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3D composite electrodes of microbial fuel cells used in livestock wastewater: Evaluations of coating and performance

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ABSTRACT

This study investigates the influence of using zinc- (FZ) and nickel-coated (FN) 3D anode electrodes on the electricity yield of the two-chambered cubic microbial fuel cells (MFCs) in terms of the electricity production efficacy. Swine wastewater is used as seed inoculums matrix that serves as feedstock in the anode chamber. The FN-electrodes exhibit a high corrosion and anti-oxidation resistance in a 28-day oxidation process based on the EDX observation. In addition, a 3D electrode structure efficiently provides a large surface area that benefits electron transfer. FN-C3 electrodes have a voltage of 638.9 mV, a power density of 138.6 mW/m^2, and chemical oxygen demand (COD) removal rate of 72.1%.

Introduction

Animal husbandry becomes more prosperous as a result of increasing population and advancing economic development, and produces more animal feces and wastewater that contain highly dense organisms and ammonia nitrogen. The organic wastewater is required to undergo certain treatments before it is discharged in order to address the water pollution. There are many commonly used treatments for manure wastewater [1,2], including physical treatment (e.g. precipitation and dehydration), chemical treatments (e.g. solidification, disinfection), biological treatments (e.g. aerobic/anaerobic treatment), and resource reuse (e.g. compost) [3,4]. In particular, physical and chemical treatments both require high operating costs and produce a considerable amount of sludge. Livestock wastewater

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is full of organisms and thus a good source of biomass energy. Moreover, microbial fuel cells (MFCs) are a device creates electrical energy by means of metabolism of microorganisms, and there is an increasing number of studies on MFCs. microbial fuel cell system operated successfully and it proved to be suitable for power generation with simultaneous COD removal [5].

MFCs are composed of an anode chamber and a cathode chamber, which are separated by a proton exchange membrane. The cathode chamber is filled with catholyte in order to provide an aerobic environment. In contrast, the anode chamber has an anaerobic environment, allowing for the metabolic response of microorganisms. The microorganisms release protons and electrons when they decompose the organic matters [6]. The electron flow then reaches the cathode via the external circuit, while the protons reach the cathode through the proton exchange membrane, thereby generating a current circuit. The electrons, protons, and oxygen in the cathode chamber are then synthesized into water [7]. MFCs can generate electricity and satisfy environmental protection in terms of reducing wastewater disposal and addressing the shortage of sources [8,9]. Moreover, the performance of MFCs highly depends on the transportation of ions, the internal and external resistance, microbial community, type of the membrane, electrode spacing, solution properties, cell configuration, electrode materials, and the bacterial attachment of the anode [10–14].

Electrodes composed of different materials have varying physical and chemical properties, such as surface area, conductivity, and chemical stability, which affect bacterial attachment, electron transfer, electrode state, and reaction rate. Usually, cathodes have an influence on the power of electric capacity of MFCs and thus should have oxidation reduction potential and can catch protons easily. Similarly, anodes are required to have high electrical conductivity, low resistance, strong biocompatibility, chemical stability, anti-corrosion, a large surface area for the bacterial attachment, high porosity, electron transfer, substrate oxidation, and a low production cost [15–17]. As a result, cathodes are commonly made of carbon cloth and carbon paper [18], while anodes are commonly made of carbon plates, carbon rods, carbon felt, carbon fibers, carbon cloth, carbon foam, carbon paper, reticulated vitreous carbon, and graphite felt [19]. The selection and development of suitable materials to make electrodes are important because the quality and cost of livestock wastewater disposal are based on the performance and cost of MFCs. Among all metallic electrodes, stainless steel is a common non-precious metal. As it has a low price, and has been thus pervasively used in different production modes [20,21]. However, stainless steel has much lower energy efficiency than nickel (Ni) as the latter has greater current density, and is considered a candidate of non-noble metal catalyst of electrodes [22,23]. For example, Nickel alloy material, such as NiW, NiMo, or NiFeMo, helps to improve the catalytic activity of Ni [23–26]. Nickel-coating alloys have good physical, and chemical properties, and electricity production. The 3D porous structure provides the electrodes with a greater surface area than a planar structure, and is thus higher catalytic active and generates greater current density [27].

The configuration of electrodes is challenging for the production of high performance MFCs that have high current recovery efficiency [28]. Electrodes can be divided into plate-shaped and three-dimensional types. For a plate-shape electrode, the anode is commonly exposed to an oxygen environment, and thus requires oxidation reduction [18]. The 3D structure creates a large surface area that benefits transmission of biological electrons as well as electrochemical reaction, which directly affects the performance of an MFC. However, a 3D structure also increases the cost of obtaining electricity yield and necessary basic equipment. The combination of 3D metallic wires and inexpensive materials, such as graphite conductive material [29], results in a large surface area, and the 3D electrodes thus can improve the bacterial attachment and power density [30]. In this study, the proposed electrodes of MFC are composed of a cathode, an anode, and filling materials as three-dimensional electrodes [31]. A crucial factor to employ a MFC system on a large scale is linked to a prohibitive production cost. It can significantly decrease the production cost of MFCs when the electrodes have a cost down of 20% to 50% [32,33]. Moreover, electrodes play a fundamental role in facilitating exoelectrogenic biofilm growth and electrochemical reactions, and are essential in improving the functionality and efficiency of MFCs. Ideal electrode materials should possess a high surface area, a high conductivity, a low cost, high stability, and a good biocompatibility. In addition, MFC uses carbon brushes as electrodes with an average cost of 300 and 500 dollars/kg. The electrodes in this study use FN/carbon composites that have features of having high degree of micro-porosity and catalytic activities. Moreover, the production cost (60 dollars/kg) is much lower than that (1500 dollars/kg) of Pt electrodes but have a higher conductivity. As a result, the proposed MFC electrodes have a great competitive potential due to a low production cost and being eco-friendly.

This study aims to develop 3D electrodes which are composed of zinc-coated metallic wires or nickel-coated metallic wires as the braiding material and carbon fibers as the core material. The metallic wires with a diameter of 0.23 mm are respectively immersed in a zinc- or nickel-plating solution. The pores, grooves, or uneven surface of the metallic wires can be coated with a smooth zinc- or nickel-layer, and the chemical plating provides the electrodes with electrical conduction and corrosion resistance against oxygen, moisture, acid, and alkali [34–36]. Moreover, carbon fibers can strengthen electrodes concerning high stiffness and strength, light weight, corrosion resistance, chemical resistivity, and thermal and electrical conductivity [37]. Finally, the 3D FZ- and FN-electrodes are tested in terms of voltage, polarization curve, chemical oxygen demand (COD) removal rate, surface area, Coulombic efficiency, surface contact angle, equivalent circuit model, X-ray diffraction (XRD), and scanning electron microscopy (SEM), examining the influence of different coating material on the electrodes of the MFC.

Materials and methods

Configuration of seed inoculums matrix

Swine wastewater is composed of pig manure (250 g), swine urine (2.5 L) and deionized water (2.5 L), which are mixed for 30 min using a magnet mixer. The swine wastewater is sieved at 500 mesh/inch^2 and its pH value is kept as 7–8. The swine wastewater (100 g) is then diluted with water (1 L) and placed in