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Review

Resource recovery from landfill leachate using bioelectrochemical systems: Opportunities, challenges, and perspectives

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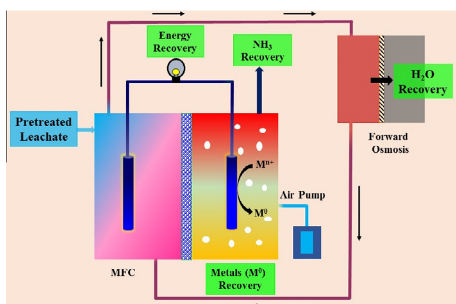
HIGHLIGHTS

- Resource recovery from leachate is critical to its sustainable management.
- Bioelectrochemical systems can be used for resource recovery from leachate.
- Energy is recovered from oxidation of organic contaminants.
- Nutrient and metals may be recovered through ion transport driven by current.
- High-quality water can be recovered by forward osmosis integrated with BES.

GRAPHICAL ABSTRACT



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ABSTRACT

Landfill leachate has recently been investigated as a substrate for bioelectrochemical systems (BES) for electricity generation. While BES treatment of leachate is effective, the unique feature of bioelectricity generation in BES creates opportunities for resource recovery from leachate. The organic compounds in leachate can be directly converted to electrical energy through microbial interaction with solid electron acceptors/donors. Nutrient such as ammonia can be recovered via ammonium migration driven by electricity generation and ammonium conversion to ammonia in a high-pH condition that is a result of cathode reduction reaction. Metals in leachate may also be recovered, but the recovery is affected by their concentrations and values. Through integrating membrane process, especially forward osmosis, BES can recover high-quality water from leachate for applications in landscaping, agricultural irrigation or direct discharge. This review paper discusses the opportunities, challenges, and perspectives of resource recovery from landfill leachate by using BES.

1. Introduction

Landfilling is a widely applied method for disposing municipal solid waste (MSW) (Zhang et al., 2008). During the stabilization in a landfill, liquid waste – leachate is produced from the dynamic degradation of wastes and infiltration of water to landfill mainly from precipitation (Damiano et al., 2014; Ganesh and Jambeck, 2013). Leachate is a complex wastewater with high pollution potential resulting in major environmental problems such as soil and groundwater pollution and human health risks (Kjeldsen et al., 2002; Renou et al., 2008). Young landfill leachate can have a relatively high BOD_5/COD ratio (0.4–0.6) indicating good bioavailability (Ozkaya et al., 2014); however, this biodegradability decreases with time because of organic degradation within the landfill (Calli et al., 2005; Renou et al., 2008). Leachate contains

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ammonium nitrogen with a concentration from 500 to 2000 mg L^{-1}, and a low amount of total phosphorous (Kjeldsen et al., 2002; Tatsi and Zouboulis, 2002). Due to the presence of high concentrations of inorganics and metal ions, leachate has a high electrical conductivity (Lin and Chang, 2000). Common metals present in the landfill leachate include Iron, Manganese, Zinc, Cadmium, Copper, Nickel, Silver, and Lead, but their prevalence is specific to the landfill (Deng et al., 2013; Harmsen, 1983; Kjeldsen et al., 2002). The composition of leachate is affected by many factors including waste types, precipitation variation, soil condition of the landfill site, and landfill age (Christensen et al., 2001; Renou et al., 2008).

The methods/technologies for treating landfill leachate have been well reviewed before (Renou et al., 2008). Those methods/technologies can effectively treat leachate for removing some of the key contaminants. However, there are also challenges associated with those methods, especially to meet the need for sustainable leachate management that desires minimal input of energy and chemicals for treatment and maximized recovery of valuable resources. For example, physicochemical treatment processes (e.g., coagulation, flocculation, adsorption, membrane filtration, etc.) are energy and capital intensive because of costs of chemicals, oxidants, and membranes (Ahn et al., 2002; Kurniawan et al., 2006); biological treatment processes (e.g., activated sludge, trickling filter, ponding, etc.) are limited by treatment effectiveness, energy requirement, and a large amount of secondary sludge (Kargi and Pamukoglu, 2003; Loukidou and Zouboulis, 2001); and electrochemical treatment processes are electricity intensive (Deng and Englehardt, 2007; Fernandes et al., 2015). Leachate contains organic compounds that can be converted into electricity by anaerobic digestion, but this approach requires proper maintenance of generators and purification of biogas (Larson, 1993; Tafdrup, 1995).

Leachate has been studied as a substrate for bioelectrochemical systems (BES). BES employs biological and electrochemical reactions to generate electricity, remove contaminants, and recover resources from a wide range of substrates (Kelly and He, 2014; Pant et al., 2010). Among various BES that have been developed, microbial fuel cells (MFC) are most commonly studied. In an MFC, anaerobic degradation of organic matter releases electrons to an anode electrode, which transfers those electrons to a cathode electrode for reducing a terminal electron acceptor (e.g., O_2); to maintain charge neutrality, ions simultaneously migrate between the anode and the cathode (Logan et al., 2006; Rabaey and Verstraete, 2005). To overcome the thermodynamic barrier of certain reducing reactions (e.g., proton reduction), an external voltage can be applied to an MFC, which is then converted to microbial electrolysis cells (MEC) (Logan et al., 2008; Zhang and Angelidaki, 2014). When an additional chamber is added to the MFC to facilitate ion separation, a microbial desalination cell (MDC) can be created (Saeed et al., 2015; Sevda et al., 2015). More information about BES can be found in various review papers (Kelly and He, 2014; Sleutels et al., 2012; Wang and Ren, 2013).

Leachate has some characteristics that could give it a great potential for resource recovery using BES. For example, the high electrical conductivity of leachate (Lin and Chang, 2000) makes it favorable for electricity generation (energy recovery) in BES (Damiano et al., 2014). It contains a high concentration of ammonium nitrogen, which may be recovered for agricultural application. Landfill leachate also contains a number of metals, which can be recovered by employing BES. To reduce the leachate volume, water may be recovered by using osmotic processes (Dong et al., 2014). Therefore, resource recovery will help accomplish a sustainable leachate management system. Although BES have been studied for leachate treatment (Wu et al., 2015), resource recovery was not well addressed in the past research. The objectives of this review paper are to discuss the opportunities for resource recovery from leachate using BES, analyze the challenges associated with the recovery, and present the perspectives for future research and development.

2. Current status of landfill leachate treatment with bioelectrochemical systems

The previous studies of using BES to treat leachate have focused on the removal of organic matter and nitrogen and the generation of bioelectricity. The organic removal by BES varies from 40% to over 80% (Ozkaya et al., 2013; Zhang et al., 2015a), and the low bioavailability of landfill leachate appears to be a great challenge (Kjeldsen et al., 2002; Zhang and He, 2013). Proper pretreatment of leachate could significantly improve biodegradability of organics. For example, pretreatment using fermentation resulted in fifteen times increase in organics removal in an MEC treating landfill leachate (Mahmoud et al., 2014). A few studies have investigated nutrient removal from leachate such as ammonia nitrogen, nitrate, nitrite, and phosphorus. Ammonia removal was reported to be from 0% to over 90%, affected by insufficient retention time, absence of beneficial microorganisms, electricity generation, etc. (Ganesh and Jambeck, 2013; Kim et al., 2008; Zhang et al., 2015a). Substantial removal of phosphorus from leachate was reported in an air cathode MFC, but the removal mechanism was not clear (Damiano et al., 2014). With leachate as an anode substrate, BES produced a maximum power density as high as 12.8 Wm^{-3} (current density 41 Am^{-3}) (Zhang et al., 2008). Energy recovery is generally not reported, and only one study presented the energy production of 0.00190 kWh per kg of COD from landfill leachate (Zhang and He, 2013).

The BES performance treating landfill leachate is affected by many factors including, electrode surface area (Galvez et al., 2009), hydraulic retention time (HRT) (Greenman et al., 2009; Puig et al., 2011), leachate dilution factor (Galvez et al., 2009; Puig et al., 2011), mode of operation (Ganesh and Jambeck, 2013; Greenman et al., 2009), electrode catalysts (Ganesh and Jambeck, 2013), organic loading rate (Zhang et al., 2008), reactor configuration (Wu et al., 2015), inoculation (Greenman et al., 2009), etc. More information about the past BES research treating leachate can be found in a recent review paper (Wu et al., 2015). Those prior studies have collectively demonstrated that landfill leachate can be used as a substrate for electricity generation in BES, and degradation of organic matter or nutrient removal occurs to a certain degree. However, they focused on the removal, instead of recovery that is important to sustainable leachate treatment. Despite the report of electricity generation, only one study has presented energy performance, which is critical to understanding energy recovery from leachate. As stated previously, leachate contains a wide range of resources such as energy, nutrients, metals, and water, which can be potentially recovered, thereby improving the sustainability of leachate treatment. In the following, the opportunities, challenges, and perspectives of recovering energy, nutrient, metals, and water from leachate using BES are discussed and analyzed.

3. Resource recovery from landfill leachate using BES

3.1. Energy recovery

Leachate contains a large amount of organic compounds that can be used to generate electricity in BES. The produced electrical energy may be used to offset the energy consumption by the treatment system, thereby realizing an energy-efficient method for leachate treatment. Although leachate can be treated by anaerobic