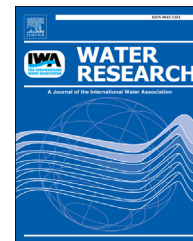




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Energy efficient reconcentration of diluted human urine using ion exchange membranes in bioelectrochemical systems

Ryan C. Tice, Younggy Kim*

Department of Civil Engineering, McMaster University, 1280 Main Street West, Hamilton, ON L8S 4L8, Canada

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ABSTRACT

Nutrients can be recovered from source separated human urine; however, nutrient reconcentration (i.e., volume reduction of collected urine) requires energy-intensive treatment processes, making it practically difficult to utilize human urine. In this study, energy-efficient nutrient reconcentration was demonstrated using ion exchange membranes (IEMs) in a microbial electrolysis cell (MEC) where substrate oxidation at the MEC anode provides energy for the separation of nutrient ions (e.g., NH_4^+ , HPO_4^{2-}). The rate of nutrient separation was magnified with increasing number of IEM pairs and electric voltage application (E_{ap}). Ammonia and phosphate were reconcentrated from diluted human urine by a factor of up to 4.5 and 3.0, respectively ($E_{ap} = 1.2$ V; 3-IEM pairs). The concentrating factor increased with increasing degrees of volume reduction, but it remained stationary when the volume ratio between the diluate (urine solution that is diluted in the IEM stack) and concentrate (urine solution that is reconcentrated) was 6 or greater. The energy requirement normalized by the mass of nutrient reconcentrated was 6.48 MJ/kg-N (1.80 kWh/kg-N) and 117.6 MJ/kg-P (32.7 kWh/kg-P). In addition to nutrient separation, the examined MEC reactor with three IEM pairs showed 54% removal of COD (chemical oxygen demand) in 47-hr batch operation. The high sulfate concentration in human urine resulted in substantial growth of both of acetate-oxidizing and H_2 -oxidizing sulfate reducing bacteria, greatly diminishing the energy recovery and Coulombic efficiency. However, the high microbial activity of sulfate reducing bacteria hardly affected the rate of nutrient reconcentration. With the capability to reconcentrate nutrients at a minimal energy consumption and simultaneous COD removal, the examined bioelectrochemical treatment method with an IEM application has a potential for practical nutrient recovery and sustainable treatment of source-separated human urine.

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* Corresponding author. Tel.: +1 905 525 9140x24802.

E-mail address: younggy@mcmaster.ca (Y. Kim).

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Nomenclature

Abbreviations

AEM	anion exchange membrane
CE	Coulombic efficiency
CEM	cation exchange membrane
COD	chemical oxygen demand
EDS	energy dispersive X-ray spectroscopy
GC	gas chromatography
IEM	ion exchange membrane
NSMEC	nutrient separation microbial electrolysis cell
MDC	microbial desalination cell
MEC	microbial electrolysis cell
MFC	microbial fuel cell
SEM	scanning electron microscopy
SRT	sludge retention time
VSS	volatile suspended solids

Symbols

D	diffusivity ($\text{m}^2 \text{s}^{-1}$)
E_{ap}	applied electric voltage to NSMEC (V)
F	Faraday constant ($96,485 \text{C mol}^{-1}$)
i	electric current (A)
R	Gas constant ($8.314 \text{J mol}^{-1} \text{K}^{-1}$)
V	volume of solution (L)
$V_{D/C}$	ratio between the diluate and concentrate volumes (–)
Λ	equivalent ionic conductivity ($\text{m}^2 \text{S mol}^{-1}$)
z	ionic charge (–)

Subscripts

C	concentrate (solution that gets concentrated in NSMEC)
D	diluate (solution that gets diluted in NSMEC)

1. Introduction

Human urine is known to contribute 80% of the nitrogen (N) and 50% of the phosphorus (P) in domestic wastewater (Larsen et al., 2009; Maurer et al., 2006). In municipal wastewater treatment, high nutrient levels require relatively expensive nutrient removal processes. Long sludge retention times (SRT > 10 d) are necessary for nitrification in activated sludge, consuming additional electric energy for return sludge and aeration. In addition, phosphorus removal by precipitation requires an extra cost for ferric or aluminum chemicals. Biological denitrification and phosphorus removal also necessitate large volume reactors to establish anoxic and anaerobic conditions and a large pumping capacity for internal recycle of wastewater. Such extra costs for nutrient removal can be greatly reduced or even eliminated in wastewater treatment if human urine is separated at the source level (Maurer et al., 2006). Source separation of urine also enables effective recovery of nutrients as valuable raw materials, e.g., struvite (MgNH_4PO_4) and gaseous ammonia (NH_3) (Kuntke et al., 2012; Udert et al., 2003a, 2003b).

Even with the beneficial aspects, several key challenges exist for practical recoveries of nutrients from source-separated urine. One significant challenge is the dilution with large amounts of flushing water at urinals and toilets, substantially decreasing nutrient concentration. Even though specialized urinals or toilets have been suggested and developed to minimize the amount of flushing water, a certain degree of dilution is still necessary to prevent precipitation and clogging problems in collection systems. Rapid hydrolysis of urea substantially increases pH and high pH conditions induce precipitation of insoluble struvite salts on the surface of collection pipes (Udert et al., 2003a, 2003b). Therefore, source separated urine should be diluted below the solubility limit of struvite (or other minerals) for sustainable maintenance of urine collection systems. For efficient recovery of nutrients the collected urine needs to be reconcentrated above the solubility limit of struvite at a centralized treatment facility. In addition, if source-separated urine is directly used as a liquid fertilizer, a reconcentration step will substantially reduce required liquid volume for land applications. Reconcentration or separation of nutrients from human urine can be achieved by various treatment processes, such as evaporation, freeze thaw, reverse osmosis and electrodialysis as previously demonstrated (Maurer et al., 2006; Pronk et al., 2006a).

Since the technologies currently available require relatively high energy consumption, this study aims to demonstrate energy efficient reconcentration of nutrients from diluted urine using energy released from oxidation of organic substrates in microbial electrolysis cells (MECs). In MECs, exoelectrogenic bacteria oxidize organic substrates and transfer electrons to the anode. Water is reduced to H_2 in water electrolysis at the cathode with a small external voltage application ($E_{ap} > 0.14$) (Liu et al., 2005a; Logan et al., 2008; Rozendal and Buisman, 2005; Rozendal et al., 2006). These coupled electrode reactions create an electric field that induces ionic transport between the electrodes. By schematically placing ion exchange membranes (IEMs) between the electrodes, nutrient ions (NH_4^+ and HPO_4^{2-}) can be reconcentrated from diluted urine (Fig. 1A). Thus, energy efficient nutrient reconcentration can be achieved as the oxidation of organic substrates at the anode partially contributes energy required for ionic separation through IEMs. This design principle was originally adopted from microbial desalination cells (MDCs) for desalination of seawater and brackish water (Cao et al., 2009). To our knowledge, none of the previous studies have applied the principle of MDCs in reconcentrating nutrient ions from diluted human urine. One of the important differences of this application with diluted urine from MDCs is the urine composition. High concentrations of organic substrates and sulfate ions induce substantial sulfate reducing bacteria activity. Also, organic substrate removal is simultaneously achieved with nutrient reconcentration with the same urine solution, requiring a different urine flow configuration from the previous stacked MDC designs (Chen et al., 2011; Kim and Logan, 2011). In addition, the target ions for reconcentration are restricted to only NH_4^+ and HPO_4^{2-} from diluted urine while MDCs do not have specific target ions for separation. Thus, unlike previous MDC studies, competitive separation of nutrient ions vs. other common ions (e.g., Na^+ , Cl^- , SO_4^{2-}) is an important aspect in this study.

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