysis

Data extracted from each study included details about: location; bioreactor design and fill media; monitoring design; and water flow and chemistry with an emphasis on nitrate (N) removal. Extracted results needed to be presented for an annual period, or at least for a full drainage season in locations where monitoring equipment was winterized. Some exceptions to this criterion were made for studies of bioreactors treating wastewater.

Some database entries were calculated post hoc when they were not directly reported, but such external calculations were minimized to remain most consistent with the original report. For example, bioreactor ages were calculated based on the reported installation date and bioreactor volume was calculated from reported dimensions.

The datasets tended to be non-normally distributed, so medians were presented in the discussion. The impacts of latitude, treatment scale, and reactor aspect ratio were studied by binning the data into groups

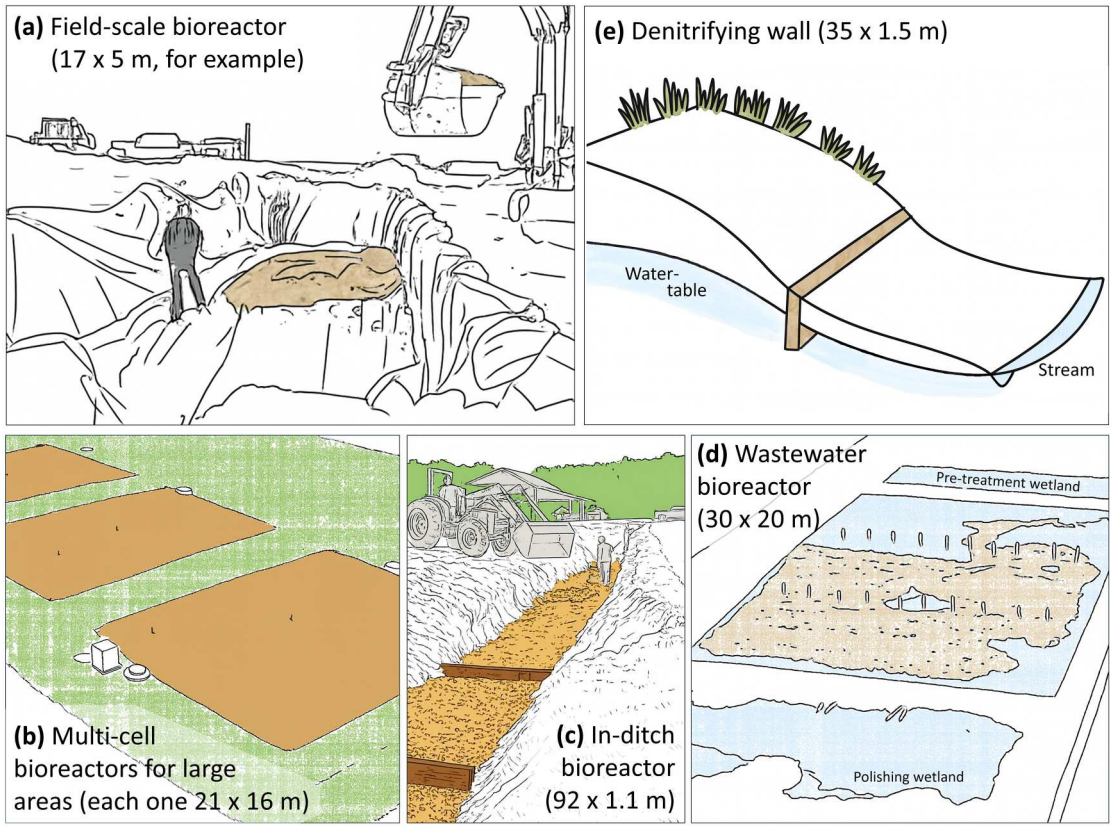


Figure 1. Stylized illustrations of the five reviewed bioreactor types with example length × width dimensions: (a) field-scale bioreactor for subsurface drainage; (b) bioreactors for catchment-scale drainage treatment (adapted from [33]); (c) in-ditch bioreactor; (d) bioreactor for wastewater treatment (adapted from [91]); and (e) denitrifying wall (adapted from [4]).

which were then compared using analysis of variance (ANOVA; Kruskal–Wallis ANOVA based on rank followed by Dunn's test for pairwise comparisons) or Mann–Whitney rank sum U testing. The binned datasets were represented using box and whisker plots where: solid and dashed lines were the median and mean, respectively; boxes edges were the interquartile range; whiskers were the 10th and 90th percentile; and dots were outliers. The continuous variable of bioreactor age was assessed for correlation with bioreactor performance metrics using Spearman's rank coefficient (ρ); results by age were illustrated using bins to better highlight differences. All tests were performed in Sigma Plot version 15.0 (Systat Software, Inc., San Jose, CA) and were assessed with $\alpha = 0.05$.

Table 1. The number of studies, unique sites, and site-years for five denitrifying bioreactor design types assessed in this review. Study details are in Table S1.

Bioreactor application		Studies	Sites	Site-years
Subsurface drainage treatment	Field-scale (<60 ha)	28	56	136
	Catchment-scale (≥75 ha)	3	8	23
Ditch or in-ditch treatment		11	10	13
Wastewater and non-ag drainage treatment		15	24	45
Denitrifying wall		15	16	51

3. Nitrate removal across design styles

The overall results across the database are presented in Figure 2 and Figure S3 with summary statistics quantified in supplemental Table S2. A detailed assessment of each design style follows in the appropriate section.

Compilation and analysis of these data illustrated wood-based denitrifying bioreactors are a flexible technology that can provide N treatment for a variety of waters. This adaptability means that the performance of the individual design styles may be most appropriately assessed using distinct criteria. For example, the current design standard in the U.S.A. for bioreactors treating subsurface drainage is based on an efficiency metric defined as the mass of N removed relative to the mass of N eluted from the field (i.e. 20% N removal assessed at the edge of the field; [27]). Treatment efficiency defined in this way is a straightforward metric for landowners and conservation professionals working in the landscape. However, bioreactors

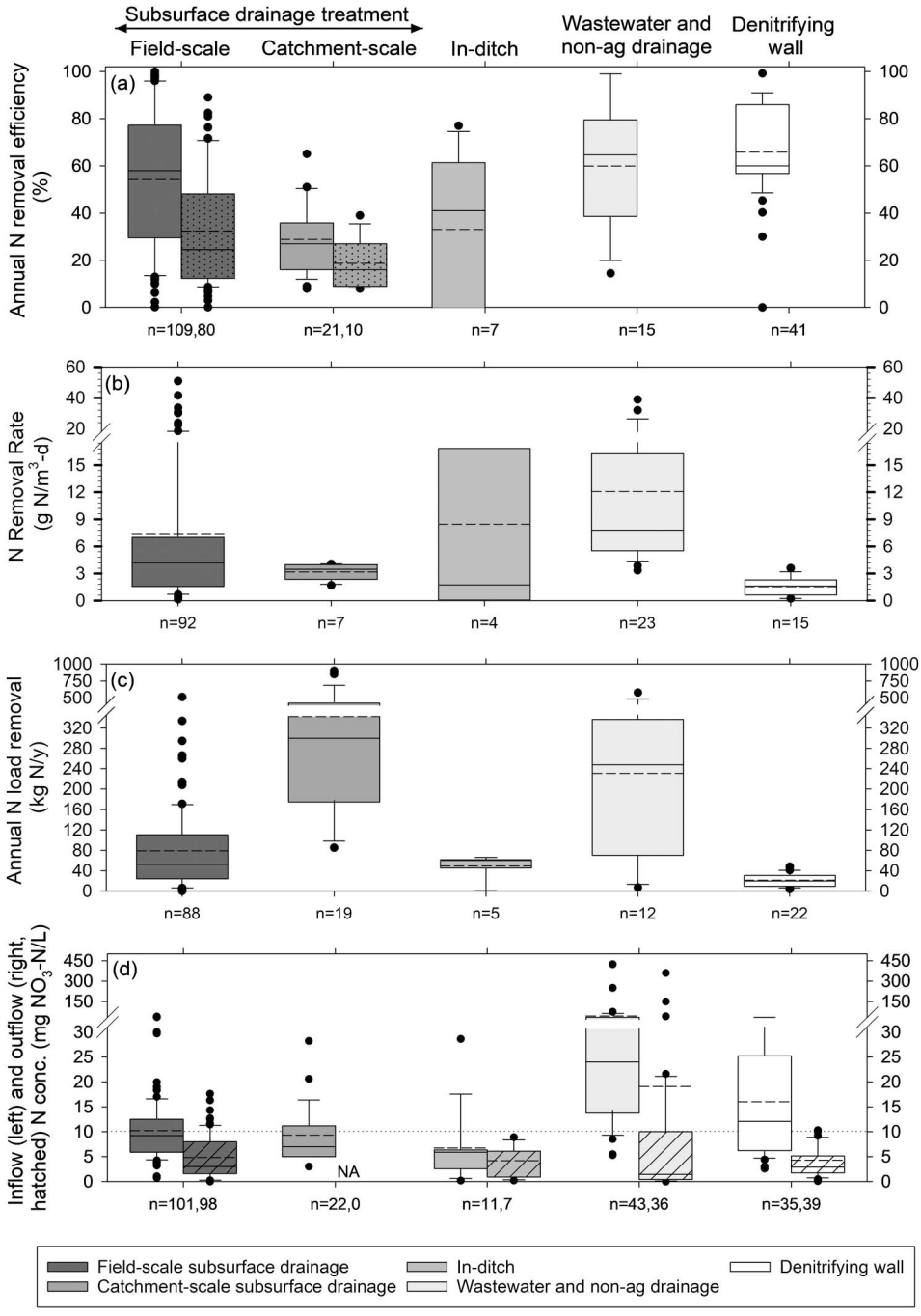


Figure 2. Ranges of annual nitrate-nitrogen (N) removal metrics from a review of five bioreactors styles: (a) removal efficiency; (b) removal rate; (c) load removed; and (d) inflow (left open box) and outflow (right hatched box) concentrations. Removal efficiency (a) was assessed for the treated water (bioreactor efficiency; open boxes) and at the edge of the field (dotted boxes) for the field- and catchment-scale subsurface drainage bioreactors that often report bypass flow.

designed with bypass plumbing often have two annual efficiencies reported: (1) the N removal efficiency of the treated water and (2) the N removal efficiency as assessed at the edge of the field which includes untreated bypass flow. This applies to both the field-scale and the catchment-scale bioreactors reviewed here (Figure 2(a)). The use of efficiency as a performance metric has an important limitation in that it is a relative parameter meaning annual efficiencies are often higher at smaller drainage areas or in drier years.

Beyond efficiency metrics, bioreactors treating wastewater or other point sources may be bound by a permitting mechanism like the National Pollution Discharge Elimination System (NPDES). Such bioreactors may be designed to achieve a given N load reduction (e.g. kg N/day; Figure 2(c)). Additional mass-based metrics like

N removal rate are also used for design and comparative assessments, especially of different bioreactor fill media or performance enhancements (Figure 2(b): g N removed per m^3 bioreactor per d). However, the calculation of this rate metric has been inconsistent across bioreactor literature [14,28]. Of the 192 N removal rates compiled here, 47% were based on the bioreactor saturated volume, 23% were based on the total woodchip volume, and 9% included the woodchip porosity in the calculation. The calculation of the remaining 20% of reported N removal rates was not clearly described.

Finally, a desired outflow N concentration may be a useful performance indicator because nutrient criteria and drinking water standards are often expressed as concentrations. All five bioreactor design styles reduced the median outflow N concentrations to below the United States Environmental Protection Agency maximum contaminant level of 10 mg NO_3-N/L for drinking water and the European Union Nitrates Directive limit of 50 mg NO_3-/L (Figure 2(d)). Use of outflow N concentrations as a performance metric may be especially relevant for denitrifying walls given the additional complexity of estimating groundwater flow [29].

Bioreactor construction cost and cost efficiency ($/kg N-y) were not reviewed here although these are important metrics that impact the practice adoption. Comparing bioreactor cost efficiencies in a literature review format is difficult because reported values vary based on the costing method as well as over time and geography. Moreover, achievement of 'cost effectiveness' differs across the applications studied here which included regulated point-sources as well as non-point sources in areas where water quality practices are adopted on a voluntary basis. Nevertheless, bioreactor construction costs have ranged from approximately $2,500 to more than $30,000 USD [14,30–33] with Maxwell et al. [34] reporting eight subsurface drainage bioreactors in Illinois averaged $16,020 ± $9,960 per bioreactor in 2023 prices. Modelling of bioreactor cost efficiencies commonly results in values of $2 to $20/kg N-y [1,35–41] although some recent empirical assessments have shown $33 to $50/kg N-y [33,34].

4. Subsurface drainage treatment

Bioreactors designed for field-scale treatment (< 60 ha treated) of subsurface drainage provided medians of 52 kg N removed annually, 4.1 kg N/ha-y removed, and a removal rate of 4.2 g N/m^3-d (n = 78-92; Figure 2(b–c); Table S2). Annual N removal efficiency for the treated water was 58% whereas edge-of-field efficiency was 25% (Figure 2(a)). These bioreactors tended to be on the order of 100 m^3 of woodchips (Figure S3a). Inflow nitrate-N concentrations ranged close to 10 mg N/L (median: 9.2 mg NO_3-N/L; Figure 2(d)). Bioreactors treating subsurface drainage were dependable with N removal observed in all site-years.

4.1. Latitude

Temperature strongly influences denitrification and thus N removal in denitrifying bioreactors. This effect is most clearly documented in small-scale studies where N removal at relatively low and high temperatures can be directly compared [42–44]. This has led to concern that some northern regions are 'too cold' for drainage bioreactors, despite bioreactors operating in or near the Arctic for other applications [45–47]. Thus, this database was used to assess the impact of latitude on drainage bioreactor N removal.

The latitude of 42 °N (approximately Chicago, Illinois, U.S.A.) was used to separate 'northern' and 'southern' North American site-years to facilitate roughly equal sized bins (n = 48 and 62, respectively; Table 2). The northern bioreactor site-years were from: South Dakota (n = 11), New York (10), Minnesota (9), Ontario (9), northern Iowa (7) and northern Illinois (2). The southern site-years were from: central Illinois (49), central Iowa (4), Maryland (8), and Virginia (1). Northern European bioreactor site-years provided additional perspective (Denmark, 10; Germany, 3).

Latitude was used as a proxy for water temperature in this analysis because temperature was only reported in approximately half of the site-years. Nevertheless, water temperatures decreased as latitudes increased as expected (Table 2). Even so, neither annual N load removed nor N removal rate significantly differed between the northern and southern North American bioreactors (Table 2). For example, the southern sites provided annual N removal of 50 kg N/y versus the northern median of 53 kg N/y. Although N removal efficiency was significantly lower for the northern vs. southern site-years, the northern site-year's 50% removal efficiency nevertheless demonstrated substantial treatment. The northern site-year's numerically higher N removal rates yet lower removal efficiency may have been related to higher inflow N concentrations documented at the northern vs. southern bioreactors (Table 2).

The field-scale bioreactor site-years from Northern Europe, which were from approximately 55°N, removed double the annual N load of the North American designs (Table 2: 119 vs. < 55 kg N/y). This high annual load reduction was notable given the low

Table 2. Median (sample size) water temperature, design, and performance metrics for northern and southern North American field-scale bioreactors (i.e. above and below 42 °N latitude, respectively) with northern European site-years for additional context. The same uppercase letter within a given column indicates the median did not differ between northern and southern North American sites (Mann-Whitney test) and the same lower case letter indicated the medians did not differ between the three location groups (Kruskal-Wallis ANOVA).

	Latitude ° N	Water temp. ° C	Inflow N conc. mg NO_3^--N/L	Drainage area ha	Bioreactor surface m^2	Bioreactor surface: drainage area %	N load removal kg N/y	Removal efficiency for treated water %	N removal rate g/m^3-d
Southern bioreactors (<42 °N)	40.6 (62) B c	10.7 (29) A a	7.5 (42) B b	14 (56) A a	84 (58) b	0.056 (55) B b	50 (50) b	58 (57) A	4.1 (50) ab
Northern bioreactors (>42 °N)	43.5 (48) A b	9.5 (22) B b	11.5 (43) A a	8.1 (39) B b	112 (42) b	0.093 (39) A a	53 (23) ab	50 (31) B	5.8 (29) a
Northern European bioreactors	55.2 (13) a	6.9 (7) b	10.0 (13) a	20 (13) a	248 (13) a	0.12 (13) a	119 (10) a	52 (13)	1.7 (7) b

median water temperature of 6.9 °C. These European bioreactors tended to treat larger drainage areas and were larger than their North American counterparts (i.e. greater surface areas; Table 2).

Overall, these empirical field-scale data illustrated northern bioreactors experience cooler drainage water temperatures compared to their southern counterparts, but when assessed at the annual scale, they still provided valuable N removal. High annual N load removal is possible at field-scale drainage bioreactors even in cold climates (e.g. Denmark, Germany). Thus, while water temperature is known to be important, it is only one of many factors that influences annual N removal at the field-scale. It would be useful to more thoroughly assess and report temperature in future bioreactor studies to better understand the effects of design features such as: upstream sedimentation basins with open water surfaces; soil or woodchip covers which may provide insulation [48]; and the surrounding soil's buffering capacity [49].

4.2. Bioreactor age

Older drainage bioreactors (up to 9 years in this analysis) exhibited significantly reduced ability to capture flow with the percentage of annual flow treated decreasing from 85 to 26% with increasing age (Figure 3(a); Figure S4b). However, increasing age did not reduce these bioreactors' N removal rates or efficiency for the water that was treated (Figure 3(b,c), Spearman $\rho \approx 0$). For example, medians of between 55 and 58% of the N entering the bioreactors were removed across age ranges. The negative impact of age on flow translated into a negative impact on edge-of-field N removal efficiency and annual N load removed (Figure 3(d), ρ:−0.34; Figure S4c, ρ: −0.25).

These data demonstrate that bioreactor performance deterioration is more strongly a function of hydraulic decline rather than a decrease in the intrinsic denitrifying capacity of the wood media [50–52]. Over time, woodchip particles degrade and media consolidation and sedimentation lead to decreases in hydraulic properties such as drainable porosity and hydraulic conductivity [42,53–55]. Accordingly, relatively lower proportions of the annual flow are able to enter for treatment at bioreactors designed with bypass flow. These lower flow rates theoretically correspond with longer hydraulic retention times (HRTs) and thus greater N removal efficiency for that water. However, there is a concomitant increase in preferential flow paths as the media consolidates, and this unequal usage of the reactor volume creates a tradeoff in residence time. Linkages between woodchip physical properties, bioreactor hydraulics, N removal, and flow over time at bioreactors designed with bypass plumbing still need to be further refined.

An inherent limitation of this age analysis was that there were few studies of older bioreactors (Figure S4a). Thus, it is possible that bioreactor N removal capacity eventually decreases (i.e. a carbon limitation with increased age), and these data were simply too young to document this. In this database, the oldest sites were denitrifying walls (19 years, [56]; 14 years, [57]). The oldest subsurface drainage bioreactors with reported annual N removal were 7–9 years old [50,58–60], although monitoring over that time is not always continuous.

4.3. Scaling treatment

The eight bioreactor systems for catchment-scale drainage treatment (i.e. > 75 ha; Table 1) reviewed here removed much larger annual N loads than field-scale bioreactors (medians: 300 and 52 kg N/y respectively; Figure 2(c); Table S2). However, this equated to lower N removal efficiencies for the catchment-scale

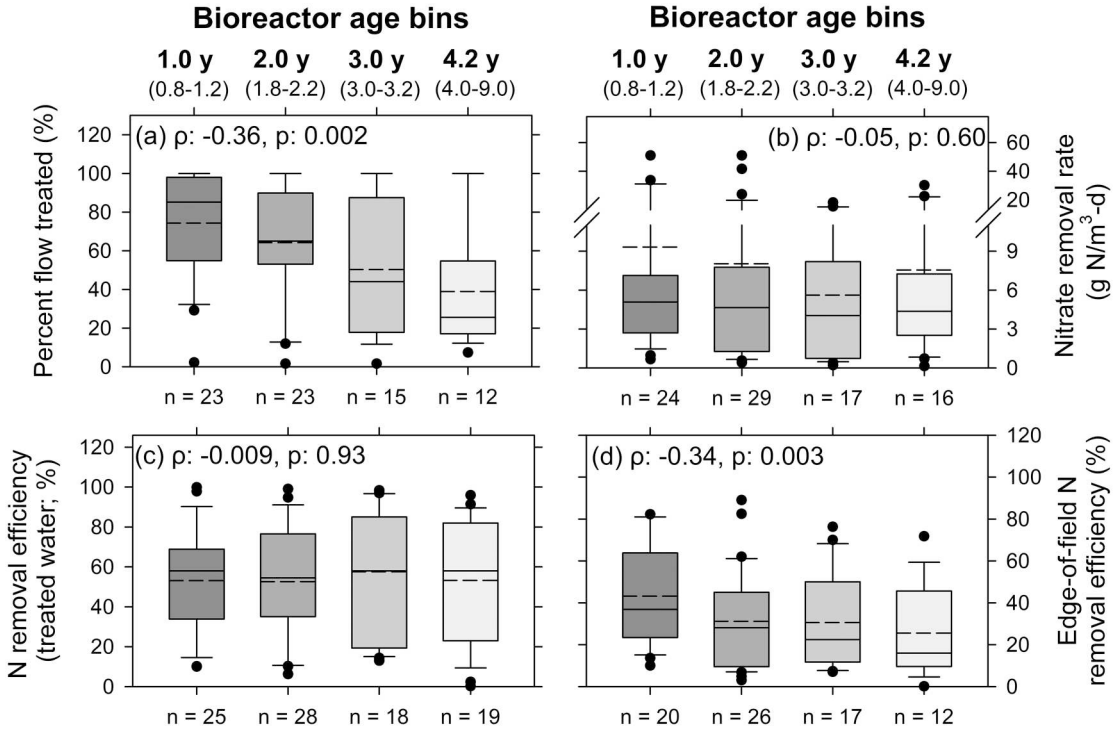


Figure 3. Field-scale subsurface drainage bioreactor age versus the annual fraction of drainage treated (a) and N removal metrics (b–d). The median (range) ages for each bin are shown at the top and sample sizes are below. The Spearman rank coefficients (ρ) are for age versus the given metric with the corresponding *p* value for the Spearman assessment.

bioreactors for both the treated water and at the edge of the field (27 and 16%, respectively; Figure 2(a)). This comparison was limited by the relatively few catchment-scale bioreactors that have been built and monitored.

A common feature of these catchment-scale bioreactors was that they were either multiple chamber units or were paired with sedimentation basins [25,33,60]. In tile-drained landscapes, large-scale conveyance networks often carry flow that is combined tile drainage and surface runoff, the latter of which contains a relatively higher sediment load. Thus, a sediment exclusion system is an important design component to protect the woodchip media and stabilize flows [50,60,61]. Feyereisen et al. [25] developed a novel sediment exclusion cutoff which routed flow to bypass the bioreactor when stream turbidity rose. Catchment-scale bioreactor facilities may also be more likely to use pumping systems compared to field-scale applications [33,60].

The use of multiple cell bioreactor systems for treatment of larger drainage areas raises the question of a breakpoint in the drainage area above which multiple cells would be required. The largest drainage areas treated by a single-unit bioreactor in the compiled database were approximately 50–60 ha, although these bioreactors used upstream sedimentation basins [33]. The smallest drainage areas routed to multiple-chamber bioreactors have been 29 and 37 ha [62,63]. Design guidance from Denmark recommends multi-chamber units be used when the drainage area exceeds 20 ha [64], but these broader empirical data indicate a slightly higher breakpoint of roughly 30 ha. More bioreactors on drainage areas larger than 20 ha will help better calibrate this breakpoint for multiple cell systems.

Scaling bioreactor treatment for larger drainage areas increases N loading and N load removal (i.e. Figure 2(c)), and such scaling improves the cost efficiency of this practice ($ per kg N removed; [34,36,37,65]). However, it is unknown if catchment-scale bioreactors provide disproportionately more N removal than field-scale bioreactors. That is, is there an economy of scale for bioreactors that leads to more efficient N removal? Conversely, is there an upper limit to bioreactor treatment (i.e. can bioreactors be too big)? To address these questions, field-scale and catchment-scale bioreactor site-years were evaluated together by binning design and treatment metrics based on practical divisions in drainage treatment area (Figure 4 bins left to right: 2–9 ha; 10–19 ha; 20–60 ha; and 75–250 ha).

Annual inflow N loading and thus N load reduction significantly increased with increasing drainage treatment area Figure 4(b,c); [33,66]. However, none of the

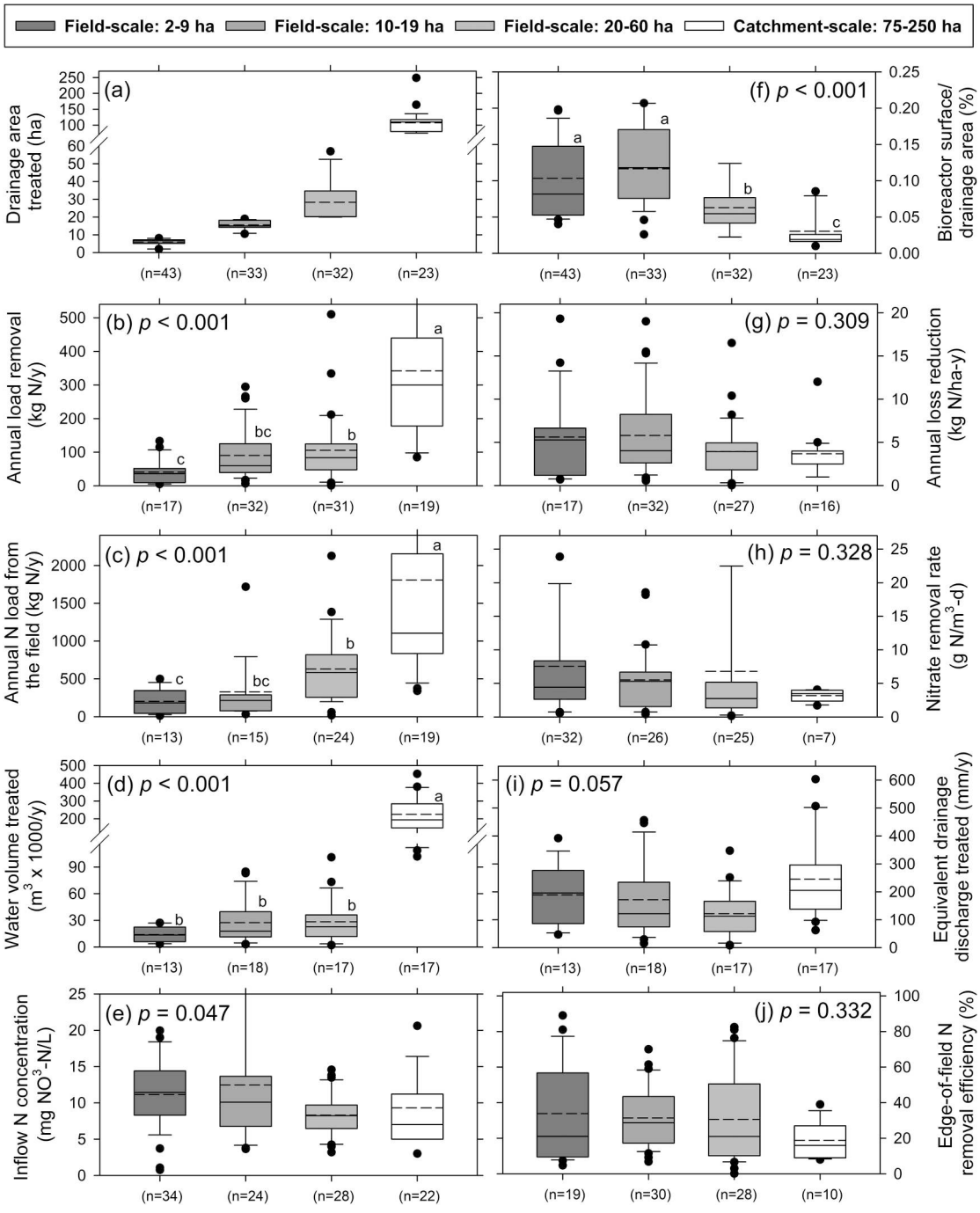


Figure 4. Subsurface drainage bioreactor performance metrics sorted by drainage treatment area where the boxes in each panel range from the smallest to largest drainage areas. The furthest right box is the catchment-scale bioreactors from Figure 2. Upper whiskers (b, c, e) and upper outliers (h) are not shown in some panels to better highlight detail.

area-normalized performance metrics differed significantly across the bins (Figure 4(g–j); $p = 0.057–0.332$). For example, median annual N loss reductions were 5.3, 4.0, 3.9, and 4.0 kg N/ha-y across the four bins (Figure 4(g)). The lack of statistical difference between bins for normalized performance metrics indicated scaling neither increased nor decreased performance as defined with these metrics.

One normalized metric that supported the hypothesis of increased efficiency with increasing scale was the ratio between bioreactor surface area and drainage treatment area. This ratio decreased with increasing drainage area, with the catchment-scale bioreactors requiring only 0.02% of the drainage area (Figure 4(f)). Thus, catchment-scale bioreactor treatment was more space efficient, although space efficiency is a well-known

benefit of bioreactors across all drainage treatment areas [13,50].

Assessing drainage treatment area in this way also begs the question: Is it better to have a number of field-scale bioreactors deployed across a watershed or one catchment-scale, more centralized bioreactor? Cost modelling by Hartfiel et al. [37] indicated it was more cost efficient to deploy a large, centralized bioreactor. In the current review, the bioreactors treating the smallest and largest drainage areas of 6.9 and 110 ha, respectively (Figure 4(a) medians), provided median annual N load reductions of 36 and 300 kg N/y (Figure 4(b)). Thus, simple calculation shows a watershed would require roughly eight (or, 300/36) small bioreactors to achieve the same overall load reduction as centralized treatment.

Those eight hypothetical bioreactors would require as many as eight landowners to be involved as well as consideration of the construction mobilization effort for eight sites. Those eight hypothetical bioreactors would require 552 m^3 of woodchips (8 x mean of 69 m^3; data not shown) which would cost more than the 464 m^3 mean woodchip volume required for one large, centralized bioreactor. This also means the dispersed bioreactors would cost more to recharge at the end of the initial design life. On the other hand, an obvious limitation for the construction of one centralized bioreactor is the land ownership and accessibility at the watershed outlet. From an operational perspective, if problems arise at a centralized bioreactor, the entire treatment system may be comprised (100% loss of treatment). However, consistent management and regular on-site assessment are more likely to occur for a centralized versus distributed treatment approach. Finally, these two approaches may impact the receiving streams differently during start-up flushing. The carbon (as well as phosphorus, tannins, etc.) loading of one large bioreactor would be more centralized albeit into a larger receiving stream versus a number of smaller dispersed bioreactors which would presumably be constructed over a period of at least several weeks.

The appropriateness of distributed small-scale versus large, centralized bioreactor treatment likely differs by watershed in the current voluntary approach to conservation in the US Midwest. It would be useful to have additional monitored catchment-scale bioreactors to help better understand challenges and opportunities at these scales. However, both approaches will likely be necessary, and the Batch and Build program in Iowa, U.S.A. provides a new example of a conservation delivery mechanism that has implemented hundreds of field-scale practices using a distributed approach [67].

5. Additional design styles and applications

5.1. In-ditch bioreactors

In agricultural landscapes, treatment of N in ditches or streams centralizes efforts compared to a paradigm of treating individual drainage outlets. In-ditch bioreactors (also known as 'stream bed bioreactors' or 'bioditch reactors'; Payne et al. [68]) are appealing because there is no loss of land from agricultural production and ditches may have more consistent flow than individual outlets [69]. Millions of agricultural ditches around the world set the context for this type of bioreactor with eleven in-ditch studies compiled in this review (Table S1: Germany, Belgium, Australia, New Zealand, Canada, and U.S.A.: Pennsylvania, Maryland, North Carolina, and Illinois). The sample sizes of performance metrics tended to be small for this type of bioreactor ($n = 4$–11; Table S2), which meant that although in-ditch bioreactors are being widely investigated around the world, the studies were often less than 2 years.

In this review, in-ditch bioreactors removed 60 kg N annually with an efficiency of 41% (Figure 2). These bioreactors tended to be closer in size to pilot-scale versus full-scale bioreactors (median volumes: 26, 25, and 100 m^3, respectively; Figure S3a), possibly because they are usually retrofit within existing landforms. One exception was the large in-ditch bioreactor reported recently by Burbery et al. [70] (450 m^3). Despite the generally small size, the flow rates reported in these in-ditch studies were some of the highest across this review (median: 2.3 L/s; Figure S3b).

Design methods for tile drainage bioreactors do not seamlessly translate to in-ditch treatment [29,71]. The purpose of man-made drainage ditches is to convey water, so restriction of that flow needs to be considered cautiously. Nevertheless, an infiltration feature in an in-ditch bioreactor is essential to direct flow into the wood media. This often takes the form of a gravel or large stone infiltration gallery generally combined with a berm or a check dam within the ditch [31,41,69,71,72].

Balancing these bioreactor design constraints in agricultural ditches has proven tricky in some cases. Maxwell et al. [73] reported a 'bioreactor bag' deployed in a ditch in Illinois, U.S.A. provided negligible N removal although the woodchips themselves had a high denitrification potential. This simple 'bag' design lacked an effective infiltration feature. Hydraulic challenges also limited in-ditch bioreactors in Queensland, Australia where large 'first-flush' events overwhelmed the bioreactors [74]. Low N concentrations in the ditch drainage (mean: 0.2 mg NO_3-N/L) further contributed to the limited N

removal. Iverson et al. [31] reported that daily mass removal rates were highest when ditch N concentrations exceeded 2 mg NO_3-N/L at an in-ditch bioreactor in North Carolina, U.S.A.

Siltation is one of the most important maintenance concerns for in-ditch bioreactors [69,71,73]. Design solutions include the use of modular bioreactor sections that can be sacrificed and valves that can be closed for sediment exclusion [25,70,72]. Other downsides include that permitting and approvals [31,72] and monitoring [29] may be more complicated for this type of bioreactor. Nevertheless, in-ditch enhanced denitrification holds promise for unique applications such as areas with a high density of on-site septic systems [31], for roadside ditches [75], or for cranberry bogs [76]. Bioreactors in or near waterways provide an opportunity for streambank stabilization and restoration, although this increases cost [31,77].

5.2. Wastewater and non-agricultural drainage applications

In this review, woodchip bioreactors for the treatment of wastewater and other effluents (non-drainage) included treatment of: aquacultural wastewater; municipal wastewater; on-site septic effluent; leachate from waste rock piles following blasting; effluent from greenhouses; and desalination brine (Table S1). These 15 studies spanned the globe which reiterated the importance of simple, low-cost N treatment for many waters: New Zealand ($n = 6$ site-years), Australia (1), Spain (1), Canada (18), Denmark (4), Sweden (5), Finland (1), and the U.S.A. (9).

These non-agricultural drainage bioreactors were notable for high N removal efficiency, annual load removal, and removal rates (medians: 65%, 248 kg N/y, and 7.8 g N/m^3-d, respectively; Figure 2(a–c); Table S2). Other bioreactor types had high removal efficiencies (denitrifying walls) or high load removals (catchment-scale drainage treatment), but not as consistently across multiple metrics. These bioreactors were some of the largest (Figure S3a) and they received the highest inflow N concentrations (median: 24 mg NO_3-N/L; Figure 2(d)). These non-drainage applications are also quickly advancing ideas for treatment of pollutants beyond N, including:

- agricultural chemicals [22,78,79];
- pharmaceutical and personal care products [80];
- plant pathogens [81];
- fecal indicator bacteria, coliforms, and viruses [82–84]
- metals and outflow toxicity: [47,85,86];
- and salinity effects [87,88].

One of the most important challenges for bioreactors treating waters and wastewaters with relatively higher chemical/biological oxygen demands (COD/BOD) or suspended solids is clogging of the wood media. Tabatabaeefar et al. [89] nicely illustrated the differences in physical versus biological clogging in phosphorus removal filters, concepts which are also relevant for woodchip bioreactors (i.e. clogging via settled particles versus excessive biofilm). Clogging in woodchip bioreactors tends to occur near the bioreactor inlet [90,91] although it is also possible in other locations [46]. This can cause head loss across the reactor, reduction in pore volume and hydraulic efficiency, and eventually, hydraulic failure [89–91]. Hydraulic impacts from excessive bacterial growth are also possible when woodchip bioreactors are dosed with liquid carbon [16,21,92].

Design solutions for minimizing clogging include use of larger media [16,70,89] and incorporating sediment pre-treatment [25,60]. Additionally, distributed feed manifolds are recommended to reduce clogging in wetlands and P filters [89,93]. Lepine et al. [94] reported a multiple-header inlet manifold resulted in slightly better N and solids removal compared to a single T-shaped manifold in bioreactors treating aquacultural wastewater over 784 d. This was a relatively inexpensive design element compared to the cost of media replacement. A vertical cleanout pipe attached to the inlet manifold that extends to the surface may be helpful [27].

From a management perspective, the ability to backwash the inflow manifold is useful [89,91] but increasing the flow rate to remove the clogging in a bioreactor has not always been successful [16]. A 'fill-and-drain' approach involving periodically draining the bioreactor to reduce bacterial growth may help [93], and such drying cycles will also boost N removal [17]. Nevertheless, despite the best design and management, bioreactors in these applications may need to consider sacrificial sections near the inlet that can be replaced more frequently than the remainder of the bed [55,70,91,93].

5.3. Denitrifying walls

Denitrifying walls (also known as sawdust walls) are a type of permeable reactive barrier where narrow excavations backfilled with a mixture of native soil and sawdust are placed perpendicular to the flow direction of shallow groundwater [1]. A variation of this is to backfill woodchips around tile drainage pipes [95–97]; this design is not common but did contribute notably to this review (20 of the 51 denitrifying wall site-years from [56]).

Denitrifying walls had some of the highest N removal efficiencies (interquartile range: 57-85%; Figure 2(a)).

However, this equated to the lowest annual N load removals (Figure 2(c)). Denitrifying walls receive relatively low loading due to slow groundwater flow (e.g. median: 0.03 L/s; Figure S3b) even though they are targeted in areas of high N concentrations (Figure 2(d)). Thus, this bioreactor style is more likely to be N-limited than other styles [1,15,98]. Denitrifying wall volumetric removal rates were the lowest of the six types assessed here (median: 1.6 g N/m^3-d; Figure 2(b)). This reaffirmed findings from the first bioreactor review where Addy et al. [15] reported removal rates of 0.7 and 4.7 g N/m^3-d for walls versus beds, respectively, although only three walls had been reported at that time.

Denitrifying walls are the simplest bioreactor style to design and construct due to their lack of plumbing [71,99], but assessment of site suitability is more complicated [1,61]. Appropriate siting and keying-in of sawdust walls is essential because groundwater can bypass around the wall [1,100–102]. It is useful to note the positive water quality influence of a denitrifying wall may extend beyond the intended zone due to leached carbon, but this could also present a concern if a sensitive stream were downgradient [99]. Burbery et al. [103] highlighted the potential risks of pollution swapping (e.g. localized mobilization of iron, manganese, and arsenic). Nevertheless, the wide geographies where sawdust walls have been assessed testify to the need for simple denitrification treatments for shallow groundwater (New Zealand, Netherlands, Australia, Canada, Lithuania, and the U.S.A.: Maryland, Iowa, and Florida; Table S1). Streamlined siting guidance and water quality crediting procedures may help accelerate implementation of these useful permeable reactive barriers.

6. Bioreactor engineering design

6.1. Bioreactor sizing models

The NRCS Conservation Practice Standard Code 605 for denitrifying bioreactors is likely the most widely used design procedure to date with hundreds of bioreactors built using this approach [27]. This design procedure links Darcy's Law with the hydraulic retention time (HRT; see Section 6.2) equation. The result is a capacity-based (i.e. 15% of peak flow) standard where performance is assessed using relative percentage metrics (i.e. 20% edge-of-field N removal efficiency; [104]). Darcy's Law underpins this and other design methods due to its relatively simplicity [64,105,106] although some report Forchheimer's equation is a better representation [107,108].

Many other bioreactor volume sizing methods also incorporate the concept of HRT. Design guidance from Queensland, Australia, describes the calculation of a required HRT using a desired concentration reduction in mg N/L and a locally-derived concentration decline rate of 0.8 mg N/L-h [61]. Krone et al. [109] also developed a concentration-based bioreactor design model for treatment of irrigation tailwater in California, U.S.A. Their model, available via github.com, uses inputs of flow rate, inflow N concentration, water temperature, and HRT to achieve a desired outflow N concentration. Inflow N concentrations in subsurface drainage applications are often not known, thus some subsurface drainage bioreactor design models have been developed independently of reaction kinetics (i.e. assuming zero-order kinetics). For example, Plauborg et al. [64] describes a more hydraulics-based volume sizing procedure for Danish bioreactors that is based on HRT, drainage area, and flow factors.

One of the most straightforward bioreactor design approaches is to assume a N removal rate and back-calculate the required bioreactor volume necessary to provide the desired grams of N removed per day [1,110]. This simple method is most appropriate for bioreactors treating consistent flow rates where N-limited conditions are unlikely.

Another relatively simple approach is to calculate a required bioreactor surface area based on a ratio of the treatment area (e.g. 0.1% bioreactor surface/watershed ratio; [13]). Verma et al. [111] used the inverse of the surface area/drainage area ratio to develop a loading density metric originally in units of treated acres/100 ft^2 bioreactor surface. The USDA NRCS uses the correlation between this loading density and N removal efficiency to guide bioreactor sizing [112] although this relationship should be better validated, especially using relatively undersized bioreactors [66].

Finally, although this is not a comprehensive review of bioreactor fill, woodchip physical and hydraulic properties are necessary inputs to some of these design methods. Knowledge of woodchip properties has advanced over the past fifteen years, but woodchip saturated hydraulic conductivity, effective porosity, and bulk density can be: highly variable in space and time; difficult to measure; inconsistently reported; and often unknown *in situ* [42,53,113,114]. Further study and improved reporting of these properties, especially over time, would be helpful for bioreactor design science.

6.2. Hydraulic retention time

Hydraulic retention time is one of the most important and commonly used concepts in woodchip bioreactor

design and operation [9,10,12]. The nominal HRT, or the theoretical time it takes a parcel of water to travel through a reactor filled with porous media, is:

$$T = \frac{\rho V}{Q} \quad (1)$$

where T is in hours, ρ is the media porosity, V is the saturated volume (m^3), and Q is the volumetric flow rate through the reactor (m^3/h). Across the database, operational HRTs for field- and catchment-scale subsurface drainage bioreactors tended to be either relatively low or high; for instance, 32% of site-years operated at 1 to 6 h whereas 28% operated at more than 48 h ($n = 85$; Figure S5). The non-drainage bioreactors were more consistent with 59% of the site-years operating at HRTs between 8 and 25 h ($n = 22$; Figure S5).

For denitrifying woodchip bioreactors, HRT is strongly positively corelated with N removal efficiency for the treated water [50,58,115–117]. This relationship can be useful for performance prediction, but perhaps more importantly, this matters for design purposes because it illustrates there is a minimum HRT below which N removal is limited. The American (USDA NRCS), Danish, and Australian bioreactor design models each use a minimum HRT which corresponds with the expected peak flow rate through the bioreactor (often termed the design or target flow rate). The minimum HRT used by the NRCS and in Australia is 3.0 h, whereas Danish guidance uses either 4.0 or 6.5 h for bioreactors treating year-round or winter-only drainage, respectively [27,61,64].

6.3. Aspect ratio

Bioreactor aspect ratio, or the ratio of length to width, ranged from 0.30:1 to greater than 50:1 across this review. Denitrifying walls and in-ditch bioreactors had the highest aspect ratios (Figure S3c: 38:1 and 8.7:1). Bioreactors designed according to the Conservation Practice Standard in the U.S.A. have an aspect ratio of 4:1 (otherwise a multi-header manifold is required; [27]) and Australian guidance recommends 10:1 [61]. Some bioreactors in Europe have been designed with lower aspect ratios (e.g. 0.7:1 and 1.3:1; [33]).

Reactor aspect ratio is interesting in that it is not considered in either HRT-based or surface area-based (e.g. loading density) design approaches. For example, assuming all else equal, Equation (1) shows that a bioreactor that is 12 m long and 3 m wide (aspect: 4:1) would result in the same theoretical HRT as a bioreactor that is 3 m long and 12 m wide (aspect: 0.25:1). If these reactors were designed using horizontal flow orientation (see Section 6.5), their flow regimes would notably differ with the higher aspect ratio bioreactor operating more consistently with plug flow theory but also potentially have a more limited ability to capture flow [118,119].

When field-scale bioreactors were binned by aspect ratio in this dataset, longer and narrower bioreactors removed a greater percentage of the inflow N compared to shorter, more squarish bioreactors (aspect ratios: 3.5:1 to 5.3:1 versus 0.3:1 to 2.0:1; median N removal: 74 vs. 58%, respectively; $p = 0.016$). However, bioreactors with relatively higher aspect ratios may be more limited in their ability to capture flow, especially at sites designed with bypass flow plumbing [66]. Capturing more flow is important because increased N loading can result in higher N removal rates [33,120–122]. Wetlands that are sized based on loading criteria often have widths greater than their lengths (aspect ratio < 1; [93]).

Aspect ratio may also be a design factor that can be used to improve bioreactor longevity. Woodchip subsidence, particle size degradation, and clogging are often the worst near the bioreactor inlet [54,55,123], so increasing the inlet width could reduce some risk in that area. Non-ideal flow regimes (e.g. preferential flow, dead zones) that may occur with wider cross-sectional areas of flow can be mitigated with the use of strategically placed baffles [46,118,124,125].

6.4. Cross-sectional shape

The majority of bioreactors constructed to date have had rectangular cross-sections, but ten sites were reported with trapezoidal cross-sections. Two of these were in-ditch bioreactors where the cross-sectional shape was determined by the shape of the ditch [32,72]. The eight bed-style bioreactors with trapezoidal cross-sections generally had side-slopes of close to 1:1 [82,122,125–127]. The steepest trapezoidal side-slope was at a bioreactor in Germany (0.63:1, [128]) and flattest was at a bioreactor in New Zealand (1.3:1, [28]). von Ahnen et al. [129] described a combined trapezoidal and rectangular cross-section design and Asgari et al. [130] illustrated a bioreactor with a triangular cross-section. Rivas et al. [127] noted their trapezoidal shape in New Zealand was done for construction safety. In the US Midwest, contactors prefer to build rectangular cross-sections.

Beyond construction considerations, cross-sectional shape may influence bioreactor performance [131]. Given two bioreactors with the same overall cross-sectional area, at low flow rates and low water depths, the geometry of a bioreactor with a trapezoidal cross-section would result in a smaller cross-sectional area of flow, smaller wetted perimeter, and thus, higher flow velocity than a rectangular design. This higher velocity could help avoid stagnation at low flows. A bioreactor

with a trapezoidal cross-section may also provide some longevity benefits in terms of reduced subsidence [123].

6.5. Flow orientation and routing

Flow orientation in full-size bioreactors is generally described as horizontal, vertical downflow, or vertical up-flow, with horizontal flow routing the most common across the database (70% of bed-style site-years). Bioreactors treating wastewater and non-agricultural drainage applications were the major exception with vertical flow orientation described in 23 of the 40 site-years this was reported (58%). There were some mixed flow orientations, for example, with Robertson et al. [84] describing a downflow/up-flow design for septic treatment.

The most comprehensive assessment of bioreactor flow routing was performed in Denmark at a set of six bioreactors that tested the three flow orientations. Horizontal and vertical downflow orientations both provided treatment benefits over a series of studies [50,132–134]. Smaller-scale bioreactor flow orientation studies have recommended downflow [135,136]. Up-flow orientation is generally not recommended [50,133,136,137].

Bioreactors treating subsurface drainage in the US Midwest use horizontal rather than downflow orientation because drain pipes are located underground and most drainage systems are gravity-fed (i.e. no pumps). Horizontal flow routing using inline water level control structures allows these designs to avoid significantly restricting drainage flow from the field. Many subsurface drainage bioreactors use separate control structures for the inlet and outlet [14], but several sites in this review used one 4-chamber structure [30,138–140]. A drawback of this horizontal flow design approach is that only the bottom portion of the woodchips are used. In terms of saturated flow depth, a few bioreactors have been constructed without a liner or with a permeable liner [117,141], but plastic liners are generally required in the U.S.A. [27].

Modifying drainage bioreactors to use a top-fed, downward flow orientation would better use the full woodchip volume and would treat greater flows due to the enlarged cross-sectional plane of flow (L × W rather than W × D; [91,132]). This could also potentially reduce short-circuiting due to the shortened flow path [135,136]. However, this type of flow orientation risks clogging and surface ponding [89,136]. Danish guidance for drainage bioreactors recommends horizontal flow orientation with vertical downflow designs only used in cases where the hydraulic gradient or the cross-sectional area of flow would be insufficient for horizontal routing [64]. Achieving this design without restricting drainage flow in the field would be a challenge in the US Midwest, but is possible [142]. The greatest possibilities for vertical downflow drainage bioreactors may be by incorporating bioreactors into ditches or by pairing bioreactors with a drainage water recycling system.

One nuance of flow routing is the relatively recent addition of 'drawdown plates' now used on bioreactors in the U.S.A. [27]. These specialized stop logs are placed in the bottom of the outlet control structure and contain a triangular hole that serves as a low level orifice [143]. The goal is to prevent development of overly long HRTs and associated negative byproducts (e.g. sulphate reduction, mercury methylation, methanogenesis; [62,144–146]) while keeping bioreactor management easy for landowners. The orifice is sized to drawdown a bioreactor within 48 h under low flow conditions [104].

6.6. Bioreactor coverings

Woodchip bioreactors are either covered, generally with a cap made of excavation spoils, or are left open with woodchips visible at the soil surface. Leaving the woodchips open at the surface was originally thought to make bioreactor recharge easier, with the assumption that woodchips could simply be 'topped up'. However, the recommended recharge process for horizontal flow bioreactors involves woodchip excavation and refilling to address hydraulic restrictions at the bioreactor bottom.

A top unsaturated zone, be it soil or woodchips, reduces greenhouse gas emissions from the bioreactor surface [103,144,147,148] and may provide an insulation barrier in colder climates [48]. Additionally, subsidence is less noticeable at bioreactors with a soil cover [123]. Anecdotally, several edge-of-field bioreactors have been farmed over [56], although traffic on top of a bioreactor is best avoided.

The presence/absence of a bioreactor cover was reported for nearly 300 site-years across the database, and more than 75% of those reported some type of cover. Most of the reported covers were soil although unsaturated zones of woodchips and rock/gravel were also used (165, 48, and 11 site years, respectively). In-ditch bioreactors were the most likely to use a rock or gravel cover since this helps prevent woodchip migration [31,32,41,149].

Danish bioreactor design guidance recommends use of 0.3-0.5 m of unsaturated woodchips on top of the saturated zone [64]. Design guidance in Australia requires a soil cover of at least 0.1 m to help shed runoff water [61]. Use of a soil cover is optional in the U.S.A. although soil covers are often used depending on the state. The

NRCS design process uses woodchip drainable porosities of 0.53 versus 0.47 when no soil cover is used versus with a 0.3 to 0.6 m soil cover, respectively [112].

7. Future direction and conclusions

After roughly a quarter century of wood-based denitrifying bioreactor research, much is known about the engineering of these treatment systems. However, this knowledge is dispersed across the globe and between different sectors and academic disciplines. The novelty of this review lies in its compilation of bioreactor design concepts where we have explored across geographic and disciplinary boundaries to add scientific value to many excellent previous studies of this treatment system. This analysis reiterated that denitrifying bioreactors are a flexible technology that can provide N treatment for a variety of waters. The five unique styles each illustrated opportunities to enhance denitrification of N pollution across the landscape.

The relative importance of each of the factors reviewed here (e.g. latitude, age, HRT, design features) will vary for both bioreactor research and implementation efforts based on local objectives, needs, and constraints. For example, bioreactors are capable of N removal across latitudes, but additional study of the impact of a soil/woodchip covering to buffer against low temperatures is more relevant in cold rather than warm climates. In general, the widely-used concept of HRT exerts some of the heaviest influence in design thinking despite limitations of its application in these reactors where the porous media changes over space and time. Bioreactor flow orientation and aspect ratio are also important but are both relatively predetermined in current implementation processes (e.g. NRCS CPS, 2020). Based on contemporary knowledge of the factors assessed here, bioreactor coverings and cross-sectional shape exert relatively smaller influences on N removal.

Another implication of this work is that the different bioreactor styles presented unique opportunities and challenges (e.g. siltation of in-ditch bioreactors). For drainage treatment in the US Midwest, one of the most significant potential future engineering design advances may be the placement of relatively undersized bioreactors on larger drainage areas (e.g. > 20 ha; [150]). As bioreactor performance begins to be defined beyond simply removal efficiency (%; [151]), lower aspect ratios (< 4:1) should also be evaluated to increase load removal.

Moving forward, more monitoring is called for to continue to inform understanding of the performance of full-size bioreactors operating *in situ* under real world conditions. There is a need for more long-term bioreactor studies, particularly including aging sites. Existing bioreactor design standards importantly validate this technology, but it is also important to design and monitor bioreactors that deviate from the standards to advance the technology for greater impact. Examples include: more bioreactors on larger drainage areas and/or treating higher flow rates; novel features like baffles or various drawdown designs; pairing bioreactors with water storage/drainage recycling, phosphorus removal filters, or automated structures. Finite element modelling for some of these bioreactor design ideas could usefully advance the design science without the expense of full-size construction. Finally, across all scales of bioreactor study, there is an ongoing need for improved transparency and where possible, consistency, in reporting (e.g. woodchip physical properties, calculation methods).

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Generative AI statement

Microsoft Copilot (version 1.25121.84.0) was used to stylistically render photos and illustrations from previously published works in Figure 1.

Data availability statement

This study was a re-analysis of existing data that are publicly available from the various published literature referenced in text.

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