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Energy production from waste: Evaluation of anaerobic digestion and bioelectrochemical systems based on energy efficiency and economic factors☆

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ABSTRACT

Anaerobic digesters (AD) and bioelectrochemical systems (BES) are becoming increasingly popular technologies for the generation of renewable energy from wastes. Synergies between these technologies exist, however, configurations to couple them have been insufficiently investigated. This study compares the theoretical energy efficiencies of converting waste directly into electricity, using AD and BES alone and in various combinations. This study reviews the experimentally demonstrated energy efficiencies reported in the literature with comparisons to the maximum theoretical efficiencies, considering thermodynamic limits. Acetate is used as an ideal substrate for theoretical calculations, whereas complex wastes are used for extended analyses of practical efficiencies. In addition, to evaluate the economic potential of this technology, a brief case study was conducted using the Oak Ridge National Laboratory (ORNL) water resource recovery facility (WRRF). Sensitivity analysis was performed on several parameters in the economic model. The results of this study indicate the combined Anaerobic Digester/Microbial Electrolysis Cell (ADMEC) process may be the best path forward due to the high energy efficiency, combined with potential economic benefits, but is not at commercial readiness. We estimate energy efficiencies of 52.9% and 45.6% for the ADMEC process, using current state-of-the-technology, for converting food waste and sewage sludge to a CH_4/H_2 mix, respectively. This study concludes with a discussion of new strategies to improve the energy efficiency of AD and BES processes.

Significance: The analysis performed in this study supports the implementation of anaerobic digestion with bioelectrochemical systems for the production of energy from complex wastes. The energy efficiency analysis alludes to research areas that should be pursued to maximize the performance of these technologies in large-scale installation, based on the performance gaps between theoretical and practical energy efficiencies determined in previous studies.

Abbreviations: AD, Anaerobic Digestion; ADMEC, Anaerobic Digestion & Microbial Electrolysis Cell; ADMFC, Anaerobic Digestion & Microbial Fuel Cell; AOP, Advanced Oxidation Process; BES, Bioelectrochemical System; BOD, Biochemical Oxygen Demand; CE, Coulombic Efficiency; CCE, Cathode Conversion Efficiency; COD, Chemical Oxygen Demand; E_x, Energy, for a particular process x; η_x, Eta, energy efficiency for a particular process x; HE, Hydrogen Efficiency; HRT, Hydraulic Residence Time; I_x, Current, for a particular process x; MEC, Microbial Electrolysis Cell; MFC, Microbial Fuel Cell; MGD, Million Gallon per Day; MSW, Municipal Solid Waste; NPV, Net Present Value; OLR, Organic Loading Rate; ORNL, Oak Ridge National Laboratory; O&M, Operation and Maintenance cost; PEMFC, Proton exchange membrane fuel cell; TS, Total Solids; V_x, Voltage, for particular process x; WRRF, Water resource recovery facility; WWTP, Wastewater Treatment Plant; Y_{H2}, Hydrogen Yield

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1. Introduction

The strong international dependence on fossil fuels for energy generation and the sensitive relationship between water and energy requires new energy technologies to perform at high standards while utilizing natural resources in an environmentally and socially responsible way [1]. In the US, fossil fuels provide 77.5% of the primary energy supply, however food wastes, sewage sludges and other wastes represent an underutilized renewable feedstock for the production of electricity, hydrogen gas, biomethane, and biochemicals that can be used to offset fossil fuel demand [2–6]. Municipal solid waste (MSW) is one of the potential sources of energy with over 60% containing organic material, including paper and paperboard. The food waste fraction alone (14.6% of total MSW) is produced at a rate of 33.5 billion kilograms (10^{12} g or Tg) per year by individuals, with an additional 27 billion kilograms generated by retailers [7,8]. In terms of chemical oxygen demand (COD), food waste represents a resource of 24.4 billion kilograms of COD per year [9]. Landfilling is the most common method of food waste disposal (~54%) but composting, incineration, anaerobic digestion, gasification, combustion, torrefaction, and pyrolysis are also used [3,7,10–12].

Similarly, wastewater sludge generated during the treatment of domestic and industrial wastewater represents a second potential energy resource. In the US, the effluent standards for secondary wastewater treatment are 30 mg/L Biochemical Oxygen Demand (BOD) [13]. In the US, each person produces approximately 80 g of sewage solids per day which are treated in water resource recovery facilities (WRRFs), leading to a production rate over 9 billion kilograms per year, which is equivalent to 13.40 billion kilograms of COD per year. [14]. Conventional disposal methods for sewage sludges include anaerobic digestion, fermentation, gasification, incineration, and pyrolysis [15–17]. A summary of the energy resources provided by food waste and sewage sludge is provided in Table 1. Many of the disposal methods for food waste and sewage sludges rely on thermochemical processes, but these are typically less energy efficient, due to high moisture content [18].

In contrast, biological processes represent a group of technologies capable of generating energy from waste without the need to reduce moisture content. Anaerobic digestion (AD) represents a mature biological treatment process but more recently, bioelectrochemical systems (BES) have been proposed to treat sewage sludge and other substrates, such as food waste, in addition to anaerobic digestion [19–21]. Furthermore, the biological treatment processes used in this study have the potential to eliminate the need for aerobic treatment, a common component of the conventional water treatment process, which consumes upwards of 1.5% of total electricity demand in developed countries [15,22–24]. AD and BES can be integrated into waste treatment processes to establish net-energy positive treatment facilities [23,25,26].

Anaerobic digestion (AD) is a robust, mature bioconversion process that can utilize both food waste and sewage sludge as substrate [10,15]. Methane produced during AD can be converted into electricity and heat, which can be used to offset energy use in MSW facilities and WRRFs. To supplement the performance of AD, it has been proposed that bioelectrochemical systems (BES) can be used as a secondary treatment stage [19]. Two BES technologies are considered in this study, microbial fuel cells (MFC) and microbial electrolysis cells (MEC). MFCs produce electricity directly from waste and MECs produce hydrogen gas. However, large differences are observed in the performance of these systems at small vs. large scale due to increases in electrochemical losses with scale, engineering issues like reactor dead space, diffusion limitations, and high internal resistances [30,31]. A review of laboratory and pilot systems was reported in Janicek et al., which states that the performance of milliliter scale systems do not directly translate to larger scales [30]. Interest in MECs has increased significantly in the past few years due to its ability to produce hydrogen and its operational advantages over MFCs [21,31]. A review of small and large-scale MECs was also reported by Escapa et al., which concludes that MECs are an immature technology facing several barriers, such as large capital costs and hydrogen management, but show promise from recent pilot scale studies and offer unique benefits, such as mediating electrical and gas grids and utilizing a wide range of organic substrates [31]. A summary of notable AD and BES studies referenced in this report are shown in Table 2.

Previous publications have reported on the principles that outline AD and BES processes, however the focus is often only on theoretical performance [3,6,32,33–35]. While these reviews are useful for demonstrating fundamental concepts for these technologies, there is a failure to address the expected performance of these technologies with complex substrates, which is required for the planning of these systems in the real world. This report proceeds in four parts: 1) an evaluation of theoretical energy efficiency and performance based on acetate as an ideal substrate, 2) a review of the state-of-the-art technology used for anaerobic digestion (AD), microbial fuel cells (MFCs), and microbial electrolysis cells (MECs) at laboratory and pilot scales, 3) estimation of energy efficiency and performance using complex wastes at large scales, and 4) calculation of potential economic, using ORNL WRRF as a case study. This WWRF has an average daily capacity of 0.2 MGD (757 m^3/d) with an average incoming COD of 300 mg/L. To address the flexibility of these technologies, in part 3, we will investigate AD and BES technologies as standalone and integrated processes (Fig. 1). The goal of this study is to investigate a group of bioconversion systems capable of maximizing the energy recovery from abundant waste streams. The study concludes with a discussion of the energy efficiency losses and current methods available to reduce the gap between theoretical and practical efficiencies.

The energy efficiency results of this study suggest that an integrated ADMEC system has potential to be implemented as an energy-positive water treatment system. However, the economic analysis shows there are several system components that must be improved in order to see positive economic returns, at least within the constraints of this case study. Biodegradability of substrate is the most significant variable, in terms of influencing energy efficiency and economic return. The discussion section includes strategies to improve the biodegradability of substrate. Pretreatment of the organic substrate prior to processing is our recommendation to improve the efficiency and economic potential of a combined anaerobic digester and bioelectrochemical system.

2. Description of system and calculations for efficiency and economic analysis

2.1. Calculation of energy efficiencies

The energy efficiencies of AD and BES systems were evaluated for multiple substrates, including acetate as an ideal substrate and food waste and sewage sludge as complex substrates. Fig. 1 illustrates the configurations used to investigate acetate, food waste, and sewage sludge as energy sources. In order to compare the different processes, a common end-product is necessary. Electricity was chosen as the

Table 1
Summary of food waste and wastewater energy content and energy recovery.

Waste Type	Resource Energy Content				
	Energy Content (kWh/kg COD)	Mass of Resource (billion kg COD)	Energy Resource (billion kWh)	Mass per Person (kg per person)	Energy per Person (kWh per person)
Food Waste	2.95	24.40	71.98	76.25	224.94
Sewage Sludge	4.08	13.40	54.67	41.88	170.84

References: [27–29].