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Advances in microbial fuel cells for wastewater treatment

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ABSTRACT

Resources scarcity and electricity demand have been dramatically increasing. Wastewater is recognized as one of resources for water, energy and plant fertilizing nutrients. Nevertheless, current wastewater treatment technologies have limitations due principally to their energy- and cost-intensive for achieving the conversion target of wastewater recovery. It is desired to develop a new technology to generate alternatives to conventional energy sources in a sustainable manner. An innovative technology based on the use of microbial fuel cells (MFCs) has been proved as a critical pathway for bioconversion processes towards electricity generation, then for addressing energy and environmental problems. Three special features including energy saving, less sludge production and less energy production make MFCs outstanding compared with the existing technologies. Multiform wastewaters could be efficiently degraded through advancing MFCs alone or integrating MFCs with other processing units. However, the low power density and the high operating cost of MFCs have greatly limited their applications on large-scale problems, and then result in some debates and doubts about their development and applications. Therefore, this paper objectively discussed the problems and applications of MFCs in wastewater treatment. Moreover, the integration of MFCs with other treatment processes was presented to verify the practicality and effectiveness of MFCs in contaminants removal. Furthermore, the primary challenges and opportunities for scaling-up and future applications of MFCs in wastewater were analyzed.

1. Introduction

Wastewater is now being considered as one of resources for water, energy and plant fertilizing nutrients [1–3]. Current wastewater treatment technologies, however, have multiple limitations as a result of their incapability of achieving these conversion targets. For example, conventional aerobic activated sludge (CAAS) treatment systems are commonly characterized by energy intensive, large quantities of residuals generation, and incapability of recovering the potential resources available in wastewater. As reported, in the US, approximately 0.5 kWh/m^3 was required for a typical domestic wastewater treatment plant employing aerobic activated sludge treatment and nearly 3% of the total electricity consumption was consumed by wastewater treatment [4]. Anaerobic digester (AD) is usually regarded as a crucial technology using wastewater as an energy source, and it can effectively convert organic content into methane (CH_4) gas that can be turned to electricity by CH_4-driven engines or chemical fuel cell. Unfortunately, some reports have confirmed that AD was inefficient in capturing the energy potential of wastewater. The treated wastewater was consequently far from sufficient to meet stringent regulatory standards, and the post-treatment step was indispensable in terms of technically demanding. More seriously, CH_4 is recognized as a powerful greenhouse gas with a global warming potential about 25 times that of CO_2 so that must be strictly controlled to escape to the atmosphere [5–8]. Furthermore, water reuse has already been widely practiced, especially in some dry areas, but it invariably requires more energy for treatment, principally arising from the increased water quality requirements for reuse.

Microbial fuel cells (MFCs) have been demonstrated as a promising and challenging technology in addressing energy and environmental issues particularly in remote areas [9–12], which are equipped with biosensors, biohydrogen production, as well as in-situ power source for bioremediation and wastewater treatment. Generally, five advantages make MFCs more sustainable when implemented in wastewater treatment: (1) the direct conversion of substrate energy to electricity; (2) less excess activated sludge compared to the processes of AD and CAAS; (3) insensitive to operation environment, even at low temperatures; (4) without any gas treatment; (5) without any energy input for aeration; (6) a widespread application in locations with insufficient electrical infrastructures.

Although the current applications of MFCs are still at lab-level, they have been proved to be of great potential industrial applications [13–

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17]. Firstly, the revealed of network of nanowire, cytochromes, and/or some conductive proteins in the extracellular polymeric matrix have improved the understanding of the mechanism of electron transfer. Secondly, the novel design and architecture of reactor has been constantly developed. Thirdly, the volume of the reactor has been enlarged to ten-liter and the operation time has been extended to years. Fourthly, multiform integration processes have been proposed to accelerate the applications of MFCs in wastewater treatment. Finally, the wastewaters investigated in MFCs range from human feces to heavy metal.

Therefore, the objective of this paper aims to objectively discuss the problems and applications of MFCs in wastewater treatment. Moreover, the integration of MFCs with other treatment processes is presented to verify the practicality and effectiveness of MFCs. Furthermore, the challenges and opportunities for scaling-up and future applications of MFCs in wastewater treatment are summarized at the end of this paper.

2. General features of the MFC

In a general MFC, it is critical to simultaneously metabolize substrates and exchange electrons with an electrode based on electrochemically active microorganisms. In anode, anaerobic respiring bacteria can efficiently degrade organic matter into carbon dioxide as end product, while electrons and protons can be generated. The produced electrons are transferred to the anode by bacteria through an external circuit. Current and protons are then generated and move between the electrodes to maintain electro neutrality. Actually, the conventional MFC is normally half biological, since only the anode side contains electrochemically-active microorganisms while the cathode is abiotic. In cathode, oxygen, ferricyanide, and hydrogen peroxide are primarily served as the terminal electron acceptor. Among them, oxygen is considered as the most suitable terminal electron acceptor due mostly to its sustainability and amount, especially for the air-cathode MFCs. The air-cathode normally consists of catalyst layer, electrode and separator. Besides, separator plays an increasingly paramount role in MFCs as compared with catalytic and electrode materials, which not only increases the internal resistance but also decreases the MFCs' performances, thus severely limits the practical applications of MFCs. Moreover, many previous efforts have focused mostly on advanced abiotic catalysts materials to improve rate of oxygen reduction reactions, but they are still costly when applied in MFCs, largely resulting from that the power and current densities in MFCs are relatively lower as compared with conventional fuel cells. In comparison, biocathodes can be selected as an attractive alternative rather than abiotic catalysts, in which bacteria are used as biocatalysts on cheap carbon cathodes. Although biocathodes are superior to abiotic cathodes, there are still few studies pertaining to metabolic mechanism of biocathodes. Thus, more fundamental researches in terms of the biocathodes are urgently required.

As reported, the design and architecture of MFCs could directly decide their applications in wastewater treatment [18]. For example, Logan and Regan [19] have pointed out that the most significant block achieving high power densities in MFCs was the system architecture, not the composition of the bacterial community. Indeed, numerous studies have shown that the performances of MFCs with mixed inoculation would be better than that with pure culture inoculation in both power density and contaminants removal efficiency. The complex natures of many waste biomass sources need a diverse microbial community to effectively degrade the various organic components. The design, characterized by easily scale-up, low cost, high performance and conveniently combined with the existing wastewater treatment facilities, would promote the commercialization of MFCs. Currently, the MFCs are still at lab-level, but some ingenious designs have been developed to incorporate/embed MFCs into other wastewater treatment processes. Actually, the energy output from MFCs is too low to meet an energy-neutral operation at practical scales, and the related cost is high both in capital and operation. Long-term stability would be another huge challenge for researchers along with the solution of power output and cost. All of these have made MFCs competitively unfavorable. In order to accelerate the progress of MFCs in wastewater treatment, it has been considered as a feasible strategy by integrating MFCs with other processes [20].

Generally, there are three outstanding features of the MFC in wastewater treatment, including energy saving, less sludge production as well as less energy production. Many researches have explored the capacity for treating different wastewaters. It has been demonstrated that the MFCs were able to remove multi contaminants, such as biological wastes, heavy metals, polyalcohol, petroleum products dyes, Phenol and phenolic compounds, furan, quinolone, pyridine derivatives [21]. However, for putting MFCs into practice, their performances must be investigated with real wastewater.

3. Performances of the MFCs in actual wastewater treatment

3.1. Municipal or domestic wastewater

Municipal or domestic wastewater not only includes a deal of feedstock but also generates a multitude of pollutants, which can be used in MFCs for electricity generation because of the reduced toxicity [22–24]. Table 1 presents some applications of MFCs in municipal wastewater [25–32]. Besides, the activated sludge from conventional aerobic treatment process is extremely large [33–35]. The operation costs for sludge at sewage treatment plants usually share more than 50% of total management investments [36]. Consequently, the total costs for wastewater treatment can be significantly reduced by decreasing the sludge treatment costs. Moreover, the sludge often contains high levels of organics (suggested by about 66%) collected from wastewater treatment plants [37].

3.2. Agricultural wastewater

Agricultural decision makers put more emphasis on animal manures wastewater, which has been thought to be the primary element of the wastes from crop farming [38–40]. Large volumes of animal manure wastewater are involved in livestock industry. It is projected that approximately 5.8×10^7 t of animal manures could be annually generated in the US alone. Animal wastewater must be treated to meet discharge regulations for avoiding water contamination and odor problems [41–44]. Water pollution also results from high concentrations of nitrate (NO_3^-) and phosphate in wastewater via eutrophication of surface water [45]. Animal manure is normally high-strength wastewater, and volatile organic acids in the wastewater are commonly associated with odor in swine manure wastewater. Some applications based on MFCs in agricultural wastewater can be observed in Table 2 [46–50].

3.3. Industrial wastewater

3.3.1. Food processing wastewater

Firstly, numerous sources of wastewater extensively exist in the beet-sugar plant, which can be served as a substrate for microorganisms in MFCs due principally to a high carbohydrate content in the wastewater [51]. Secondly, starch processing wastewater always consists of high concentration of starch and protein, leading to being an energy resources for the MFCs' applications. Thirdly, some several environmental problems result from cooling (e.g., saccharification cooling, fermentation) and washing units when a large quantity of beer brewery wastewater is generated from these units. If high CODs were not taken into consideration, brewery wastewater with much of organic matter could be chosen as a suitable substrate for microbes, which has been treated with electricity generation in MFCs by many