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Performance improvement of microbial fuel cells for waste water treatment along with value addition: A review on past achievements and recent perspectives

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ABSTRACT

Due to depletion of fossil fuel and rapid industrial development there is urgent need to find environment friendly and sustainable technology for alternative energy. Microbial fuel cells (MFCs) are considered as a promising technology to extract energy from different sources and turn them into electricity. However, due to practical limitations, MFCs are still unsuitable for high energy demands. Since waste water contains several organic substances, therefore, production of electrical energy from waste water using MFC can offer an economical solution to the problem of environment pollution and energy crisis in near future. Therefore, the technological development for bioelectricity generation from waste water is becoming commercially worthwhile. In this review, discussion has been made critically on overall performance improvement strategies of microbial fuel cells and its application on waste water treatment along with effective power generation. The extensive research work has been carried out on microorganism selection, suitable MFC designs, appropriate electrode materials and optimum level of process parameters which would accelerate commercialization of this technology in near future. Therefore, this review has critically addressed the issues including usefulness of various cultures and their maintenance, applicability of different mode of operation and effectiveness of various MFCs to achieve sustainable power generation from waste water. In addition the various strategies for cost effective bioelectricity generation from waste water including novel reactor design as well as simultaneous treatment strategies have also been critically reviewed.

1. Introduction

Fossil fuels such as coal, natural gas etc. were formed thousands of years ago by natural processes. These fossil fuels are very efficient sources to generate power. In the past few decades human civilization has been utilizing these fossil fuels for power generation. However these fuels are not sustainable, since their underground levels are diminishing at an alarming rate. In addition the many of these fossil fuels may no longer be available in a few decades. Hence it is imperative to look at alternative sources of energy for sustenance of the modern industrialized civilization [1].

In the recent years, the focus has been on renewable sources of energy as they are eco-friendly. Renewable energy is generated from natural processes which are continuously replenished and cannot be exhausted. This includes sunlight, geothermal heat, wind, tides, water, and various forms of biomass. Based on research reports, 19% to our energy consumption was contributed from renewable sources of energy in 2012 [2]. Therefore, government has given priority to use of renewable energy as an alternative energy source [3] that is also environment friendly [4]. Recently, the production cost of renewable energy has come down significantly due to technological uplift and research activities in this field.

The increasing demand for rapid urbanization, changing consumption, population growth and fast socio-economic development has

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inevitably led to an increased anthropogenic impact on the biosphere which led to environment pollution [5]. Therefore, the control of environmental pollution in addition to energy crisis is an alarming issue in many countries. Water pollution continues to be a great concern as there are problems in removing pollutants from wastewater [6,7]. The effluents generated from domestic and industrial activities constitute the major sources of the natural water pollution load such as organic substances, heavy metal, cyanide, toxic organics, nitrogen, phosphorous, phenols, suspended solids, colour and turbidity. Prevention of water pollution and protection of public health by safeguarding water supplies to prevent the spread of diseases, are the two fundamental reasons for treating wastewater [7,8]. There are several methods applied for wastewater treatment which include chemical precipitation coagulation, membrane technology, electrolytic reduction, ion exchange and adsorption [5,9,10]. However, no current treatment technologies were found to be a sustainable. Therefore, there is an urgent need to explore all possible sustainable technology and to study their feasibility for waste water treatment system.

The electrical energy generation through microbial fuel cells (MFC) using microorganisms is one such renewable and sustainable approach which is now considered to be most efficient [11–13]. MFCs acts as reactor where chemical energy is being converted using bacteria as a biocatalyst through the oxidization of available biodegradable substrates. Therefore, the MFCs can be used for wastewater treatment and production of domestic energy [14,15]. Wastes are inexpensive and easily processed therefore production of electrical energy from waste using MFC can offer a cheap and reliable solution for addressing the environmental pollution and energy crisis issues in the near future. Therefore, this review addresses with the recent progress on the MFC technology, technical challenges, future outlook, key players and their research on MFC.

2. Microbial fuel cells

MFCs are devices that convert chemical energy to electrical energy directly using microorganisms. The important components of a MFC are an anode, a cathode, an electrolyte medium which are connected with two electrodes, an external circuit PEM and microorganisms [16–19]. The basic MFC design is shown in Fig. 1 [20]. In an MFC, microbial community remain in the anode compartment. The microorganism produces electrons and protons by utilizing organic substrates as fuels to produce electrons [21,22]. These electrons are passed through electron transport chain by nicotinamide adenine dinucleotide (NADH). These electrons are further transferred to terminal electron acceptors and then translocated to the outer membrane proteins [12,23]. The electrons are further transferred from external membrane to anode through bacteria and reach the cathode through an external electrical circuit, there by producing electric current [12]. PEM helps to diffuse the generated protons to the cathode where it combines with the electrons and oxygen to form water. As oxygen inhibits electricity generation, therefore, anaerobic condition is strictly maintained in the anode compartment. However, the cathode is exposed to oxygen to help in the formation of water [24]. It is true that carbon dioxide and water along with electricity are produced through the breakdown of the biodegradable substrate [25]. Moreover, carbon dioxide has no useful energy content and is less harmful, therefore, it is not required to undergo further treatment [26].

2.1. Electron transfer mechanisms

There are two established mechanism reported for transfer of electrons from the substrates to electrodes (Fig. 2) [27] which can be either a direct transfer or an indirect electron transfer [28]. Several microorganisms transfer electrons through c-type cytochromes, biofilms and highly conductive pili (nanowires) from inside the cell to extracellular acceptors [29]. These bacteria are *Shewanella putrefaciens, Geobactersul ferreducens, G. metallireducens and Rhodoferax ferrireducens* etc. The mechanism behind direct electron transfer is the formation of biofilms on the anode surface due to high coulombic efficiency of these microorganisms. The biofilms act as electron acceptors and transfer electrons to the anode directly. Since the electrons transfer happen directly, therefore, production of more energy takes place [30,31].

However, in indirect electron transfer, electrons are transported from bacteria to the electrode surface through a mediator which is either microorganism's mediator in case of *Shewanella oneidensis, Geothrix ferementans or* other. The mediator facilitates the extracellular electron transfer and provides a platform for bacteria to produce electrochemically active products that are in reduced state. They are also called electron shuttles for MFC. The reduced form of the electron shuttles are permeable to the cell and accept electrons from the electron carrier. They have an ability to transfer the electron on the surface of electrode [32]. There are several microorganisms such as *Proteus vulgaris*, *Escherichia coli, Streptococcus lactis*, and *Pseudomonas species* which cannot transfer electrons outside the cell, therefore, several redox mediators are used. Usually neutral red, thionine, methylene blue, anthraquinone-2, 6-disulfonate, phenazines and iron chelates are used as mediators [25] as they are non-toxic to microbes and are able to penetrate into the cell and accept the electrons from the electron carriers. It has been found that they increase electron transfer from the metabolite and are stable during long periods of redox cycling [25,33].

3. Microbial fuel cell for wastewaters treatment

Microbial Fuel Cells (MFCs) have gained interest over the past few years as a promising sustainable technology for simultaneous energy generation and wastewater treatment. It has been reported that MFC is advantageous for wastewater treatment over conventional technologies due to enhanced conversion efficiency and also due to low generation of solid waste [34]. It can also be used for treatment of low-strength wastewaters which are not suitable for anaerobic digestion [35,36]. In addition, it has an ability to operate at ambient temperature [37]. It has been found that the power densities of 4200 mW/m^3can be produced by MFC through the complete removal of chemical oxygen demand (COD) and other contaminants [38–40].

3.1. Strategy for high power generation from waste water

Water pollution continues to be a great concern due to the increase in population and industrial expansion especially in the developed countries like India [6,7]. In addition, many treatment systems in India are unsustainable and unsuccessful as they were built on western treatment systems blueprints without considering the appropriateness of the technology for the culture, land, and climate. It has been found that the improper handling of these waste materials causes the environmental pollution. The treatment units for waste water are struggling hard for converting the waste into value added products; therefore, it has been focused on utilizing these resources for valorisation which can play a significant role in the economic upliftment of a country. Therefore, it is wisely urged to all scientists that they utilize these waste materials in the production of value added products. Though the MFC has been used for wastewater treatment and tested for power generation at remote area [33], however, it is still in infant stage for commercialization. The high power output is still a technically challenging issue which is required for market readiness.

It has been found that a wide variety of bacterial communities have the ability to oxidize organic compounds present in waste water and transfer electrons to the anode. It is true that the mixed cultures and pure bacterial cultures were experimented in MFC [16], however, the mixed cultures create more resistance towards process disturbances, substrate consumption and higher power output [21,41]. Since differ-