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Review

Evaluation of energy consumption of treating nitrate-contaminated groundwater by bioelectrochemical systems

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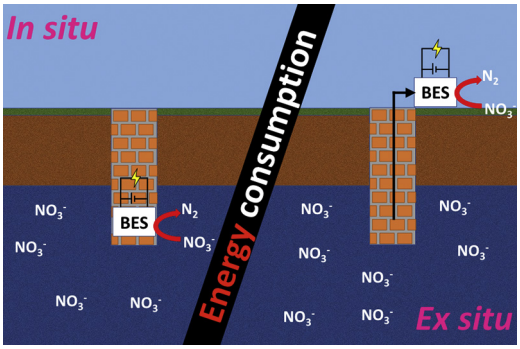
HIGHLIGHTS

- Energy consumption of groundwater denitrifying BES is analyzed.
- Four scenarios with MFC and CBD under two installations are considered.
- Extraction pump is the major contributor to energy consumption of MFC treatment.
- Power supply requires most energy demand for CBD treatment.
- The MFC treatment has much lower energy consumption than the CBD treatment.

GRAPHICAL ABSTRACT



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ABSTRACT

Nitrate contamination of groundwater is a mounting concern for drinking water production due to its healthy and ecological effects. Bioelectrochemical systems (BES) are a promising method for energy efficient nitrate removal, but its energy consumption has not been well understood. Herein, we conducted a preliminary analysis of energy consumption based on both literature information and multiple assumptions. Four scenarios were created for the purpose of analysis based on two treatment approaches, microbial fuel cells (MFCs) and controlled biocathodic denitrification (CBD), under either *in situ* or *ex situ* deployment. The results show a specific energy consumption based on the mass of NO_3^--N removed (SEC_N) of 0.341 and 1.602 kWh kg NO_3^--N^{-1} obtained from *in situ* and *ex situ* treatments with MFCs, respectively; the main contributor was the extraction of the anolyte (100%) in the former and pumping the groundwater (74.8%) for the latter. In the case of CBD treatment, the energy consumption by power supply outcompeted all the other energy items (over 85% in all cases), and a total SEC_N of 19.028 and 10.003 kWh kg NO_3^--N^{-1} were obtained for *in situ* and *ex situ* treatments, respectively. The increase in the water table depth (from 10 to 30 m) and the decrease of the nitrate concentration (from 25 to 15 mg NO_3^--N) would lead to a rise in energy consumption in the *ex situ* treatment. Although some data might be premature due to the lack of sufficient information in available literature, the results could provide an initial picture of energy consumption by BES-based groundwater treatment and encourage further thinking and analysis of energy consumption (and production).

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1. Introduction

Groundwater is a major drinking water source in many European countries and rural areas in the U.S. (Rivett et al., 2008; Rotiroti et al., 2017). The presence of nitrate in groundwater is an increasing concern for drinking water supply (Liu et al., 2005; Squillace et al., 2002; Wheeler et al., 2015). The concentration of nitrate in a contaminated groundwater due to anthropogenic activities can exceed 22.6 mg NO_3^--N L^{-1} (Matiatos, 2016), and a natural background concentration up to 3.55 mg NO_3^--N L^{-1} has also been reported (Menció et al., 2011). Excessive consumption of nitrate-contaminated drinking water can cause severe health issues such as methaemoglobinemia, and the ingestion of its reduced form - nitrite - is also dangerous for human health due to the possible formation of carcinogenic nitrosamine (Coss et al., 2004; Fan and Steinberg, 1996). Hence, U.S. EPA suggests a nitrate concentration limit of 10 mg N L^{-1} in drinking water for safety concerns (USEPA, 2010). To achieve this nitrate limit, various methods have been developed to treat nitrate-polluted groundwater. Reverse osmosis is a common method for efficient nitrate removal from groundwater, but it requires a post-treatment due to the production of brines (Epsztein et al., 2015). Adsorption has lower operational costs and its effectiveness depends on the type of adsorbent (Bhatnagar and Sillanpää, 2011). Ion exchange using resin has been widely applied for nitrate removal; a major drawback is related to the need for regeneration of the resins when their capacity of exchanging ions has ended (Twomey et al., 2010). Electrodialysis relies on the use of electricity to facilitate the ion-exchange process, and like reverse osmosis, it requires much energy input and can generate a nitrate-rich brine that needs to be treated (Koter et al., 2015).

Recently, bioelectrochemical systems (BES) have achieved promising results for nitrate removal. Microbial fuel cells (MFCs), a representative of BES, could remove 51.27 g N m^{-3} NCC d^{-1} (NCC: net cathodic chamber volume) from groundwater in their cathode while generating electricity from a low-grade anodic substrate such as wastewater (Pous et al., 2013). MFCs have achieved denitrification in the presence of a low conductivity (<1.0 mS cm^{-1}) in groundwater (Puig et al., 2012). Nitrate can also be removed from groundwater in the biocathode of a denitrifying BES coupled an abiotic anode using a power supply to create a bias between two electrodes (Prosnansky et al., 2002; Sakakibara and Nakayama, 2001) or a potentiostat to supplement electrons to the cathode (Cecconet et al., 2018; Pous et al., 2017). Biocathodic denitrification prefers a neutral pH of 7 (Clauwaert et al., 2009), and nitrate reduction could be accomplished with an extremely low hydraulic retention time of 1.2 h (Pous et al., 2017). BESs can successfully and readily adapt to a change in the influent nitrate load or concentration (Cecconet et al., 2018). Most of the previous studies on nitrate removal by BES treating nitrate-contaminated groundwater preferred an *ex situ* setup (Pous et al., 2017; Puig et al., 2012), *i.e.* groundwater has to be extracted from the aquifer before being treated above the ground. *In situ* treatment was less investigated as BES must be placed inside the aquifer/well, rendering continuous nitrate removal within the aquifer. The denitrifying performance of a buried biocathode was described by Nguyen et al. (2016), showing a deteriorated denitrification rate with the increased portion of biocathode being buried. Physical diffusion was revealed as a major mechanism in BES for *in situ* nitrate removal (Tong and He, 2014), and enhanced migration *via* generated electric field has been proved to be a possible driving force to nitrate enrichment in a bioanode where heterotrophic denitrification took place (Tong and He, 2013).

Despite promise in nitrate removal from groundwater by using BES, a key parameter - energy consumption - has not been well presented or understood. It was claimed that BES generally require low or no energy investment (Logan and Rabaey, 2012), but oftentimes energy consumption was not reported in BES studies at all. Until recently, energy consumption by BES started to be revealed *via* detailed analysis of various energy consumers during operation (Zou and He, 2018). For example, a large amount of energy would be required to power recirculation pumps (Ge et al., 2014), which are not considered in most studies. In groundwater remediation, pump-and-treat (*ex situ*) consumes a large amount of energy associated with water pumping, and this could also happen with *ex situ* BES treatment. Thus, *in situ* or *ex situ* treatment setups could render a large difference in energy consumption due to the variations in system management and nature of the treatments (Modin and Aulenta, 2017). Recovery of energy, for example bioelectricity generation in an MFC, can potentially offset some energy consumption, but such an approach has not been well investigated or analyzed.

To enable a better understanding of BES's application niche in nitrate removal from groundwater, we conducted an evaluation of energy consumption in two major types of BES, MFCs with both a biotic anode and a biotic cathode and a half cell with controlled cathodic potential for denitrification (controlled biocathodic denitrification, or "CBD" in this work), under either *in situ* or *ex situ* setup. Both energy recovery (*i.e.* electricity generation) and energy consumption (*e.g.* recirculation pumps and operational systems) were investigated. The BES performance data were obtained from published literature and the energy analysis was conducted according to our prior study (Zou and He, 2018). Due to the lack of sufficient details in the available literature, assumptions were made when necessary.

2. Analysis methods

The power needed for recirculation, feeding and extracting pumps (P, expressed in kW) was computed using the formula reported in Zou and He (2017):

$$P = \frac{Q_{pump} \times (H_{hydraulic} + H_{dynamic})}{1000 \times \eta} = \frac{v\pi d^2/4 \times (\rho g h + \rho v^2/2)}{1000 \times \eta} \quad (1)$$