This manuscript is in press. It has been accepted for publication in *Transactions of the ASABE*. When the final, edited version is posted online this in-press version will be removed. Example citation: Authors. Year. Article title. *Trans. ASABE* (in press). DOI number.

The DOI for this manuscript, active after publication, will be https://doi.org/10.13031/trans.14300.

TECHNO-ECONOMIC ANALYSIS OF CONSTANT FLOW WOODCHIP BIOREACTORS

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Highlights

- Techno-economic analysis of multiple scales of bioreactors operated under a variety of conditions
- Unit cost decreased as bioreactor size increased
- Unit cost increased in bioreactors with greater HRTs and bypass flow due to reduced treatment capacity
- One large bioreactor was more cost effective than multiple smaller bioreactors

Abstract. *Woodchip denitrification bioreactors are a relatively new, edge-of-field technology used to reduce nitrate-nitrogen (NO_3-N) from subsurface tile drainage. The removal rate of nitrate is influenced by many factors including temperature, dissolved oxygen, and hydraulic residence time (HRT). The objective of this study was to conduct a techno-economic analysis (TEA) for four scales of woodchip denitrification bioreactors operating at three HRTs (2, 8, and 16 h), designed with bypass flow and with a low probability of bypass flow, in order to determine the cost to remove 1 kg of NO_3-N at each bioreactor scale and at each HRT. Several assumptions were made: the same flowrate to achieve a 2 h HRT on a per m^3 basis could be achieved at all scales; the same mass removal of NO_3-N was achieved on a per cubic meter basis; and the 2 h HRT did not have any bypass flow at each scale. With these assumptions, the lowest unit cost was observed in the large-scale bioreactor sized to have a low probability of bypass flow at a 16 h HRT with a resulting cost of \$0.74/kg NO_3-N removed. The highest unit cost was observed in the pilot-scale bioreactor designed with bypass flow to achieve a 16 h HRT at a cost of \$60.13/kg NO_3-N removed. At higher HRTs with bypass flow, a greater percent removal of nitrate has been observed with a lower mass removal rate; by having a low probability of bypass flow in the design, a higher mass removal* *and percent removal of nitrate was observed leading to the above results. Contrasting this trend, the total and annual costs are greatest for the large-scale bioreactor and lowest for the pilot-scale bioreactor; however, it was determined that a 783%, 280%, and 54% increase in total cost for the pilot-, small-, and medium-scale bioreactors occurs to implement several bioreactors (66, 24, and 4, respectively) to treat the same volume of flow as one large bioreactor. These results can be used to inform future design decisions and inform stakeholders of an approximate unit cost of installing a denitrifying woodchip bioreactor over a range of expected field conditions. While a larger bioreactor with a low probability of bypass flow may represent a more cost-effective investment, the potential for unintended, negative byproducts needs to be considered in the design.*

Keywords. *Woodchip bioreactor, Nitrate, Water quality, Denitrification, Tile Drainage.*

Agriculture has seen tremendous developments in the past century leading to increased crop production; one of these developments being subsurface drainage which is commonly found in the upper Midwest region of the United States. In the state of Iowa, there is an estimated 3.6 million ha of land with artificial subsurface drainage installed out of the roughly 14.6 million ha of land in the entire state, representing roughly 25% of the land (Baker et al., 2004). Because of subsurface drainage, agricultural land has become more productive for crop production, with a 627 to 2,825 kg ha^{-1} and 269 to 1,009 kg ha^{-1} yield increase for corn and soybeans, respectively, in Iowa and contributes to reduced runoff (Kanwar et al., 1988). While drainage has resulted in some positive water quality measures such as reduced erosion, increased nitrate leaching is also observed (Baker et al., 2004) which can have adverse health impacts when consumed as well as downstream aquatic impacts (US EPA, 2017; US EPA, 2008).

Nitrate from subsurface drainage in the Upper Midwest can impact water quality in the Gulf of Mexico as evidenced in the large hypoxic zone. As a result of this hypoxic region, the EPA released the Gulf Hypoxia Action Plan in 2008 asking the twelve states within the Mississippi River Watershed to reduce their nitrogen (N) and phosphorus loads (US EPA, 2008). Iowa developed their own nutrient reduction goals to meet the objective of reducing their nutrient contributions to decrease the size of the hypoxic zone in the Gulf of Mexico. It has been estimated that non-point source total N will need to be lowered by 41% to meet the overall objective of 45% reduction of total N (Iowa Nutrient Reduction Strategy, 2017).

One conservation practice that is being implemented in Iowa and other midwestern states to reduce this hypoxic zone in the Gulf of Mexico is woodchip denitrification bioreactors. These are essentially large, lined pits of woodchips which act as a carbon source for denitrifying bacteria that convert the nitrate from incoming subsurface drainage into N_2 gas (Cameron and Schipper, 2010; Christianson et al., 2010). The nitrate removal of these systems is influenced by temperature, dissolved oxygen, age of the bioreactor, hydraulic residence time (HRT), and influent nitrate concentration (Christianson et al., 2012a). Nitrate-N (NO_3-N) removal can be expressed in terms of a percent or mass removal with a wide range of both percent (30 to >90% at HRTs of 4 to >10 h) and mass removals (0.38 to 121 g N m^{-3} d^{-1}) reported (Christianson et al., 2011; Christianson et al., 2012a; Roser et al., 2018). While these systems appear to be effective at removing nitrates, a human health and ecotoxicity concern, a wide range of removals and efficiency has been observed due to variations in environmental conditions.

The current design standard for bioreactors requires the treatment of at least 15% of the peak flow from the drainage system or at least 20% NO_3-N reduction of the long-term average annual flow from the drainage system while accounting for bypass flow (USDA NRCS, 2020). It is typical to design bioreactors with a bypass flow option so that under high flow conditions the bioreactor does not restrict discharge, prolonging water retention in the field or allow for high flows that might create preferential flow pathways in the bioreactor or flush the woodchips out of the bioreactor (Christianson et al., 2011). An important role in the denitrification process is HRT as it represents the amount of time the denitrifying bacteria are in contact with the tile drainage, but it also impacts greenhouse gas production; an optimal HRT range of 6 to 8 h has been observed to minimize greenhouse gas production while still allowing for ideal nitrate removal rates to occur (Davis et al., 2019; Martin et al., 2019).

Due to the variability of nitrate removal observed in woodchip denitrifying bioreactors, an evaluation of the operating costs of a woodchip bioreactor under a variety of scenarios is warranted. Our goal was to conduct a techno-economic analysis (TEA) for two scenarios of bioreactor operation under constant flow conditions. Our objectives were to (i) evaluate the cost for four scales of bioreactors operating under a variety of mass removal rates and HRTs, with bypass flow being used to achieve the varying HRTs, (ii) evaluate the cost for the same four scales of bioreactors re-sized to be operated with a low probability of bypass flow, allowing for different mass removal rates to occur, and (iii) compare the costs for the different scenarios and scales designed with and without expected bypass flow. Previous TEAs conducted for woodchip bioreactors focused on specific bioreactors that generally performed well (Christianson et al., 2013a; Christianson et al., 2013b; Law et al., 2018). This study developed a more generalized TEA to account for the great variation that has been observed in these systems, at a variety of bioreactor scales and operating conditions, to assess the cost-effectiveness of the different design scales. Our intention was to inform future design decisions.

MATERIALS AND METHODS

In this TEA, two scenarios were considered: the cost of removing NO_3-N from bioreactors with bypass expected or with a low probability of bypass flow, assuming constant flow conditions (fig. 1). Constant flow conditions were assumed for this analysis rather than historical flow due the dependence of the results on the selected flow dataset. The climatic conditions greatly affect the nitrate removal; for these reasons, the constant flow conditions were assumed to make a consistent comparison of the scenarios and scales. The first scenario evaluated multiple scales of bioreactors at HRTs of 2, 8, and 16 h, to determine the impact that size and HRT have on the cost to remove NO_3-N. The baseline flow for the scenarios was set so that all the water could be treated at a 2 h HRT. To achieve the HRTs of 8 and 16 h, the differential flow was bypassed. At higher HRTs, higher percent removal of NO_3-N has been observed, but when bypass flow is taken into consideration, a lower NO_3-N mass removal occurs (Martin et al., 2019). Due to the greater potential for NO_3-N removal at longer HRTs, the second scenario evaluated the cost of removing NO_3-N from bioreactors that have been scaled up in size to treat the same amount of flow as at the 2 h HRT, but at HRTs of 8 and 16 h so that a low probability of bypass flow occurs.

The same costs were assessed for the two scenarios of bioreactor operation. In both scenarios, the necessary materials for the bioreactor installation as well as the infrastructure for bypass flow were included in the costs of the system. These two scenarios were chosen and evaluated simply to provide a wider range of nitrate mass removals and therefore unit costs for nitrate removal. These scenarios provide cost estimates for a variety of woodchip bioreactor sizes ranging from pilot-scale (6.38 m^3) to large-scales (up to 3235 m^3).

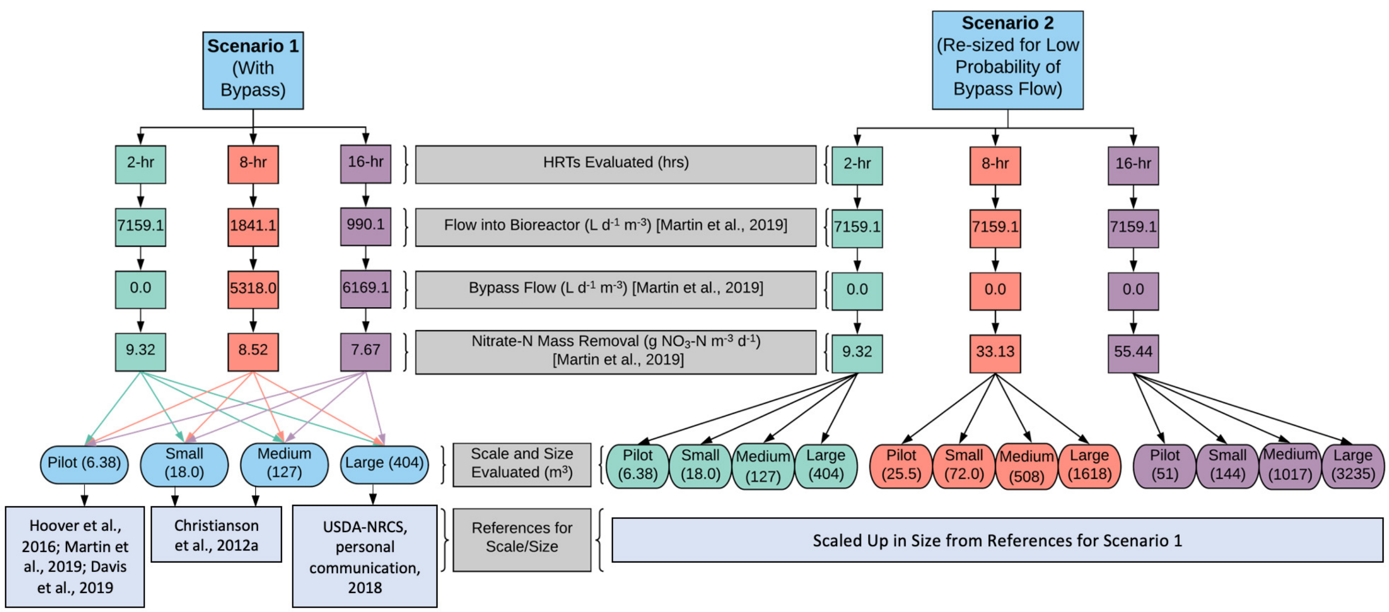

Figure 1. Flow chart depicting the different scenarios and conditions evaluated for the TEA. Bioreactor sizes originate from Table 1 for the scenario with bypass flow, and Table 2 for the scenario with a low probability of bypass flow. NO_3-N mass removal (g NO_3-N m^{-3} d^{-1}) differs based on the scenario of expected bypass or low probability of bypass due to the varying volume of flow that is treated at each HRT.

BIOREACTOR SCALES

With Bypass for Bioreactors

The goal of this TEA was to provide estimates of the cost to remove 1 kg NO_3-N for a pilot-scale bioreactor and three scales of field bioreactors under a variety of nitrate mass removals at HRTs of 2, 8, and 16 h. The four scales of bioreactors (referred to as pilot-, small-, medium-, and large-scale) were selected for their range in size and information available regarding their dimensions (table 1). The pilot-scale bioreactor for this analysis is scaled the same as the pilot bioreactors at the Iowa State University's Agronomy and Agricultural Engineering Research Farm located west of Ames, Iowa (42°01'01"N, 93°46'48"W) previously described in Davis et al. (2019), Hoover et al. (2016), and Martin et al. (2019). To achieve a 2 h HRT, 45,675 L d^{-1} were treated in the pilot-scale bioreactor. At the 8 and 16 h HRTs, 11,746 and 6,317 L d^{-1} were treated, respectively, with the remaining flow being bypassed (33,929 and 39,359 L d^{-1}, respectively). Each of these flows (L d^{-1}) was converted to the flow per m^3 of the bioreactor per day (L m^{-3} d^{-1}) and are summarized in figure 1. The amount of flow treated by the small-, medium-, and large-scale bioreactors was scaled up based on the per m^3 flow of the pilot-scale bioreactor since information about the drainage areas, hydraulic gradients, etc. were not available for all sites/scales. Therefore, the 2 h HRT is assumed to not have bypass flow at all scales while the 8 and 16 h HRTs are achieved through bypass flow in this analysis for all scales.

Table 1. Dimensions of the four scales of bioreactors used in the multi-scale techno-economic analysis as well as the sources for the data.

Scale of Bioreactor	Length (m)	Width (m)	Total Depth (m)	Average Active Depth[1] (m)	Total Volume (m^3)	Source
Pilot	5.8	1.0	1.1	0.9375	6.38	Hoover et al. (2016), Martin et al. (2019), Davis et al. (2019)
Small	30	0.5	1.2	0.9375	18	Christianson et al. (2012a)
Medium	15.2	7.6	1.1	0.9375	127	Christianson et al. (2012a)
Large	36.6	10.4	1.1	0.9375	404	USDA-NRCS, personal communication (2018)

[1]The average active depth is based on the work of Martin et al. (2019) and assumed to be the same for all of the scales due to the similar depths of the bioreactors.

The small- and medium-scale bioreactors are based on the Pekin, Iowa and Greene County, Iowa bioreactors described in detail in Christianson et al. (2012a). The large-scale bioreactor was installed in 2018 in central Iowa near the end of a 35.56 cm main tile line (Boone Co., Section 9 – T82N-R25W, Garden Township). This site consists of a dual chamber bioreactor, which is essentially two bioreactors connected in parallel, designed to treat approximately 36.8 hectares. The bioreactors were filled with woodchips sourced from J. Pettiecord, Inc. in Bondurant, Iowa (Sean McCoy, USDA-NRCS, personal communication, 2019-2020). The large-scale bioreactor for the TEA was scaled the same as one of these bioreactors which were selected for this assessment as they are the largest bioreactors that have been installed in Iowa to the best of the authors' knowledge. All of the scales of bioreactors feature bypasses for high-flow conditions to better control the HRT.

The type of materials needed for the pilot-, small-, and medium-scale bioreactors was based upon those used in the large-scale bioreactor to be consistent across all scales. Materials used in the bioreactors included plastic lining for the sides and bottom of the bioreactors, geotextile fabric for the top of the bioreactor, two water control structures, fourteen 17.78 cm stop logs for the water control structures, non-perforated tile to connect the bioreactor to an existing tile line and to a drainage ditch, stream, etc. An additional factor and cost was the excavation needed. The plastic lining was assumed to be the material needed to cover all sides and the bottom of the bioreactor with an additional 15% to account for necessary overlap. The geotextile fabric was assumed to be the material needed to cover the top of the bioreactor. The non-perforated tile needed was assumed to be 68 m long for all scales and of varying diameters to achieve the desired flowrates. This accounts for the tile needed to connect the bioreactor to an existing tile line, outlet, as well as bypass line. This is a small factor in the overall bioreactor cost and was kept the same for all scales and scenarios to be conservative. The excavation cost was evaluated based on the estimated volume of earth to be moved. This was assumed to be the volume of the bioreactors plus an additional 60% to account for soil replaced as a cap on the bioreactor as well as the potentially uneven original surface of the bioreactor.

With Low Probability of Bypass for Bioreactors

Another scenario was assessed in which the pilot-, small-, medium-, and large-scale bioreactors were scaled up from their original size so that there was a low probability of flow being bypassed. By scaling up the bioreactors, different mass removals can be achieved. At longer HRTs, higher percent removal of nitrate is achieved. By scaling up the bioreactors to treat a larger volume of flow, a higher mass removal of NO_3-N is also achieved. To scale the bioreactors, the daily treatment capacity for the pilot bioreactor (45, 675 L d^{-1}) was converted to the flow per m^3 of bioreactor per day (7159.1 L m^{-3} d^{-1}) (fig. 1). Based on the per cubic meter flow of the pilot bioreactors, the flow (L d^{-1}) needed in the small-, medium-, and large-scale bioreactors to have a low probability of bypass flow was determined. The average active depth of the pilot bioreactors was used in the calculation of the average active volume used for calculating HRT for all the scales as their total depths were essentially the same. The determined flow rate was held constant across all HRTs so that bypass flow had a low probability of occurring. Therefore, the HRT and flow rate were fixed, and the bioreactor volume was back-calculated. For all scales, an HRT of 2 h resulted in no bypass flow based upon the per m^3 per day flow rate determined from Martin et al. (2019); therefore, no changes in dimensions were made to the 2 h HRT for all scales. To achieve the same volume of flow in each bioreactor as at the 2 h HRT, the volume of the bioreactors at the 8 h and 16 h HRTs were increased. To scale the bioreactors' size up, the average active depth and length to width ratio of the bioreactor was held constant. The scaled dimensions of the bioreactors so that a low probability of bypass occurred can be seen in table 2. The same methods for estimating quantities of materials were used as for the bioreactors with bypass flow as well as the same types of materials.

Table 2. Dimensions of the four scales of bioreactors used in the multi-scale techno-economic analysis when scaled so that a low probability of bypass flow occurs.

Scale of Bioreactor	HRT (h)	Length (m)	Width (m)	Total Depth (m)	Average Active Depth (m)	Total Volume (m^3)
Pilot	2	5.80	1.00	1.10	0.9375	6.38
	8	11.60	2.00	1.10	0.9375	25.52
	16	16.40	2.83	1.10	0.9375	51.04
Small	2	30.00	0.50	1.20	0.9375	18.00
	8	60.00	1.00	1.20	0.9375	72.00
	16	84.85	1.41	1.20	0.9375	144.00
Medium	2	15.20	7.60	1.10	0.9375	127.07
	8	30.40	15.20	1.10	0.9375	508.29
	16	43.00	21.50	1.10	0.9375	1016.58
Large	2	36.60	10.40	1.10	0.9375	404.36

8	73.15	20.73	1.10	0.9375	1617.46
16	103.45	29.31	1.10	0.9375	3234.54

NITRATE REMOVAL RATES

With Bypass for Bioreactors

To assess the cost to remove 1 kg of NO_3-N for four scales of woodchip bioreactors, nitrate removals previously observed in pilot-scale operations described in Martin et al. (2019) were used. The percent removal accounted for bypassed flow and covered HRTs of 2, 8, and 16 h. The HRT of 2 h did not have any bypass flow as the bioreactor was assumed to be able to handle all the received flow; therefore, only the 8 and 16 h HRTs had bypass flow. At the different HRTs, different mass removal rates of NO_3-N were observed which are summarized in table 3. A variety of mass removal rates were desired to provide best-case, worst-case, and in-between scenarios of the costs associated with installing a woodchip bioreactor. It was assumed that the same NO_3-N mass removal rates (g NO_3-N m^{-3} d^{-1}) as the pilot-scale were achievable for the small-, medium-, and large-scales at each HRT despite their varying volume of flow and dimensions.

Table 3. Summary of NO_3-N concentration and removals for three HRTs from Martin et al. (2019) when the bioreactor has bypass flow or does not have bypass flow.

		With Bypass		Without Bypass	
HRT (h)	Influent NO_3-N Load (g NO_3-N m^{-3} d^{-1})	Percent Removal (%)	Mass Removal (g NO_3-N m^{-3} d^{-1})	Percent Removal (%)	Mass Removal (g NO_3-N m^{-3} d^{-1})
2	103.14	9.04%	9.32	9.04%	9.32
8	103.14	8.26%	8.52	32.12%	33.13
16	103.14	7.44%	7.67	53.75%	55.44

With Low Probability of Bypass for Bioreactors

The scenario of scaling up the size of the bioreactors so a low probability of bypass flow occurs allows for greater flow to pass through the bioreactor. At longer HRTs, higher percent removal of NO_3-N has been observed (Christianson et al., 2011; Chun et al., 2009; Hoover et al., 2016; Martin et al., 2019). The percent removal without accounting for bypass flow from Martin et al. (2019) was used as well as the influent NO_3-N concentration to determine the mass removal rate of NO_3-N that could be observed without bypassed flow. By not bypassing the flow of the bioreactors, a higher mass removal rate of NO_3-N can be achieved (table 3), allowing for a comparison of the total and the unit cost of bioreactors with different HRTs, sizes, and removal rates, which has not been previously conducted.

Techno-economic Analysis

The TEA was conducted using a functional unit of 1 kg of NO_3-N removed by the bioreactor. The total annualized cost was assessed by first computing the total estimated cost based upon the quantity of materials needed (plastic and geotextile lining, excavation, control structures, stop logs, non-perforated tile, woodchips, trenching, and grass seed cover) and the cost per unit of material (table 4). For the first scenario, where HRTs of 2, 8, and 16 h were evaluated for four scales of bioreactors with bypass flow, there was only one total cost for each scale since the size of the bioreactor did not change to achieve varying HRTs. For the second scenario, where the bioreactors were resized to achieve HRTs of 8 and 16 h with a low probability of bypass flow, there were three different sizes of bioreactors for each scale resulting in three different estimates of the total cost per scale.

The geotextile lining, excavation, woodchips, and trenching costs include labor costs for installation in the cost estimate. The woodchips represent one of the greatest costs in the bioreactor, and the cost used in this study is reflective of one point in time and will fluctuate over time. The cost of woodchips has been trending upward recently (Chris Hay, Iowa Soybean Association, personal communication, December 2020; Shane Wulf, Iowa Department of Agriculture & Land Stewardship, personal communication, December 2020). The tile size and water control structure size vary depending on the scale of the bioreactor (10.16 to 25.4 cm in diameter), but all water control structures were assumed to be 1.83 m in height. The tile size needed for each scale was determined based on the desired flowrate and assuming a 0.5% gradient.

To convert the initial equipment cost (present value) into an annual payment, an interest rate of 5% compounded annually for a service life of 15 y were used. A 15% salvage value was also used to address the value of the equipment that would not need replacing at the end of that lifetime, coupled withthe straight-line depreciation method (Department of Treasury, Internal Revenue Service, 2019). The woodchips are the major component to be replaced at the 15 y timepoint, with the structures being expected to last beyond that time. This salvage value was considered and addressed in the depreciation cost. Lastly, taxes were also included in the annual fixed cost assessment which were assessed at 0.35% of the initial equipment cost per year. The only variable, or operational, costs for this system were the maintenance of the stop logs in the water control structures. The maintenance includes the labor cost to adjust the stop logs (minimum of two times per year) and if maintenance is needed on any of the stop logs. This cost is quite minimal in the overall budget, but was included, regardless.

Table 4. Summary of unit costs for the bioreactor materials and for maintenance. A range of costs is presented for the control structures, tile, and stop logs to reflect the variations in the size of materials needed for the different bioreactor scales.

	English Units		Metric Units		
Materials	Cost Per Unit	Unit	Cost Per Unit	Unit	Source
4 mil Plastic Lining	$0.50	yd^2	$0.60	m^2	Grainger
Geotextile Fabric	$2.28	yd^2	$2.73	m^2	USDA NRCS Practice 747 (2014)
Excavation	$2.15	yd^3	$2.81	m^3	USDA NRCS Practice 747 (2014)
Control Structures	$665.84-$905.90	One structure	$665.84-$905.90	One Structure	Agri Drain
Non-perforated tile (10.16-25.4 cm)	$1.50-$5.53	ft	$4.92-$18.14	m	USDA NRCS Practice 747 (2014) Menards
Bottom Stop Log	$12.25-$16.54	One stop log	$12.25-$16.54	One stop log	Agri Drain
General Stop Log	$9.02-$11.46	One stop log	$9.02-$11.46	One stop log	Agri Drain
Woodchips	$21.62	yd^3	$28.28	m^3	USDA NRCS Practice 747 (2014)
Trenching	$3.69	ft	$12.11	m	USDA NRCS Practice 747 (2014)
Grass Seed Cover	$0.02	ft^2	$0.22	m^2	Tyndall and Bowman (2016)
Maintenance	$50.00	y	$50.00	y	Tyndall and Bowman (2016)

Once an annualized cost was determined for each of the scales, the cost per 1 kg of NO_3-N removed could be assessed. Using the entire range of NO_3-N mass removals found in table 3, the mass of NO_3-N removed by each scale of bioreactor could be determined. It was assumed that the bioreactor received flow for six months (180 d) of the year and could achieve the average removal rates found in table 3 during that time. The removal rates reported by Martin et al. (2019) used in this study are within the range of other reported removal rates (Christianson et al., 2017; Jaynes et al., 2016; Schipper et al., 2010), and represented the average removal rate during that study. To annualize the NO_3-N mass removal (kg NO_3-N y^{-1} removed), the daily NO_3-N removal (g NO_3-N m^{-3} d^{-1} removed) was multiplied by the 180 d of expected operation and the total volume of the bioreactors. The annualized cost was then divided by the total kg of NO_3-N removed by the bioreactor per year to determine the cost to remove 1 kg of NO_3-N by the bioreactor.

RESULTS

TECHNO-ECONOMIC ANALYSIS

Total Cost for Bioreactors with and without Expected Bypass

The total cost of each of the four scales of bioreactors was estimated prior to determining the annualized capital and operational costs, hereafter referred to as yearly cost for the various conditions analyzed. Regardless of whether the bioreactors had expected bypass flow or not, the total cost increased by approximately \$36.70 per m^3 increase in size. For the bioreactors with bypass flow, the total cost ranged from \$2,451 to \$18,326 for sizes ranging from 6.38 m^3 to 404 m^3. This represents a 648% (7.5-fold) increase in cost for a 6,232% (63-fold) increase in size. For the bioreactors with a low probability of bypass flow, the total cost ranged from \$2,451 for the pilot-scale with a 2 h HRT to \$120,847 for the large-scale bioreactor resized to have a low probability of bypass flow at the 16 h HRT. The sizes ranged from 6.38 m^3 to 3,235 m^3, representing a 4,830% (49-fold) increase in cost for a 50,598% (507-fold) increase in size. For all scales resized to have a low probability of bypass flow, there was a 700% increase in the size of the bioreactor at a 2 h HRT to the size at a 16 h HRT. The total costs for both scenarios are summarized in table 5.

Table 5. Summary of total, annual, and unit costs for the four scales of bioreactors with or without expected bypass flow. NO_3-N removal (kg/y) are summarized as well for each scale of bioreactor and each HRT.

		With Bypass Flow					With a Low Probability of Bypass Flow				
Scale	HRT (h)	Size (m^3)	Bioreactor Total Cost (\$)	Annual Cost (\$/y)	Unit Cost (\$/kg NO_3-N removed)	NO_3-N Removal (kg/y)	Size (m^3)	Bioreactor Total Cost (\$)	Annual Cost (\$/y)	Unit Cost (\$/kg NO_3-N removed)	NO_3-N Removal (kg/y)
Pilot	2	6.38	\$2,451	\$532	\$49.78	10.68	6.38	\$2,451	\$532	\$49.78	10.68

	8				$54.47	9.76	25.5	$3,152	$669	$4.40	152.2
	16				$60.13	8.84	51.0	$4,081	$852	$1.67	509.3
	2				$20.61	30.13	18.0	$2,905	$621	$20.61	30.13
Small	8	18.0	$2,905	$621	$22.55	27.54	72.0	$4,889	$1,011	$2.35	429.4
	16				$24.89	24.95	144	$7,509	$1,526	$1.06	1,437
	2				$6.75	212.7	127	$7,057	$1,437	$6.75	212.7
Medium	8	127	$7,057	$1,437	$7.39	194.4	508	$20,845	$4,146	$1.37	3,031
	16				$8.16	176.1	1,017	$39,211	$7,755	$0.76	10,144
	2				$5.39	676.9	404	$18,326	$3,651	$5.39	676.9
Large	8	404	$18,326	$3,651	$5.91	618.7	1,618	$62,285	$12, 290	$1.27	9,645
	16				$6.52	560.5	3,235	$120,847	$23,798	$0.74	32,277

Yearly Cost for Bioreactors with and without Expected Bypass

The cost of a bioreactor was annualized using a life expectancy of 15 y (Christianson et al., 2013a). This life expectancy is relatively unknown at this point in time as this is a new technology where few bioreactors have reached end of life. The yearly cost of the bioreactors increased with the size of the bioreactor linearly (fig. 2). Data points for the four scales of bioreactors with and without expected bypass are included in this identified trend. Regardless of if the bioreactor is designed to have bypass flow or a low probability of bypass flow, the yearly cost increases by $7.22 per m^3 increase in size. The yearly cost ranges from $532 for the pilot-scale bioreactor with bypass to $23,798 for the large-scale bioreactor with a low probability of bypass at the 16 h HRT, representing a 4,376% (45-fold) increase in the cost for a 50,598% (507-fold) increase in size. The yearly costs are summarized in table 5 for both scenarios.

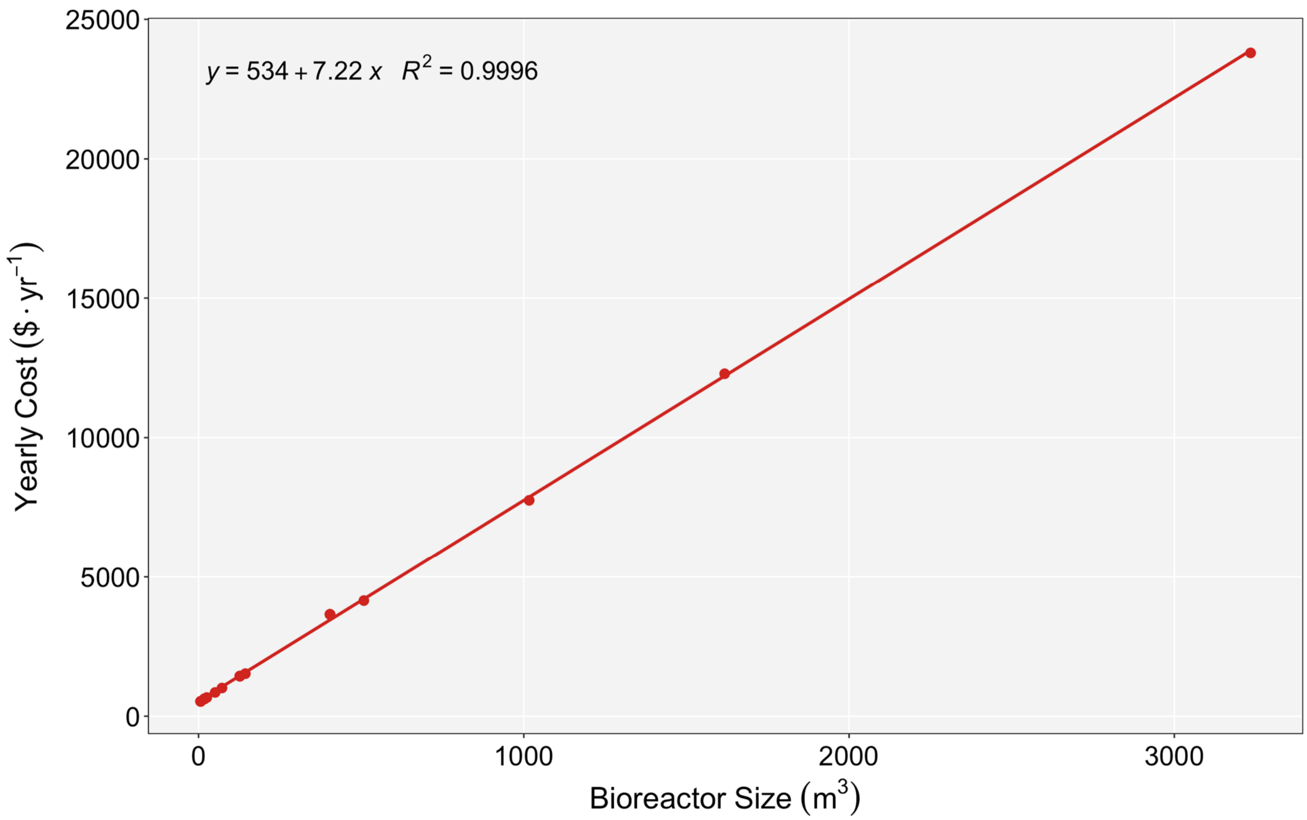

Figure 2. The annualized, yearly cost for four scales of bioreactors designed with and without expected bypass. The probability of bypass in the bioreactor did not affect the linear trend of increasing cost with increasing size of the bioreactor.

Unit Cost of Bioreactor Operation With Bypass Flow

At all HRTs, the unit cost of the bioreactors ($/kg NO_3-N removed) increased as the size of the bioreactor decreased. From the pilot-scale to the large-scale, there was a 6,232% increase in size with an 89% reduction in unit cost at the 2, 8, and 16 h HRTs. The reasoning for the increased unit cost at smaller scales was due to the lower capacity to treat the subsurface drainage and remove NO_3-N (kg y^{-1}). The unit cost also increased as the HRT increased for bioreactors with bypass flow. For all scales, the unit cost increased by 9.4% from the cost at the 2 h HRT to the cost at the 8 h HRT. Again, for all scales, the unit cost from the 8 h to 16 h HRT increased by 10.4%. This increase in cost results from the lower capacity to remove NO_3-N (kg y^{-1}) as the HRT increases since the remaining flow is bypassed. The annual cost, unit cost, and NO_3-N removal for bioreactors with bypass flow are summarized in table 5. The variations in unit cost at the three HRTs are quite similar for each scale due to the similar NO_3-N removal rates used in this analysis from Martin et al. (2019). From the 2 h to 8 h HRTs, the unit costs vary by \$4.69, \$1.94, \$0.64, and \$0.51 for the pilot-, small-, medium-, and large-scales, respectively. From the 8 h to 16 h HRTs, the unit cost varies by \$5.66, \$2.34, \$0.77, and \$0.61 for the pilot-, small-, medium, and large-scales, respectively, resulting in the very similar trend lines for unit cost at varying HRTs (fig. A1).

Unit Cost of Bioreactor Operation With Low Probability of Bypass Flow

In the bioreactors that were scaled up to treat all the flow without bypass being expected, the unit costs (\$/kg NO_3-N removed) were observed to decrease as the HRT increases. From the 2 h to 8 h HRT, the unit cost decreases by 91.2%, 88.6%, 79.7%, and 76.4% for the pilot-, small-, medium-, and large-scale bioreactors, respectively. From the 8 h to 16 h HRT, the unit cost decreased by 62.0%, 54.9%, 44.1%, and 42.1% for the pilot-, small-, medium-, and large-scale bioreactors, respectively. The amount of NO_3-N (kg y^{-1}) that can be treated by these scaled up bioreactors is 1325% and 4668% greater than at the 2 h HRT for the 8 h and 16 h HRTs, respectively, when not bypassing flow, thereby reducing the unit cost (fig. A2). The annual cost, unit cost, and nitrate removal for the bioreactors scaled up to not have bypass flow are summarized in table 5.

Comparison of the Unit Costs With and Without Expected Bypass Flow

A comparison of the unit costs to operate the bioreactors with or without bypass flow at HRTs of 8 h and 16 h were conducted. Since it was assumed that no bypass flow occurred in the 2 h HRT, no comparison was made at that HRT. A similar trend is observed in the comparison of the 8 h HRT and the 16 h HRT (fig. 3). At both of these HRTs, the unit cost was consistently lower for the bioreactors without bypass flow expected, regardless of bioreactor size. At the 8 h HRT, the unit cost for the scaled-up bioreactors to have a low probability of bypass flow are reduced by 91.9%, 89.6%, 81.5%, and 78.4% for the pilot-, small-, medium-, and large-scale bioreactors, respectively, from the bioreactors with bypass flow. At the 16 h HRT, the unit cost for the scaled-up bioreactors to have a low probability of bypass flow are reduced by 97.2%, 95.7%, 90.6%, and 88.7% for the pilot, small-, medium-, and large-scale bioreactors, respectively, from the bioreactors with bypass flow. As the bioreactor size increases, a plateau in the unit cost begins to occur in the bioreactors without bypass flow. At the 8 h HRT, this plateau begins to occur at a bioreactor size of approximately 500 m^3 while at the 16 h HRT, this plateau begins to occur at roughly 1000 m^3. The reduction in unit costs from the pilot- to large-scale bioreactors with a low probability of bypass is 71.0% at the 8 h HRT and 55.9% at the 16 h HRT.

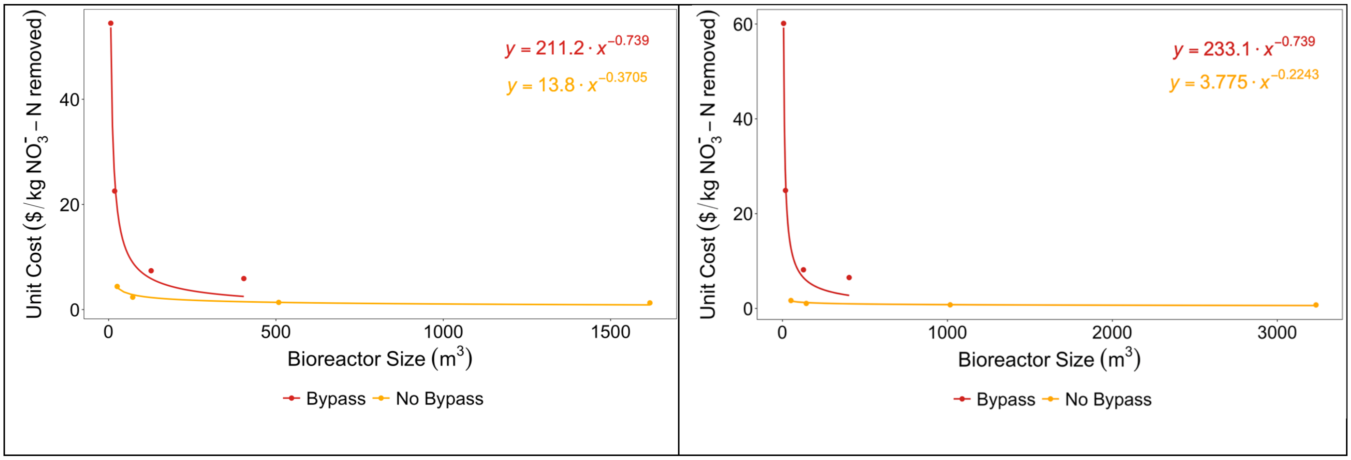

Figure 3. A comparison of the unit costs of four scales of bioreactors operated with or without expected bypass at an HRT of 8 h (left) and an HRT of 16 h (right). The bioreactors with bypass flow (red) are smaller in size with greater unit costs as compared to the bioreactors with a low probability of bypass flow (yellow).

In the bioreactors with bypass flow, the lowest cost observed was $5.39/kg NO_3-N removed for the large-scale bioreactor with a 2 h HRT. The highest cost observed was $60.13/kg NO_3-N removed for the pilot-scale bioreactor with a 16 h HRT. In the bioreactors without bypass flow expected, the lowest cost observed was $0.74/kg NO_3-N removed for the large-scale bioreactor with a 16 h HRT while the highest cost was $49.78/kg NO_3-N removed in the pilot-scale bioreactor at the 2 h HRT.

DISCUSSION

Previous literature has not evaluated the costs of bioreactors scaled up in size to not have bypass flow; therefore, our study is compared to the unit cost of the bioreactors with bypass only. The unit costs of our study are generally similar but slightly higher than previously reported by Christianson et al. (2013a), Christianson et al. (2013b), and Law et al. (2018). Variations in assumptions in costs assessed account for the higher costs observed in our study; the other studies typically did not include operating or depreciation costs or had varying interest rates. In the study by Law et al. (2018), a 100 m^3 bioreactor was determined to have a NO_3-N removal cost of \$4.86/kg NO_3-N, which ranges \$3.30/kg NO_3-N to \$1.90/kg NO_3-N less than the values observed in the similarly sized medium-scale bioreactor (127 m^3) with bypass flow in our study. Christianson et al. (2013a) reported similar values to Law et al. (2018) with removal costs of \$4.94/kg N and \$4.09/kg N for treating 30% of the peak flow for two sites or \$4.65/kg N and \$12.26/kg N for 8 h or 10 h HRTs, respectively, for bioreactors ranging from 220 to 343 m^3. The costs for the large-scale bioreactor (404 m^3) fall within this range of unit costs at \$6.52/kg NO_3-N at a 16-h HRT to \$5.39/kg NO_3-N at a 2 h HRT. Additional discrepancies are expected as the other studies used varying NO_3-N removals. Therefore, the values reported in this study are reasonable as they include additional costs at an accepted estimate of the lifespan of a woodchip bioreactor. Additionally, this study evaluated multiple sizes of bioreactors, some of which had not previously been reported based on the best of the authors' knowledge.

The large-scale bioreactor has the greatest yearly and total cost, however, it represents a more cost effective option when considering the number of pilot-, small-, and medium-scale bioreactors that would be needed to treat the same amount of flow as the large-scale bioreactor. For example, the pilot-, small-, medium-, and large-scale bioreactors each treat 45,675 L d^{-1}, 128,863 L d^{-1}, 909,720 L d^{-1}, and 2,984,975 L d^{-1}, respectively. These values were estimated by scaling up the per m^3 per day treatment from the pilot-scale bioreactors, as described in the Methods section; to provide perspective, the large-scale bioreactor treats approximately the same amount of flow as the total discharge from a 221.2 ha subwatershed (Brendel et al., 2019). With these treatment volumes, it would require 66, 24, and 4 pilot-, small-, and medium-scale bioreactors, respectively, to treat the same volume of water as the large-scale bioreactor, rounding to the nearest whole number. Similarly, it would require 20 and 8 pilot- and small-scale bioreactors to treat the same amount of flow as the medium-scale bioreactor. This results in a 783%, 280%, and 54% increase in total cost for the pilot-, small-, and medium-scale bioreactors, respectively, to implement the number of bioreactors needed to treat the same volume of flow as the large-scale bioreactor with bypass flow. In terms of yearly cost, a 861%, 308%, and 57% increase in cost would be observed for the pilot-, small-, and medium-scale bioreactors to treat the same flow as the large-scale bioreactor. A similar trend is seen in the bioreactors that are scaled up to have a low probability of bypass flow. From this analysis, it is more cost effective to install one large bioreactor instead of several smaller bioreactors to treat the same volume of flow. While the large-scale systems are considerable in size (tables 1 and 2), we believe they are reasonable when considering their potential applications. These large-scale systems could be an option for treating a subwatershed or drainage district rather than implementing several smaller bioreactors at the edge of a field.

The authors do acknowledge that it is unlikely for the HRTs of 2, 8, and 16 h to be maintained for the entire 180-d period used in this analysis, especially for the field-scale bioreactors operated in a natural environment. This assumption was made to provide a starting basis for evaluating the variety of removal costs for various scales and operating conditions observed in the bioreactors. These constant flow estimates were also used in place of historical flow data due to the dependence of the results on the flow data used. For example, the flow conditions would be representative of the particular climate conditions in any given year, which very much impacts the N-removal. In a low flow year, the bioreactor treatment capacity would be underutilized, and the $/N removal value would be greatly impacted. Similarly, in a year of higher flow the bioreactor would run at capacity and thus the $/N removal would be lower. There are instances where a more constant flow and HRT could be achieved in field-scale bioreactors such as treatment of springs rather than subsurface drainage (Easton et al., 2019), groundwater flow, or in a pumped bioreactor system. Assumptions regarding the hydraulic gradient of the bioreactors and the amount of flow that the bioreactor could treat were also made in this analysis. Especially in the large-scale bioreactors, the hydraulic gradient may limit the minimum HRT that can be achieved in the bioreactor. This is because as the length and width increase, the depth of the bioreactor is kept the same, decreasing the hydraulic gradient and in turn increasing the minimum HRT that can be achieved.

It was assumed that the same NO_3-N mass removals (g NO_3-N m^{-3} d^{-1}) occurred in each bioreactor despite variations in dimensions and volume of flow treated, and that the amount of flow treated by each bioreactor could be scaled up from the per m^3 flow of the pilot-scale bioreactor with all flow being treated at the 2 h HRT without bypass flow being expected. The NO_3-N mass removals based on pilot-scale data would likely vary from bioreactor to bioreactor as the removal is influenced by many natural parameters such as carbon source, microbial community, influent nitrate concentration, temperature, etc. (Christianson et al., 2012b; David et al., 2016; Feyereisen et al., 2016; Warneke et al., 2011).

This study provides insightful information for estimating the unit costs for multiple scales and designs of bioreactors which could be used to inform future design decisions. Bioreactors that have been scaled up in size could produce unintended harmful byproducts (methylmercury and greenhouse gases) during low flow conditions (Hudson and Cooke, 2015; Shih et al., 2011; Davis et al., 2019); although, this could be remedied by completely bypassing the bioreactor during these conditions. Another area of interest would be the use of a large-scale bioreactor to treat drainage at a drainage district outlet instead of implementing several small bioreactors. Future work could include the use of modeling such as the dual porosity model developed by Jaynes et al. (2016) or simulations based on historic precipitation data as an input to the TEA that would consider the varying conditions of the bioreactor or flowrates into the bioreactor which could then be reflected in the cost.

Conclusions

A techno-economic analysis (TEA) of multiple scales of bioreactors (referred to as pilot, small, medium, and large) was conducted to assess the cost to remove 1 kg of NO_3-N for a woodchip denitrifying bioreactor operated under a variety of operating conditions. For each scale of the bioreactors, the cost was assessed for operations of HRTs of 2, 8, and 16 h with the HRTs of 8 and 16 h being achieved through bypass flow. A second scenario was assessed where each scale of bioreactor was scaled up in size to achieve the HRTs of 8 and 16 h with a low probability of bypass flow, allowing for greater mass removals of NO_3-N to occur. Through this analysis, it was observed that the lowest unit cost occurred in the large-scale bioreactor operated at an HRT of 16 h without bypass flow expected with a cost of \$0.74/kg NO_3-N removed. In contrast, the highest unit cost observed occurred in the pilot-scale bioreactor operated at an HRT of 16 h with bypass flow with a cost of \$60.13/kg NO_3-N removed. A comparison of costs was also made for the bioreactors operated with or without expected bypass at HRTs of 8 and 16 h. Regardless of scale, it was observed that the bioreactors scaled up to have a low probability of bypass flow had lower unit costs than those with bypass flow due to the increased capacity to remove NO_3-N. The total and annual costs are a result of the materials required for the bioreactors and were therefore greatest in the large-scale bioreactor. However, it was also observed that an 783%, 280%, and 54% increase occurred in the total cost to implement several pilot-, small-, and medium-scale bioreactors (66, 24, and 4, respectively) to treat the same volume of flow as the large-scale bioreactor. Implementing one large bioreactor instead of several smaller bioreactors represents a more cost-effective investment, but the potential for negative, unintended byproducts will also need to be considered in the design decision. A large-scale bioreactor could be an area of interest moving forward for the treatment of drainage from a drainage district outlet. The results of this study can be used to inform future design decisions as well as provide estimates of the unit cost expected from installing a variety of woodchip bioreactor sizes ranging from pilot-scale (6.38 m^3) to large-scales (up to 3235 m^3).

ACKNOWLEDGEMENTS

This material is based on work supported by the National Science Foundation under Grant No. DGE-1828942. The authors acknowledge the National Institute of Food and Agriculture, U.S. Department of Agriculture, award number 2018-672 67016-27578 awarded as a Center of Excellence for financial support.

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APPENDIX

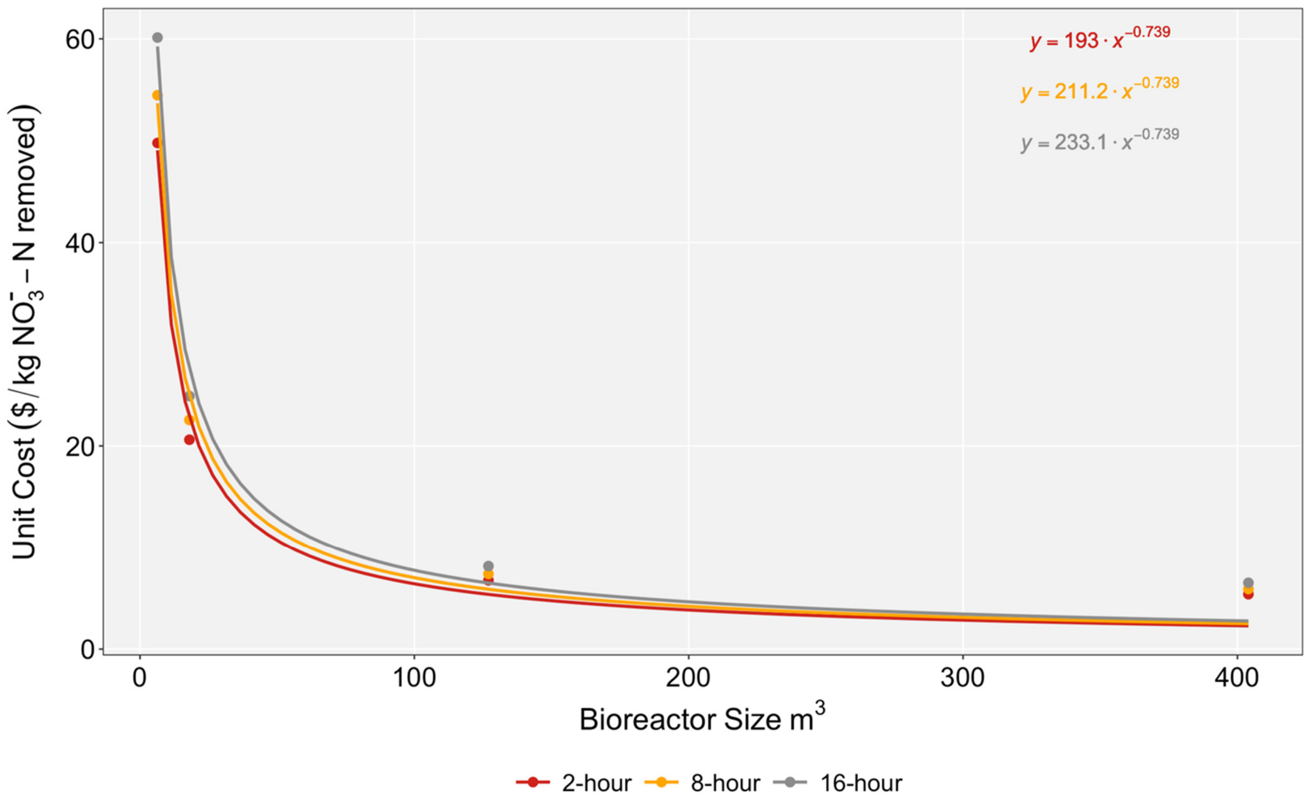

Figure A1. The unit cost of four scales of bioreactors with bypass flow at three HRTs. At an HRT of 2 h (red), the unit cost for each size of bioreactor is lowest followed by the 8 h HRT (yellow) and the 16 h HRT (gray), respectively.

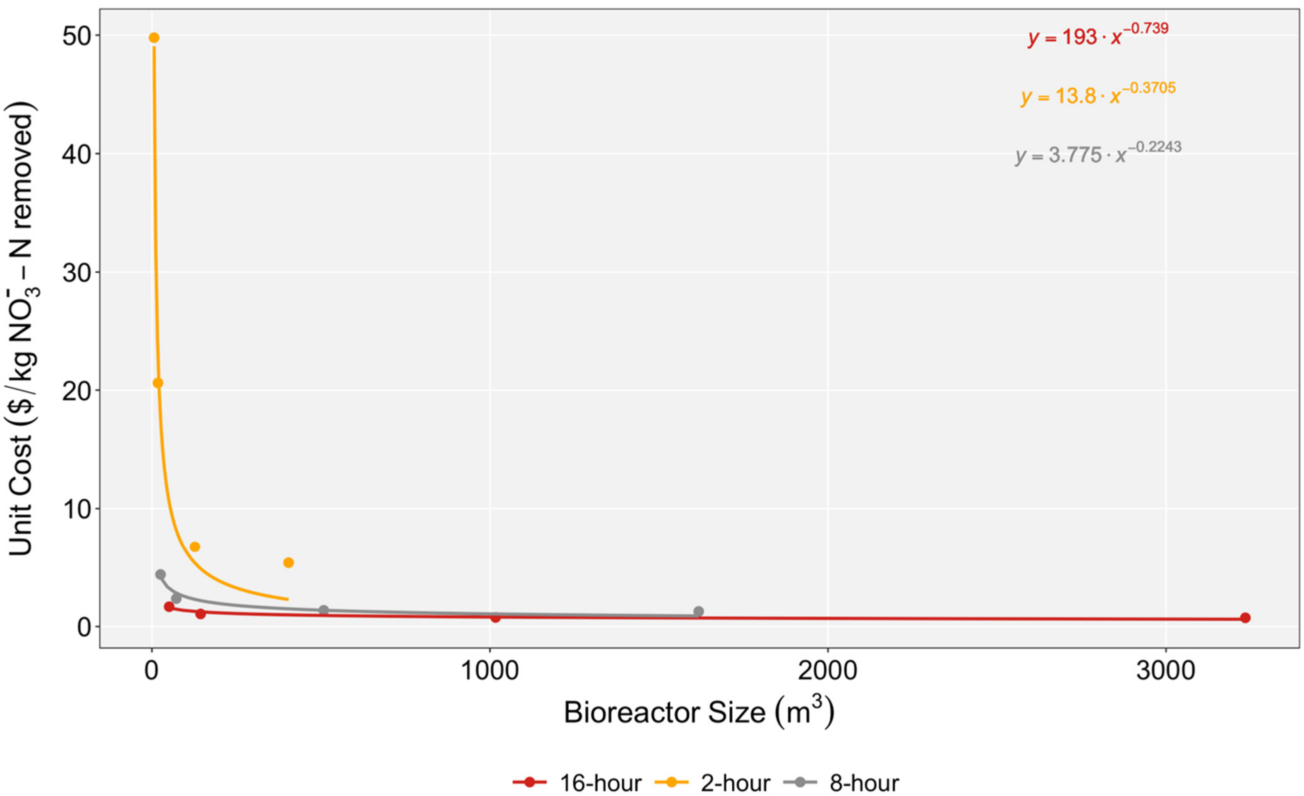

Figure A2. The unit cost of four scales of bioreactors re-sized to have a low probability of bypassed flow at three HRTs. At an HRT of 16 h (gray), the unit cost for each size of bioreactor is lowest followed by the 8 h HRT (yellow) and the 2 h HRT (red), respectively. The change in unit cost is minimal as the size of the bioreactor increases beyond 1000 m^3.

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