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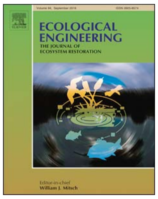

Research Paper

Electrical stimulation for enhanced denitrification in woodchip bioreactors: Opportunities and challenges

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ABSTRACT

Woodchip bioreactors are being implemented for the removal of nitrates in groundwater and tile water drainage. However, low nitrate removals in denitrifying woodchip bioreactors have been observed for short hydraulic retention time (HRT) and low water temperature (< 10 °C). One potential approach to improve woodchip bioreactor performance is to provide an alternative and readily available electron source to the denitrifying microorganisms through electrical stimulation. Previous work has demonstrated the capability of bio-electrochemical reactors (BER) to remove a variety of water contaminants, including nitrate, in the presence of a soluble carbon source. The objective of this study was to evaluate the denitrification efficiency of electrically augmented woodchip bioreactors and conduct a simple techno-economic analysis (TEA) to understand the possibilities and limitations for full-scale BER implementation for treatment of agricultural drainage. Up-flow column woodchip bioreactors were studied included two controls (non-energized, and without electrodes), two electrically enhanced bioreactors, each using a single 316 stainless steel anode coupled with graphite cathodes, and two electrically enhanced bioreactors, each with graphite for both anode and cathodes. Both pairs of electrically enhanced bioreactors demonstrated higher denitrification efficiencies than controls when 500 mA of current was applied. While this technology appeared promising, the techno-economic analysis showed that the normalized N removal cost ($/kg N) for BERs was 2–10 times higher than the base cost with no electrical stimulation. With our current reactor design, opportunities to make this technology cost effective require denitrification efficiency of 85% at 100 mA. This work informs the process and design of electrically stimulated woodchip bioreactors with optimized performance to achieve lower capital and maintenance costs, and thus lower N removal cost.

1. Introduction

The benefits of nitrogen fertilizer addition to increase agricultural yields are well recognized, but subsequent nitrogen losses from agricultural land have significant negative environmental impacts when nitrogen is conveyed to surface and ground waters (Robertson and Vitousek, 2009). While hypoxia is the most common problem, excessive nutrients in aquatic ecosystems also may result in acidification of these aquatic systems (Camargo and Alonso, 2006). In addition, nitrate poses risks to human and animal health when occurring in drinking water at concentrations exceeding 10 mg/L as N (Camargo and Alonso, 2006; USEPA, 2009), and such concentrations are regularly found in tile drainage of high-production agricultural landscapes (Hofmann et al., 2004; Ikenberry et al., 2014; Kalita et al., 2007; Lawlor et al., 2008).

The Hypoxia Task Force (2013), a collaboration of state and federal agencies led by the U.S. EPA, aims to reduce non-point source nitrogen export in Iowa by 41 percent through the implementation of multiple nutrient reductions strategies. The Iowa Nutrient Reduction Strategy (INRS) includes changes in land management practices, land-use practices, and edge-of-field practices to meet these goals (IDALS, 2013). Among edge-of-field practices, woodchip bioreactors are recognized as one of the promising technologies to remove nitrate from tile drainage (IDALS, 2013). A comparative study of field bioreactors at four separate locations in Iowa reported an average nitrate removal of 43 percent for treated drainage water (Christianson et al., 2012), demonstrating that such systems could achieve reductions close to those targeted by the Hypoxia Task Force. However, the performance of bioreactors is highly variable, with lower removal efficiencies occurring when temperatures

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Abbreviations: BER, bio-electrochemical reactor; DE, denitrification efficiency; SS, stainless steel; C, carbon

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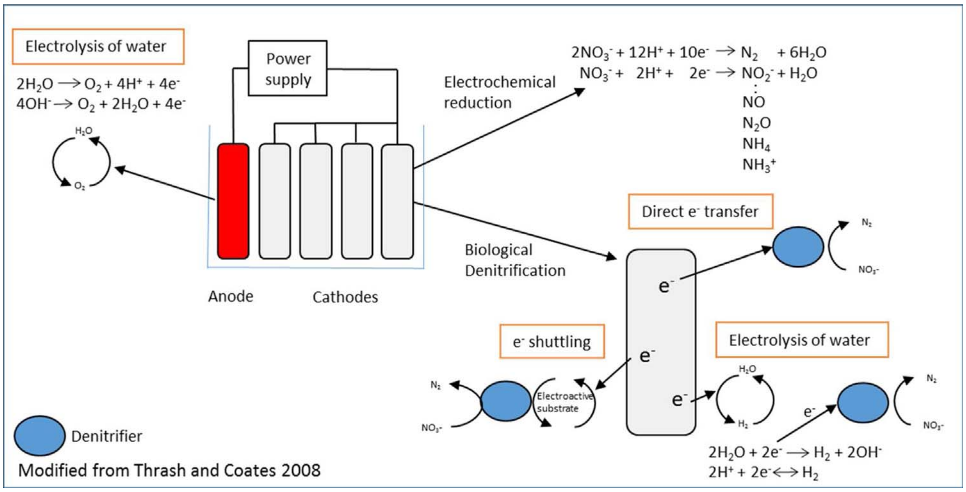

Modified from Thrash and Coates 2008

Fig. 1. Summary of potential electron transfer mechanisms for denitrification in a bio-electrochemical reactor.

are low, or flow is high (i.e., when hydraulic retention time (HRT) are low) (Hoover et al., 2015; Robertson et al., 2008). This is one of the motivations to improve bioreactor performance under such conditions, which typically occur in the early spring or high-flow season.

One potential approach in improving nitrate removal is to provide electrical power to an electrode system within the bioreactor, thus providing more readily available electrons as an energy source to the denitrifying microorganisms (Sakakibara and Kuroda, 1993). Such electrical stimulation of microbial metabolism to remove toxic pollutants has been practiced for over 50 years, and electrically-enhanced nitrate removal has previously been demonstrated (Thrash and Coates, 2008). Electrical stimulation is attractive because no chemical addition is necessary. Bio-electrochemical treatment potentially has the advantage of lower cost when treating a larger volume of wastewater as compared to addition of chemical amendments, which may have a higher cost of operation. Prosnansky et al. (2002) used electrical stimulation to remove nitrate in synthetic groundwater and estimated operating costs of 0.15–0.48 $\$/m^3$ of treated water with current densities set between 2.7 and 6 A/m^3. If electrification can improve denitrification rate and thus volumetric removal, then it could facilitate smaller bioreactors which are even more attractive for edge-of-field treatment.

While there is great potential for the exploration of this technology, the bio-electrochemical reactor (BER) requires a higher capital cost than traditional woodchip bioreactors due to the material cost of electrodes and operating cost of power supply. Since the implementation of INRS, including bioreactor, is voluntary by land owners, the extra cost of this modification may be a challenge for wider adoption of BER at the field-scale. At such, there is a need to conduct a preliminary technoeconomic analysis (TEA) to determine the operating conditions under which the BER is economically feasible.

The primary goal in designing an effective BER is to create a distinct zone with ideal conditions for denitrification to take place by controlling the pH, oxidation reduction potential (ORP), and dissolved oxygen (DO) levels in the reactor. This is because the hydrolysis of water resulting from electrical stimulation can cause changes in pH, ORP and DO gradients, which may favor or inhibit the microbial processes that drive denitrification. BER design parameters include selection of electrode materials, placement of electrodes, flow direction relative to electrode placement, HRT and current density. In fact, previous studies have shown that different reactor configurations have different nitrate removal, but optimal design required an external pH buffer to maintain pH of the water (Hao et al., 2013; Prosnansky et al., 2002; Prosnansky et al., 2005). At the field scale, pH buffer addition would likely be cost prohibitive, and thus an alternative approach is sought. In these experiments, we aimed to improve the denitrification rate without the need for extensive modifications such as creating exclusively distinct oxidizing or reducing zones using baffles. To our knowledge, no previous studies have been conducted to evaluate the effect of electrical stimulation in woodchip bioreactors. By understanding the factors affecting the denitrification rate in this simple system, we hoped to provide insight on how woodchip-BER configurations can be optimized for nitrate removal. The objective of this study is to compare the nitrate removal in woodchip BERs with control woodchip (no electrical stimulation) bioreactors. To shed light on the mechanisms that might explain differences in performance between BERs and control reactors, parameters including pH, ORP and DO were monitored. In addition to the experimental work, a preliminary TEA was conducted to understand the possibilities and limitations for full-scale BER implementation for treatment of agricultural drainage.

1.1. Theory

Denitrification is a multi-step biological process accomplished by bacterial communities capable of enzymatic reduction of nitrate to nitrogen gas. These denitrifiers require an electron donor to reduce nitrate to nitrite, and eventually to nitrogen gas. Conventionally, hydrolysis products of woodchips are used as the sole electron donor in woodchip bioreactors. As is typical for biologically mediated reactions, decreasing temperatures result in lower reaction rates (Feyereisen et al., 2016; Hoover et al., 2015). For most bioreactor processes that are not mass-transfer limited, shorter HRTs are also associated with decreasing fractional nitrogen removal in these systems (Hoover et al., 2015). By stimulating the bioreactors with electricity, additional electrons can be readily produced to enhance the denitrification processes (Prosnansky et al., 2002; Thrash and Coates, 2008). As illustrated in Fig. 1, the electrons can be transferred to the denitrifiers from cathodes in three possible ways for biological denitrification: direct electron transfer, indirect electron transfer through electroactive substrates, and indirect electron transfer through hydrolysis of water (Thrash and Coates, 2008).

Direct electron transfer from a graphite cathode to microorganisms to reduce nitrate was demonstrated using pure cultures of *Geobacter* species (Gregory et al., 2004). Furthermore, mixed-culture denitrifying microbial communities enriched from wastewater sludge have been documented to have such capabilities (Park et al., 2005; Wrighton et al., 2010). This suggests the potential of woodchip bioreactors, which employ a diverse microbial consortium (Feyereisen et al., 2016), for the removal of nitrates through direct electron transfer.

Indirect electron transfer from cathode to microorganism via electroactive substrates is also known as electron shuttling (Thrash and Coates, 2008). Without being degraded, these substrates can accept