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Effective control of biohythane composition through operational strategies in an innovative microbial electrolysis cell

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HIGHLIGHTS

- Biohythane is successfully produced from a scaled microbial electrolysis cell.
- Anolyte recirculation rate significantly affects the biohythane composition.
- External resistance influences the composition via affecting hydrogen production.
- Hydraulic retention time impacts the organic removal performance.

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ABSTRACT

Biohythane is a renewable energy fuel composed of methane and hydrogen gas at a certain ratio. Microbial electrolysis cells (MECs) have been employed to produce biohythane but the composition of the produced gas is not well controlled. Herein, an innovative MEC system was developed at a large scale of 19 L to investigate biohythane production affected by operational factors. The goal was to understand the interaction between operation and performance towards the development of effective strategies for controlling biohythane composition. To achieve this goal, the performance of this MEC system was studied by varying the key operational factors including anolyte recirculation rate, external resistance, and hydraulic residence time (HRT). It was found that the optimized operational condition for this MEC system included the anolyte recirculation rate of 800 mL min^{-1}, external resistance of 1 Ω, and HRT of 24 h. This condition led to the biohythane production of 0.64 ± 0.06 L day^{-1} with 16.5% H_2 proportion and positive net energy recovery of 1.52 ± 0.19 kW h day^{-1}. The ANOVA test indicated that the anolyte recirculation rate significantly impacted the methane production rate while the external resistance strongly affected the proportion of hydrogen gas in biohythane. HRT had a minor effect on the biohythane composition but could significantly influence organic removal rate. This is the first study that attempted to use operational factors to control biohythane composition, and its results will provide important implications to formulate control strategies for biohythane production and to scale up MEC systems towards practical applications.

1. Introduction

Fossil fuels (e.g., gasoline, diesel, and compressed natural gas) are commonly recognized for their potential problems of limited storage, strong greenhouse effect (e.g., emission of carbon dioxide), and environmental pollution [1,2]. Despite the discovery of new fossil fuel like shale natural gas, both rapid growth of worldwide population and improved living standard have created an increasing demand for energy. Thus, alternative and renewable fuel is of strong interest and importance to address global energy crisis. Among various renewable energy sources, bioenergy from wastes is considered sustainable because of simultaneous waste treatment and resource recovery [3]. It has been practiced for a long time to produce methane gas from organic wastes via anaerobic digestion. When adding hydrogen gas into methane gas, a new gas fuel - biohythane is created. Biohythane, which is composed of hydrogen (volume ratio: 10–25%) and methane (volume ratio: 75–90%), is a promising alternative to the traditional fossil fuel because of its higher fuel and heat efficiency [4,5]. The addition of hydrogen gas can reduce carbon emission, increase burning speed, extend flammability range, and enhance combustion efficiency to assist methane combustion in the car engines [3,6–8].

Biohythane is mainly produced from the renewable biomass, and

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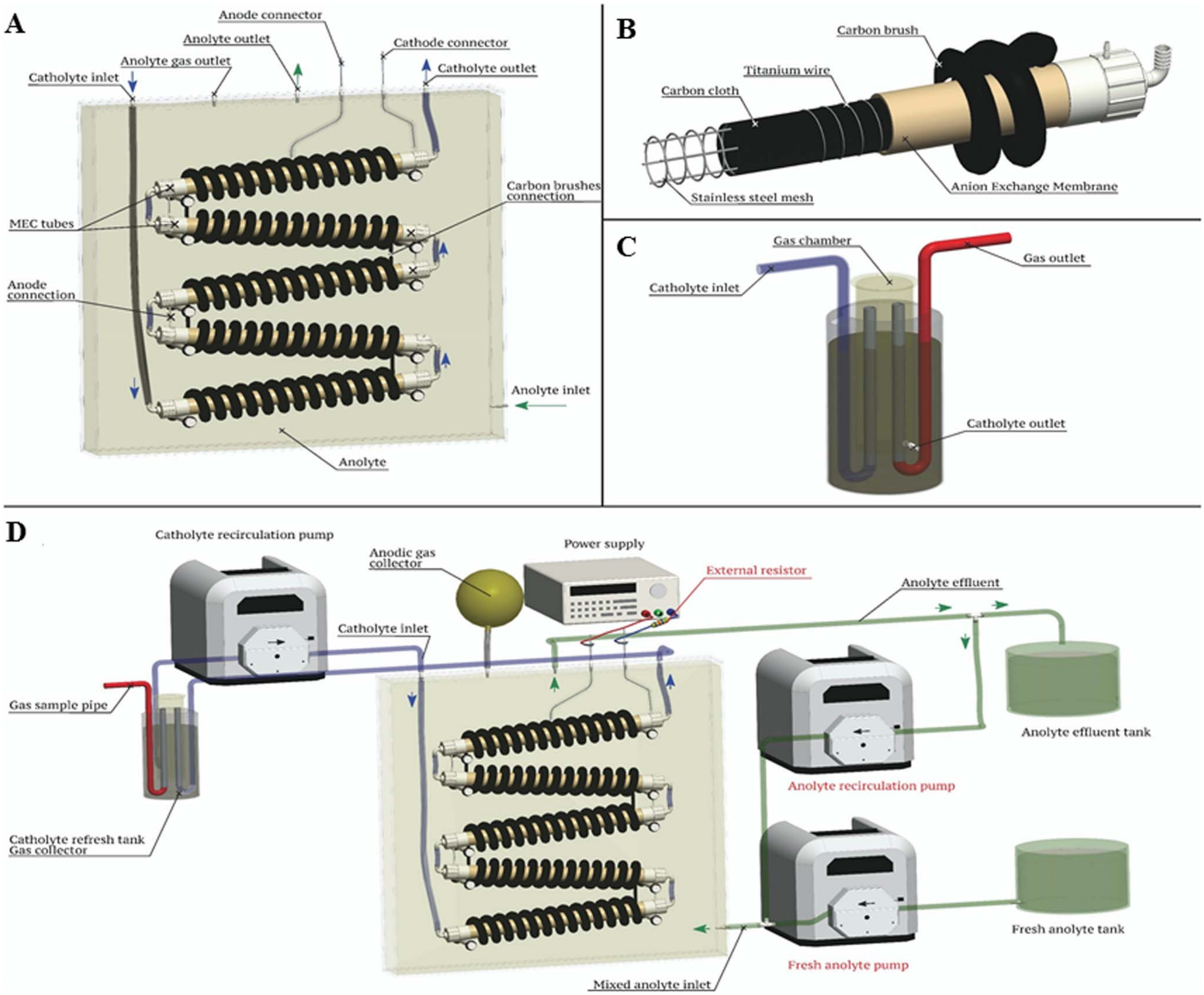

Fig. 1. Schematic diagram of the MEC in this study: (A) structure and components of the MEC reactor; (B) internal structure of the cathode and installment of carbon brush (anode material) surrounding cathode; (C) cathode gas collection; and (D) the whole setup of the experiment.

the traditional method is to use anaerobic digestion [9]. Both acidogenesis and acetogenesis are involved in hydrogen production, while methanogenesis produces methane [9,10]. In this way, biohythane can be produced from agricultural and food wastes [9,11]. However, in a single-phase digestion reactor, the produced hydrogen gas can be easily consumed by the methanogenic populations, and thus hydrogen production will be limited [9]. To solve this problem, a two-phase digester system was employed to separate acidogenesis/acetogenesis and methanogenesis, leading to a higher energy yield than that of the single-phase process [9]. Hydrogen production from an anaerobic digester has a low conversion efficiency, reported to be only ~17% (2 mol hydrogen/mol glucose) [12]. In addition, the complex substrates will cause the unpredictable change in the microbial consortia during the fermentation process, and ultimately lead to the significant variation of the hydrogen proportion in biohythane (from 1 to 75%) [6]. This variation presents a great challenge to achieve stable combustion performance in the automobiles [6,7], because a stable hydrogen proportion is needed to guarantee high combustion efficiency. For example, 16.5% hydrogen content in biohythane was reported to achieve the highest combustion efficiency [13]. Therefore, a method for producing biohythane with effective control of hydrogen proportion will be needed.

Microbial electrolysis cells (MECs) have been studied to produce biohythane from organic wastes [14]. MECs are an emerging technology that can use exoelectrogenic bacteria to degrade organic compounds in wastewater and accomplish hydrogen evolution reaction (HER) for hydrogen production with a small applied voltage (0.4–0.8 V) [15–17]. MECs could achieve a higher hydrogen yield than the traditional fermentation with stronger controllability by electricity generation [18]. It was reported that the fermentation effluent could be further treated by an MEC, to achieve a total hydrogen yield up to 81% (9.6 mol hydrogen/mol glucose) [12]. The maximum hydrogen production rate in a bench-scale MEC could reach as high as 50 m^3 m^{-3} MEC reactor day^{-1} [19]. In the presence of methanogens, either in the anode or the cathode of an MEC, methane can be produced from organics (anode) or hydrogen gas (cathode). A single-chamber MEC with Ti/Ru electrodes was reported to increase the hydrogen and methane production by 1.7–5.2 and 11.4–13.6 folds, respectively, compared to the traditional anaerobic digester [20]. It has been reported that a single-chamber MEC could successfully produce biohythane, with a higher production rate (0.083 L methane L^{-1} reactor and 0.006 L hydrogen gas L^{-1} reactor) than traditional anaerobic digesters (0.064 L methane L^{-1} reactor and 0.005 L hydrogen gas L^{-1} reactor) [14], However, the drawbacks of this single-chamber MEC are also obvious. For example, the co-existence of methanogens and hydrogen-producing bacteria in the anode would convert the produced hydrogen gas to methane in a long-term operation and thus reduce the hydrogen