SOLAR POWERED BIOFILM ELECTRODE REACTOR FOR AQUATIC DENITRIFICATION

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1.0 EXECUTIVE SUMMARY

Contemporary agricultural practices release excessive amounts of nutrients to the environment, causing eutrophication, one of the largest water quality issues in the world. Efforts made to address the surplus nutrients, specifically nitrate, have fallen short because of the challenging characteristics of non-point source pollution from agricultural runoff. The sizeable and grid-dependent nature of a conventional treatment plant required to remedy wide-spread contamination renders chemical-dependent, ex-situ treatments infeasible.

Digger Denitrification realizes the imminent importance of finding a treatment technology that can feasibly treat the nitrate contamination from non-point sources, and proposes the use of a biofilm electrode reactor (BER). BERs are unique because autotrophic denitrifying bacteria can directly use electricity to reduce nitrates into harmless nitrogen gas, instead of relying on harmful chemicals, such as organic carbon. The reactor is capable of incorporating solar power, allowing for in-situ treatment of eutrophic water with a sustainable and reliable energy source, making implementation in a remote area a practical option.

The bench-scale reactor designed by Digger Denitrification operates a maximum denitrification rate of 12.4 mg/L/day while being supplied 1.8V from a battery source. Preliminary trials of the reactor have produced a nitrate removal efficiency of 84%, proving the efficacy of the BER technology. Based on these results, the bench scale BER provides effective treatment at a cost of $4.14/g.

2.0 INTRODUCTION

Nitrate is an essential nutrient for metabolic processes of plants in addition to being a limiting factor for growth. An excess of nitrates in waters causes eutrophication – an uncontrolled algal growth that depletes oxygen, leading to the deterioration of the ecosystem health.

Additionally, excessive nitrates in water is harmful to human health. For example, consumption of nitrates is linked to methemoglobinemia, also known as blue baby syndrome. The presence of nitrates also likely indicates the presence of various pathogenic bacteria or pesticides linked to sewage and agricultural sources.[1]

Significant amounts of nitrate comes from non-point sources, specifically, agricultural activities. An increase in agricultural fertilizer use has led to a spike in the presence of nitrate in surface and ground waters.[2] Non-point source contamination is challenging to fully assess and treat. Current nitrate-reducing treatment technologies lack the ability to treat the extensive nitrate contamination due to their dependence on harmful chemical additions and ex-situ tendencies.

Digger Denitrification's proposed solution for nitrate-reduction in waters is the use of a biofilm electrode reactor (BER). A BER operates with the addition of electrical power, rather than potentially harmful chemicals. It requires only a minimal amount of electrical power that can be supplied through solar power, enabling the BER treatment technology to be operable in remote locations, where the most eutrophication issues reside.

2.1 Problem Statement

Digger Denitrification addressed the open task category of the 2018 WERC competition. There is a lack of available treatment technologies for rural nitrate contaminations. To fill this void, Digger Denitrification designed a BER - an innovative, sustainable solar powered microbial denitrification system. The proposed treatment technology is comparable to current treatment technologies for denitrification. Digger Denitrification's system feasibility and operational results are explained in the following sections.

2.2 Current Denitrification Technologies

The available nitrate-reducing technologies are not designed for water-shed scale nitrate remediation. These technologies include chemical methods created for drinking water treatment, such as Ion Exchange (IE) and Reverse Osmosis (RO), or ex-situ microbial methods for point source wastewater treatment, such as heterotrophic denitrification.

2.2.1 Ion Exchange

Ion Exchange (IE) is among the best available technologies for nitrate removal in waters. The Environmental Protection Agency (EPA) recognizes IE as an acceptable treatment method for nitrate rich waters. IE is advantageous because of design simplicity and the quick startup time.[3] This treatment technology involves the adsorption of the nitrates onto various types of anion exchange resins, producing a high purity effluent with up to 90% removal of nitrates.[4] However, the designed resins must frequently be regenerated, resulting in expensive upkeep costs making this infeasible for non-point source treatment. Additionally, the wastewater derived from the resin regeneration must be disposed of, creating additional costs to the system.[5] This treatment technology requires a pre-treatment filtration for the influent, and an adjustment of pH following the flow through the resin.

2.2.2 Membrane Technology

Reverse Osmosis (RO) is the most common type of membrane technology for denitrification of waters and the second most common denitrification technology[3]. Pressure forces water through a semipermeable membrane that traps the contaminants while clean water continues to flow. The RO system can treat multiple contaminants at once, including nitrates, at high efficiency.[4] The membranes used in RO can easily be fouled, compromising their performance by decreasing water production rate and degrading product water quality. Furthermore, concentrated brine waste is produced through RO, requiring an additional waste disposal step, or treatment technology added to the process. RO can be a complex treatment option with high energy and chemical demands[4] making it impractical for non-point source denitrification.

2.2.3 Heterotrophic Denitrification

Heterotrophic Denitrification is the more developed biological treatment technology as compared to autotrophic denitrification (the mechanism in a BER). Heterotrophic organisms require organic substrates, including carbohydrates, to obtain their required energy inputs. Although heterotrophic denitrification is widely used and researched of the microbial systems, the necessity of an external carbon source for heterotrophs usually results in higher operating costs[4], as compared to autotrophic denitrification. Additionally, the addition of carbon sources can be potentially toxic to waterbodies, if added in an in-situ treatment system.[5]

3.0 CONCEPTUAL DESIGN

Digger Denitrification designed a BER system that can remedy non-point source eutrophication issues across the United States. The BER system uses solar power to make this technology accessible to remote locations. The BER does not produce a waste stream, can be used for on-site treatment, and is grid-independent.

3.1 Biofilm Electrode Reactor (BER)

The efficacy of BERs is dependent on numerous design criteria.[5] Prior to solidifying specific design criteria to optimize the operational results of the BER, Digger Denitrification created the following conceptual design model:

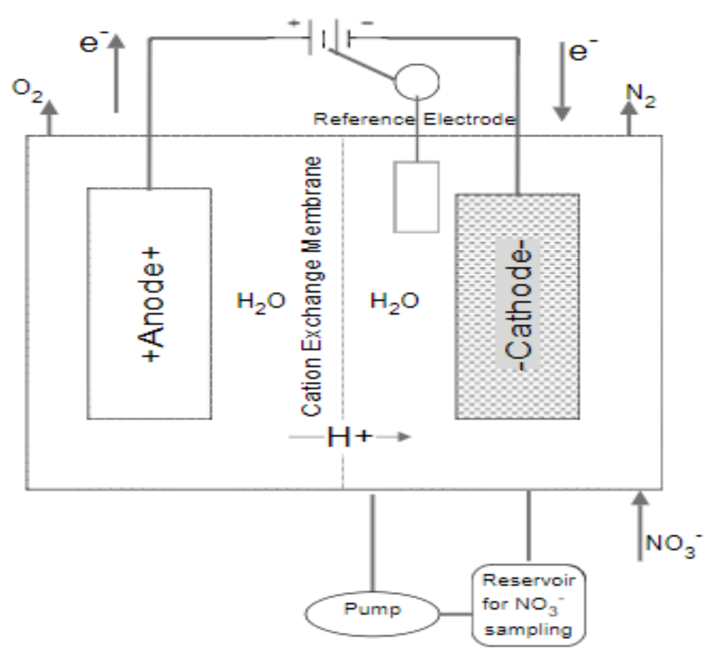

Figure 1: Conceptual BER

The design in Figure 1 consists of a two-cell reactor: the cathode cell and the anode cell. The electrode (cathode), where nitrate-reducing microbes are immobilized, serves as the direct electron donor to the microbes.[1] With a continual flow of hydrogen ions from the anode chamber and electrons from the cathode, microorganisms will reduce nitrate to harmless nitrogen gas. The reduction of nitrate in the cathode cell, on the cathode, follows the stoichiometric reactions listed below:

$NO_3^- + 2e^- + 2H^+ \rightarrow NO_2^- + H_2O$ $E_{ox} = +0.433$ V (vs. SHE*) *(Eq. #1)*

$NO_2^- + e^- + 2H^+ \rightarrow NO + H_2O$ $E_{ox} = +0.350$ V (vs. SHE) *(Eq. #2)*

$NO + e^- + H^+ \rightarrow \frac{1}{2} N_2O + \frac{1}{2} H_2O$ $E_{ox} = +1.175$ V (vs. SHE) *(Eq. #3)*

$\frac{1}{2} N_2O + e^- + H^+ \rightarrow \frac{1}{2}N_2 + \frac{1}{2} H_2O$ $E_{ox} = +1.355$ V (vs. SHE) *(Eq. #4)*

*Standard hydrogen electrode (SHE)

With a stable and robust population of denitrifying microbes and a constant supply of electricity, the BER will reduce nitrates.

The second half of a BER, the anode chamber, contains the counter electrode and serves as the location for the oxidation of water. The following chemical equation defines the half reaction of the electrolysis of water that is taking place on the anode cell:

$2H_20 \rightarrow 4H^+ + O_2 + 4e^-$ $E_{ox} = 1.23$ V (vs. SHE) *(Eq. #5)*

The subsequent electrons will flow through the electrical wiring that connects to the reactor. These wires connect to a potentiostat during the inoculation of the microbes on the cathode, and then transfer to a simple source of energy, for example, a battery, once fully functioning. Additionally, hydrogen ions will cross the cation exchange membrane separating the two chambers, which are required for the reduction of nitrates in the cathode chamber.

3.2 Microbial Denitrification

Organisms that synthesize their own food in the absence of oxygen are defined as autotrophic, anaerobic microbes. A BER utilizes these microbes for their ability to respire various inorganic molecules, including nitrate, in a mechanism termed, “nitrate respiration.”[6] The microbes can use nitrate and its reduced forms in their respiratory process to generate energy for cellular function, reducing nitrates to nitrogen gas.

Keeping the cathode chamber anaerobic is crucial to the growth of the nitrate-reducing microbes. If oxygen, the more favorable electron acceptor, is present the microbes will consume it and adapt to aerobic conditions. Therefore, the microbial biofilm in a BER must be acclimated in anaerobic conditions to ensure the maturation of the right type of microbes. Additionally, nitrate-reducing bacteria thrive in neutral pH's, ranging from 6.8 to 7.2. For this reason, the cathode solution was prepared to a pH of 7.0, as explained in Section 4.2.

To maximize microbial growth, the surface area available for the microbes to attach is an important design consideration. Digger Denitrification chose a graphite felt cathode, creating a large area available for the contaminant to come into contact with the microbial community and providing adequate space for the entrapment of the denitrifying bacteria.

The growth of the microbes requires an energy input, or electron flow, delivered by a power source connected to the cathode. The amount of energy required is minimal and can be supplied in a sustainable manner (i.e. solar power). Digger Denitrification has addressed this energy need with the application of solar power.

3.3 Application of Solar Power

Solar power serves as a low-cost source of energy. Prices of solar panels have declined over recent years with changing energy policies and markets. This trend is likely to continue due to a world-wide shift away from non-renewable resources. Digger Denitrification recognized the changes in the energy sector when designing the solar power component to the BER. This design supports the use of renewable resources in a cost-effective way. Additionally, the use of a solar panel allows for the placement of a BER treatment technology in rural areas where excessive nutrients in the waters is common due to agriculture. With the addition of a solar panel, the BER becomes a self-sustained system.

4.0 LAB EXPERIMENTATION

4.1 Reactor Fabrication

The bench scale design created by Digger Denitrification is given below in Figure 2.

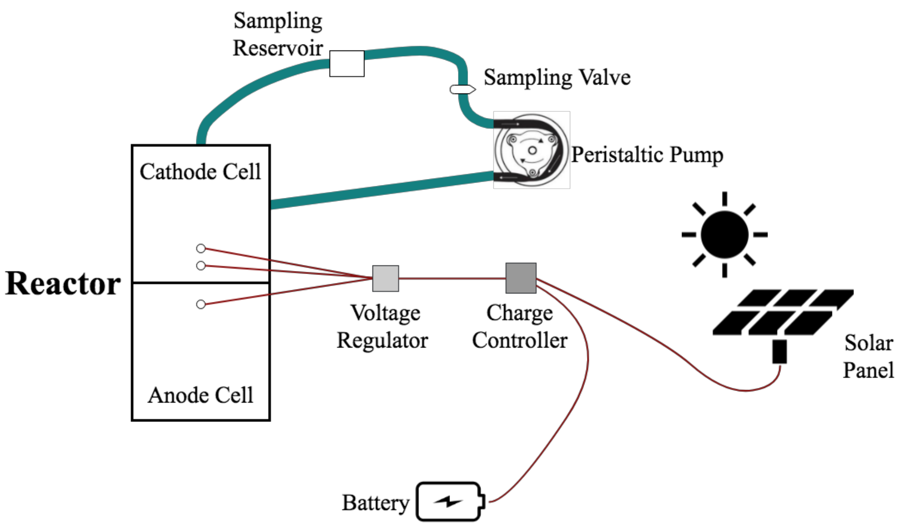

Figure 2: BER bench-scale design

Digger Denitrification designed a two-chamber BER constructed of acrylic sheets assembled in two halves: cathode chamber and anode chamber (approximately 785 mL each). In Figure 3, below, the cathode chamber is located on the left, while the anode chamber is located on the right.

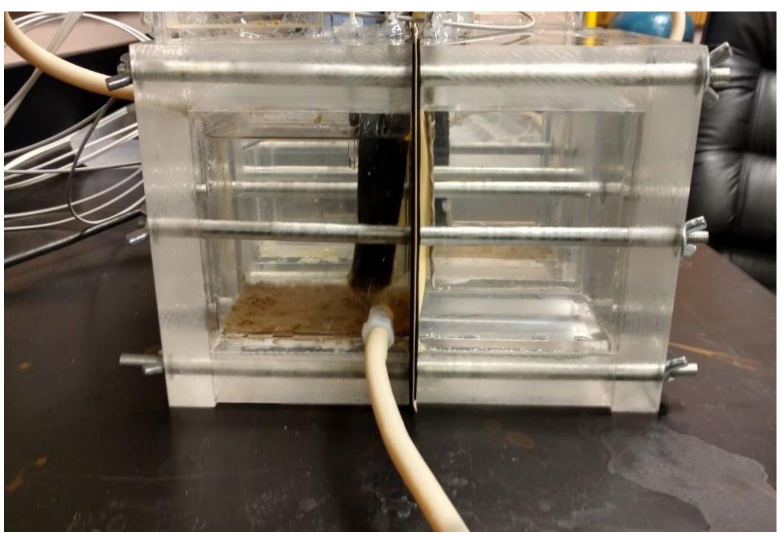

Figure 3: Digger Denitrification's BER

To maximize the surface area of the cathode for the microbial growth, Digger Denitrification used high-surface-area graphite fiber felt cathodes. Two graphite fiber felt cathodes were combined by using a platinum-coated titanium mesh electrode with wire that connects and holds the cathodes together as one for each reactor. This method doubles the surface area for the cathode reaction to take place. To eliminate corrosion and create an adequate connection, a titanium mesh electrode, coated with platinum was used as the anode. Lastly, a silver/silver chloride standard reference electrode was placed in the cathode chamber to keep a constant cathode potential during the acclimation of the microbes.

Digger Denitrification took several precautions to ensure that the cathode compartment remained anaerobic including the use of non-permeable tubing, Teflon tape and silicon to seal openings. Prior to introducing solutions into the cathode chamber, the solution was sparged with nitrogen for approximately 20 minutes, removing any oxygen present in the solution.

To assemble the reactor, Digger Denitrification placed two rubber gaskets on the end of each compartment, with a cation exchange membrane serving as the intermediate between the two compartments. Digger Denitrification sterilized the compartments and cathode material using HCl acid wash.

The BER can function with the combination of a solar panel, a charge controller, and a lead-acid battery. For the bench-scale Design, Digger Denitrification implemented a 14-watt solar panel and a 12-volt lead-acid battery (3.5 Ah). Additional or larger solar panels and batteries can be added to the solar charge controller to adjust for site-specific characteristics during the implementation of the full-scale BER. While operating, the bench-scale BER has shown to have varying performance depending on voltage. To ensure that the BER operates at maximum performance for nitrate removal, an adjustable voltage regulator is included in Digger Denitrification's design.

4.2 Seed biomass and electrode solutions

The abundance of microorganisms in wastewater treatment plant sludge is used as a "seed" for the nitrate-reducing microbes. However, immobilizing the nitrate-reducing microbes requires specific conditions. A cathode solution made up of nutrients and buffers was created to ensure correct conditions. The makeup of the cathode solution included sodium nitrate (0.085g/L); sodium dihyrdogren phosphate (3.22 g/L); disodium hydrogen phosphate (10.39 g/L); sodium chloride (2.5 g/L); magnesium sulfate (0.5 g/L); calcium chloride (0.075 g/L); and wastewater treatment sludge (100mL).

The cathode solution consists of nitrates, buffers, and electrolytes. The nitrates serve as the terminal electron acceptor, requiring the microbes to "consume" the nitrates, thereby reducing the contaminant. The phosphate buffers used, NaH_2PO_4 and Na_2HPO_4 are to ensure that the solution maintains a neutral pH, which is ideal for the growth and continual functioning of the biofilm. The electrolytes will reduce the ohmic resistance in the cathode chamber.

4.3 BER acclimation

Digger Denitrification collected wastewater treatment sludge, as a microbial "seed," from the Butte-Silverbow Metro Sewer Plant. Digger Denitrification implemented the activated sludge into the reactors within two days of receiving the sludge from the sewage treatment plant to ensure the bioactivity of the sludge remained high. Approximately 100 mL of wastewater treatment plant sludge in addition to the cathode solution were pumped into the cathode chamber.

The anode cell was filled simultaneously. The solution in the anode cell consists of distilled water, phosphate buffers, and trace amounts of electrolytes. Throughout the inoculation, Digger Denitrification replaced the substrate in both the cathode and anode cells three times to replenish nutrients in each cell, in addition to regulating the pH in the reactor.

Digger Denitrification connected the reactor to a potentiostat, allowing for the control of the voltage delivered to the system, in addition to reading, recording, and graphing data on the current consumption of the reactor. For microbial inoculation, the potentiostat was set to -0.2 V between the reference electrode and the cathode.

Digger Denitrification observed the accumulation of the microbial community through tracking the current on the potentiostat and assumed a current production of approximately 0.5 mA can be considered a well-established biofilm.

4.4 Analytical methods

Nitrate and pH readings of both the anode and cathode solutions were logged every other day while the potentiostat continuously recorded the current. Nitrates were measured with a ThermoFisher Orion 9700 BNWP. These readings are produced in mV, and then converted to mg/L nitrate using a calibration curve. A Fisherbrand Accumet AP115 portable pH meter kit was used to measure pH, calibrated once a month. The current was monitored using a CH Instruments 1000C Series multi-potentiostat.

5.0 Results

5.1 Current consumption

To determine the voltage associated with the maximum nitrate reduction rate, Digger Denitrification tested three different voltages on the BER: 1.6V, 1.8V, and 2.0V. In theory, the greater the area under the current vs time graph, the greater the mass of nitrates reduced. Figure 4 shows the current vs time data for different cycles under different electrical potentials.

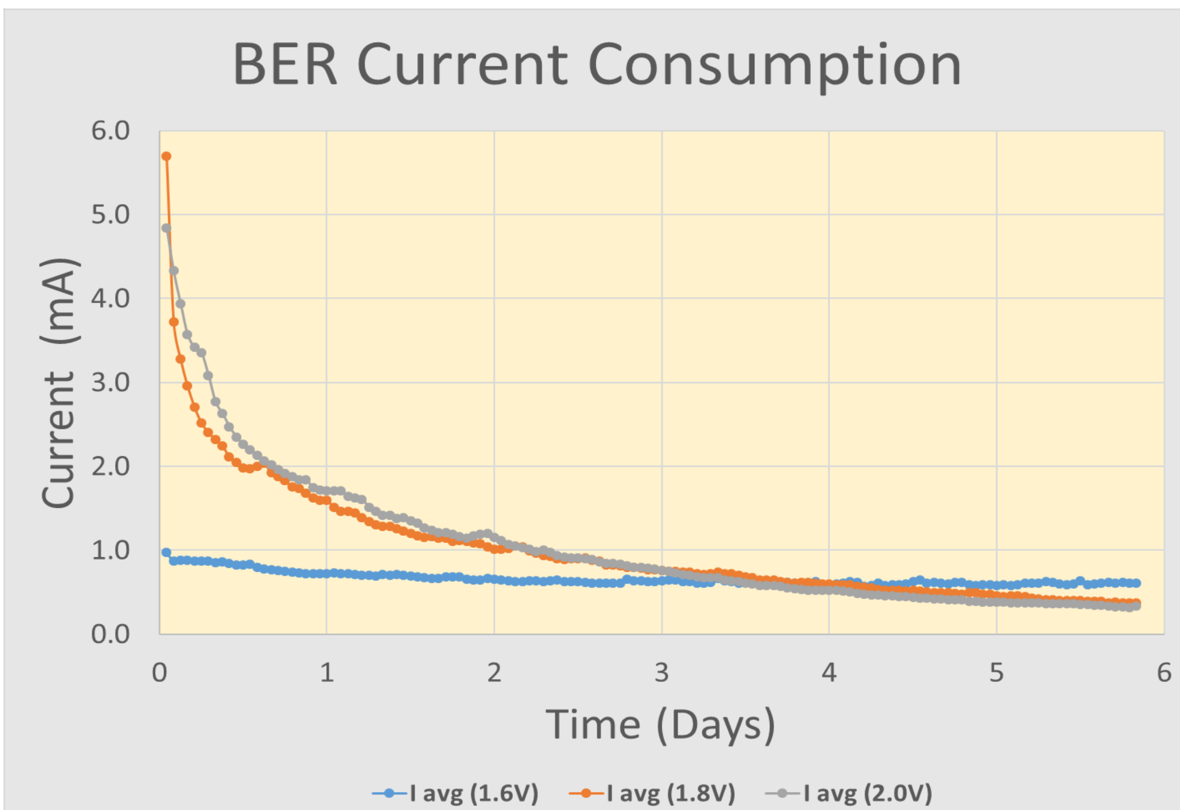

Figure 4: BER current consumption

Theoretically, the current supplied to the system is related to the amount of nitrate reduced based on the stoichiometric reduction and oxidation reactions that are occurring in the reactor. The minimum amount of voltage required for the total reduction of nitrates to nitrogen gas is 0.949 V, as shown by the calculation below. This value demonstrates the largest difference between the cathode and anode chamber for the series of reactions that occur during denitrification.

$$E_{overall} = E_{cathode} - E_{anode} = 0.350\ V - 1.23\ V = \underline{-0.949\ V} \qquad \textit{(Eq. \#6)}$$

Digger Denitrification was cautious to not apply excessive power to the system, as this would result in the full hydrolysis of water in the cathode compartment. Therefore, the theoretical range that Digger Denitrification tested for an optimum voltage is between 0.949 V and 1.23V. To account for various electric losses throughout the system, Digger Denitrification tested a voltage range higher than the theoretical range.

5.2 Nitrate removal

Nitrate reduction results varied depending on the electrical potential difference between anode and cathode compartments. The slope of each lines corresponds to a nitrate reduction rate associated with a specific electrical potential as given in Figure 5. Nitrate reduction ranged from 10.36 mg/L/day to 12.164 mg/L/day. It is evident from the information presented in Figure 5 that the BER functions with an optimum nitrate-reduction rate at a voltage of 1.8V. In conclusion, a full-scale BER must be operated under this same voltage to maximize the efficiency and efficacy of the treatment technology.

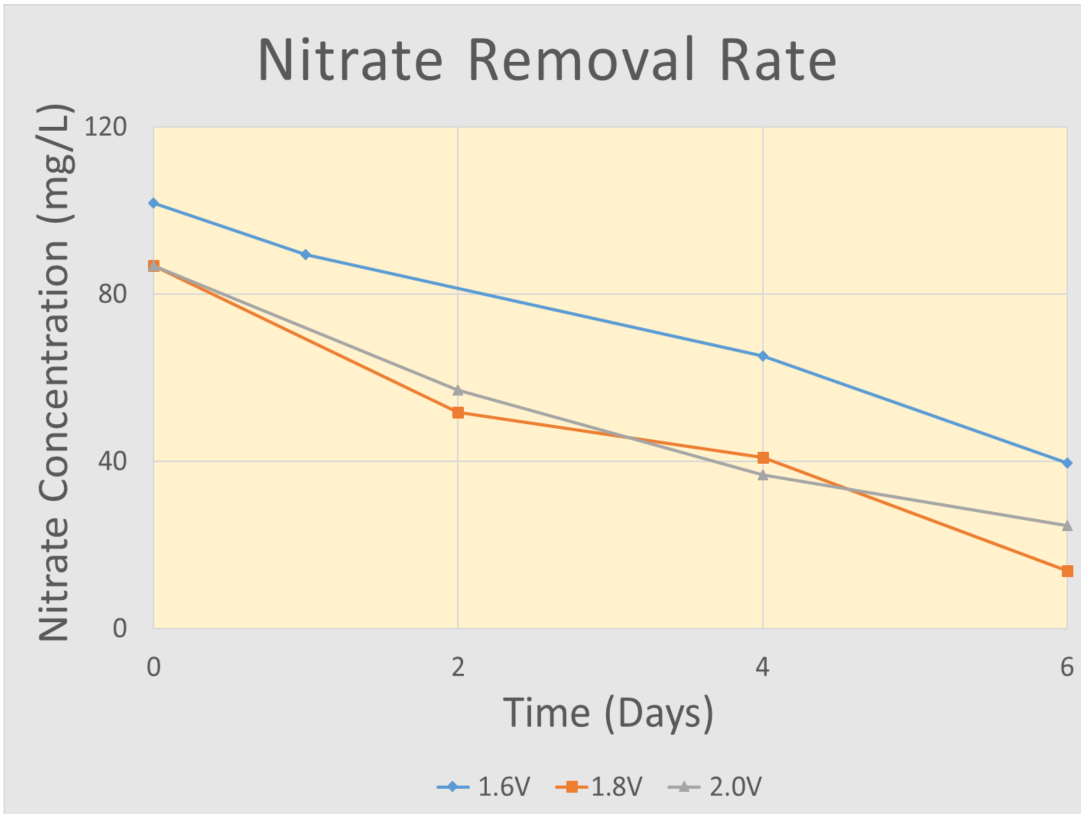

Figure 5: BER nitrate removal rate

5.3 Scaled up outlook

The solar-powered BER is a proof of concept in early stages of development. At this juncture, a linear assumption is the most sensible approach for large-scale implementation. If the BER is scaled to approximately 20 times its bench-scale size, the resulting BER would have a reactor volume of 15.7 Liters and a carbon felt electrode surface area of 1.19 ft^2. The corresponding rate of nitrate removal would ideally reach 2480 mg/L/day.

Successful application of the BER is predicated on the assumption that the biofilm adhered to the felt surface is sufficiently robust to handle environmental conditions. Several factors such as influent flow rate and influent concentration of nitrates would shape large-scale application. The time-intensive nature of this process has limited Digger Denitrification's ability to perform further experiments that would result in a more accurate vision for implementation of a full scale system. Thus far, the BER has proven to have the potential to fill a gap in the solution to eutrophication; though, further development is needed to properly forecast BER application.

6.0 ECONOMIC AND ENVIRONMENTAL ANALYSIS

6.1 Cost Analysis

The size of a full-scale BER will vary depending on the magnitude and type of application. For this economic analysis, Digger Denitrification assumes a full-scale BER of twenty times the size of the bench-scale model as this could be reasonable sizing for real-world application. Table 1 shows the specifications, costs, and service life of each component in a full-scale BER.

Table 1: Large-scale BER economic analysis

Component	Specifications	Cost	Service Life
Graphite Cathode	Diameter - 66 in. Thickness - 0.35 in.	$110*	1 year*
Anode	Width - 40 in. Height - 60 in.	$250*	15 years
Battery	12 Volt 3.5 Ah	$30	3 years
Solar Panel	14 Watt	$40	15 years
Charge Controller	-	$20	15 years
Circuit Parts	-	$50	5 years
Labor (Installation)	-	$250*	-
Labor (Operation & Management)	-	$3000*	15 years

* Extrapolated from lab setup.

Using the values in the table above, Digger Denitrification determined that the total cost of continuously running a full-scale BER for 15 years, 7 days a week, 24 hours a day will be $5510 (2017 dollars). This cost does not consider disposal costs, as Digger Dentification anticipates that each component can be re-used and recycled. According to the United States Environmental Protection Agency, a small wastewater treatment plant's biological nutrient removal (BNR) system has a capital cost of $1,167,914.[7] Additionally, the costs associated with operation and management are $162,169/year when run at 100,000 gallons per day (gpd). For a BNR with a 20 year service life, the price per gram of nitrate removed is approximately $0.21/g (see Appendix A).

By comparison, Digger Denitrification's solar powered BER would have a total cost of $4.14/g. The cost per gram of nitrate reduced by a solar powered BER was calculated by multiplying Digger Dentification's bench-scale reactor reduction rate of 12.1416 mg/L/day or 0.0124 g/L/day of nitrate per day by 20. As a result, a full-scale reactor should be expected to reduce 0.243 g/L/day with a 15-year service life. This value assumes that the full-scale BER will have a reduction rate proportional to size.

An important note on comparing a solar powered BER to a BNR is that the BER is designed to treat nitrates in a low flow, in-situ treatment using microbes and electricity. Contrarily, BNR is an ex-situ treatment that removes a variety of compounds, including nitrates, using microbes and chemicals. Because of this, a BNR can treat nitrates effectively from a point source, such as sewage. Digger Denitrification's solar-powered BER will treat non-point sources such as agricultural runoff, which currently has no economically feasible treatment.

The specifications for the full-scale BER described in Table 1 would be ideal for treating a eutrophic lake, however; the most effective cost savings when applying a solar-powered BER would come from groundwater remediation. Cost savings result from the use of a BER when compared with conventional groundwater ex-situ treatments because of their dependence on the pump and treat system. Another important note is that solar-powered BERs are still a developing technology, so there is potential that costs will decrease in the future.

6.2 Marketing

The primary market for solar-powered BERs are state governments seeking to remediate eutrophic or otherwise nitrate-polluted groundwater and surface water. According to Dodds et al.[8], eutrophic waters cost the United States approximately $2.2 billion dollars each year. This several billion-dollar cost is the result of lost recreational water usage and drinking water, decreasing value of waterfront properties, and recovery of endangered species.

Digger Denitrification plans pitch the solar powered BER technology to state environmental regulatory agencies and the United States Department of Agriculture (USDA). The states with the highest agricultural activity per capita will be the primary targets for marketing.

6.3 Applicable Permits and Regulations

The presence of excessive nitrates in waters often impairs the water body, producing risks to human health, ecosystem functions, and recreational use of the water body. Infants, children, the elderly, and individuals with inadequate immune systems, are at especially high risk if consuming water with concentrations of nitrate over 10 mg/L, according to the Safe Water Drinking Act.

Under the Clean Water Act (CWA), surface water quality regulations for nitrates is state dependent. Many states have no regulations on nitrates, while others heavily regulate nitrate discharges, depending on the potential impact the addition could have on the water body.[9] For states without water quality regulations, the EPA has established enforceable standards, which do not include nitrate regulations. State agencies identify and list the surface water bodies that are impaired, characterized by a contamination of pollutants, including nitrate. The nitrate load reduction required, also known as total maximum daily load (TMDL), for the water body is determined by the use of the water body. A full-scale BER can address the load reduction requirements created by the EPA.

The implementation of Digger Denitrification's scale up design requires the acquisition of a United States Army Corps of Engineers Section 404 permit under the Clean Water Act, if the device is placed in a "water of the United States."[9] This permit will be applicable for the installation of a biofilm developed for denitrification in lakes or creeks (non-tidal waters). For in-situ groundwater remediation, permits will be required, differing with the state that the treatment technology is located in.

Due to the use of microbes, the implementation of a BER may be subject to 40 CFR Part 158, Subpart V - Microbial Pesticides. This requires any “microbial agent” that is used for water treatment be tested for various product, residue and toxicology data prior to being placed in the field.[10]

The proposed design created by Digger Denitrification will be in compliance with the national, state, and local regulations by obtaining the appropriate permits, and meeting or exceeding the water quality standards described above.

6.4 Environmental Assessment

Implementation of the BER will have minimal effect on the environmental conditions of the site. Most eutrophic water bodies have low dissolved oxygen levels and, consequently, low aquatic life. The low dissolved oxygen levels will allow for nitrogen to remain the main electron acceptor, rather than oxygen, increasing the efficiency of the biofilm. The absence of aquatic life will ensure that no migratory or biological habits of animals present will be impacted during treatment.

7.0 HEALTH AND SAFETY

Denitrification through a solar-powered BER requires few safety precautions. Digger Denitrification analyzed the General Duty Clause, Section 5(a)(1) of the Occupational Safety and Health Act of 1970 and developed the following the safety precautions and procedures listed below to ensure that no injuries or accidents occur while the BER is operating:

- Though the BER uses a minimal amount of power, electrical safety measures include:
  - Cover all exposed metal wires.
  - During servicing, the disconnect the BER from the power source
  - In remote case of a shock, disconnect the source of electricity

- In case of a spill from the cathode compartment, use safety glasses, nitrile gloves, and close-toe shoes to avoid exposure to potential biohazards. Pour bleach on contaminant and clean up immediately with paper towels.
- When handling the lead-acid battery, wear acid-resistant goggles and gloves. If acid gets on your skin or in your eyes, rinse affected area immediately. Eyes must be flushed with water for 15 minutes and seek medical attention.

These safety measures and precautions shall be practiced at all times to ensure the hazards associated with the BER are minimized.

7.1 Community Relations

Rural communities make up the primary population of concern for eutrophic water bodies in the United States. Nitrate is produced primarily from rural communities that lack the ability to moderate nitrate levels in surface and groundwater due to insufficient funding and infrastructure.

The BER is designed to mitigate the impact of these agricultural nitrate sources without impacting the agricultural process itself and the farmer's livelihood. Digger Denitrification proposes the following two-pronged approach for improving community relations with the implementation of a BER:

1. Utilize local extension centers, a service offered by local colleges or universities to provide a source of unbiased education to community members. Extension centers can promote the importance of lowering nitrate levels in water resources using a BER.
2. Host monthly town meetings prior to the implementation of a BER to inform the community on the water quality benefits associated with nitrate removal. While the technology is in effect, recurrent town meetings can be held to update the community on the efficacy of the treatment technology and the future of the project.

8.0 SUMMARY AND CONCLUSIONS

The solar-powered BER is a potential solution for eutrophication. Digger Denitrification's BER design uses electricity, instead of chemicals, to reduce nitrates into nitrogen gas, producing no waste stream. Renewable energy sources like solar power enable the BER to be applied to off-grid bioremediation for nitrate-rich waters.

Although the acclimation of the microbial community creates a long start-up period, the treatment technology is capable of long-term treatment, without frequent maintenance. Based on the bench-scale results, a BER is capable of nitrate removal rates of 12.4 mg/L/day. This highly efficient design can treat contaminated waters, reducing nitrate levels to the required limits set by the EPA. Digger Denitrification estimates that the cost of nitrate removal by the BER is $4.14/g.

Further research is required prior to upscaling the BER design, particularly on the effects of differing water characteristics and decreasing the biofilm startup time. BER technology is still in the development stages and cannot be adequately compared to other nutrient removal technologies because BER technology is the only means of treating non-point source nitrate pollution.

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Appendix A: Cost Analysis

Wastewater Biological Nutrient Removal Costs

Influent Concentration	10	mg/L
Effluent Concentration	2	mg/L
Concentration Removed	8	mg/L
4-Stage Process Capital Cost	$ 1,167,914.00	
Operation and Maintenance Cost per year	$ 162,169.00	
Lifetime Operation and Maintenance Cost	$ 3,243,380.00	
Total cost	$ 4,411,294.00	
Flow	100000	Gal/day
Design Service life	20	years
Run time	350	Days/year
Volume of Water Treated During Service Life	700000000	Gallons
Volume of Water Treated During Service Life	2649500000	Liters
Mass of Nitrate Removed in lifetime	21196000000	mg
Mass of Nitrate Removed in lifetime	21196000	g
Cost per gram of Nitrate	$ 0.21	

Wastewater Biological Nutrient Removal Calculations:

Lifetime Operation and Maintenance Cost

$162,169/year * 20 years = $3,243,380

Total Cost

$1,167,914 + $3,243,380 = $4,411,294

Volume of Water Treated During Service Life

$$100{,}000 \text{ gal/day} * 350 \text{ days/year} * 20 \text{ years} * 3.785 \text{ L/gal} = 2.65*10^9 \text{ L}$$

Mass of Nitrate Removed

$$8 \text{ mg/L} * 2.65*10^9 \text{ L} * 1\text{g}/1000\text{mg} = 21.2*10^6 \text{ g}$$

Cost per gram of Nitrate

$$(\$4,411,294)/(21.2*10^6 \text{ g}) = \$0.21/\text{g}$$

Digger Denitrification Solar Powered BER Costs

Graphite Cathode	$	1,650.00
Anode	$	250.00
Battery	$	150.00
Panel	$	40.00
Controller	$	20.00
Circuit Parts	$	150.00
Labor (Installation)	$	250.00
Labor (Opeartion and Management)	$	3000.00
Total Cost	$	5510.00

Digger Denitrification Solar Powered BER Calculations:

Nitrate Removal after 15 year Service Life

$$12.16 \text{ mg/day} * 20 * 15 \text{ year} * 365 \text{ day/year} * 1 \text{ g}/1000 \text{ mg} = 1331.5 \text{ g}$$

Cost per gram of Nitrate

$$(\$5510)/(1051.2\text{g}) = \$4.14(\$5510)/(1331.5\text{g}) = \$4.14$$

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March 8, [redacted]

To Whom It May Concern:

On Wednesday, March 7, [redacted], I met with representatives from the design group, Digger Denitrification, to complete an audit of the team's cost analysis for their project, Solar Powered Biofilm Electrode Reactor for Aquatic Denitrification.

In completing this audit, I identified areas that needed addressing prior to the group finalizing their project. I believe that the group understood these recommendations and will properly implement the necessary changes before concluding their report.

Please contact me if you have any questions regarding this confirmation.

Sincerely,

[redacted]

[redacted]

March 13, [redacted]

Environmental Design Team
[redacted]

Per your request, I have reviewed the [redacted] submission titled Solar Powered Biofilm Electrode Reactor for Aquatic Denitrification.

In my opinion, this submission correctly identifies that the Clean Water Act, 33 U.S.C. 1251 et. seq. and the Safe Drinking Water Act, 42 U.S.C. §300f et. seq as the controlling federal authority. The submission correctly concludes that any discharge must meet either the State or Federal requirements.

In addition, the submission correctly concludes that any large scale implementation of this technology will require a permit from the Army Corps of Engineers for surface waters, and groundwater treatment or discharge would be controlled by the applicable state law. Thank you for the opportunity to review this project.

Sincerely,

[redacted]

Environmental Engineering Department

MEMORANDUM

March 8, 2018

TO: WERC Evaluators and Task 7 Design Team

FROM:

RE: Safety and Health Audit of Task 7 - Open
Solar Powered Biofilm Electrode Reactor for Aquatic Denitrification

I have reviewed the Health and Safety section of the report and provide the following comments:

The plan for both the bench-scale and full-scale design involves the denitrification of water through the use of a biofilm electrode reactor (BER). The initial design uses a potentiometer as a power source, while the final design will use solar power as the source. The initial design uses wastewater treatment plant sludge as a source of microorganisms.

The safety plan correctly identifies hazard recognition, evaluation and control as well the applicable OSHA requirements. In my opinion, the report properly covers the safety and health concerns associated with Task 7.