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Plant microbial fuel cells: A promising biosystems engineering

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ABSTRACT

Conversion of waste to energy via a biological process establishes microbial fuel cells (MFC) as a prominent source of sustainable energy. MFC has been investigated for bioelectricity production through organic degradation of wastewater by microbial consortium. The potential of MFC applications in biosensors, desalination and hydrogen gas production has been explored. Many descendants of an MFC have been developed in recent years based upon the configurations, structures and purposes such as sediment MFC, mud MFC, soil MFC, constructed wetland MFC, photosynthetic MFC and biovolt-photogalvanic MFC. A plant microbial fuel cell (PMFC) is a promising modification of MFC that exercises the unique plant-microbe relationship at the rhizosphere region of a plant and converts solar energy into bioelectricity. In-situ bioelectricity and biomass production, rather than the supply of external substrates, make this technology different from traditional MFCs. Thus, designing and understanding PMFCs should be viewed from a biosystems engineering perspective rather than only through MFC methodology. Plant-microbe harmony at the soil interface, driven by rhizodeposition coupled with efficient engineering, ultimately directs towards its real applications. Thus, this paper reviews three main paradigms. Firstly, effects of plants in PMFC via rhizodeposition and photosynthetic activity are explored. Secondly, the role of microbes driven by soil physiochemical and biological characteristics are shown. Thirdly, the engineering aspects involved in designing an efficient configuration are revealed and an attempt is made to interpret the PMFC with biosystems principles. Furthermore, an overview of a PMFC system is done, along with the future perspectives and challenges.

1. Introduction

Excessive use of fossil fuels poses environmental hazards and has resulted in the pursuit of sustainable sources of energy. In such circumstances, the technology that devises production of crop/biomass along with the harness of bioenergy to mitigate the effect of climate change would be a suitable candidate. A plant microbial fuel cell (PMFC), a biological cell that converts the solar energy into the bioelectricity with an aid of the microbes at the rhizosphere region of plant, seems to be an emergent source of sustainable energy. Concurrent bioelectricity and biomass production make PMFC an appealing choice for the future green energy [1–5]. Wind, solar, geothermal, and hydro-electric power undoubtedly decrease CO_2 footprints; however, they have some disadvantages, such as landscape transformation, energy-intensive processes, and geographic limitations [6]. In contrast, PMFCs can generate continuous energy without competition for food and can be operated at any location. Mild operating conditions make PMFC more attractive than these traditionally viewed alternative sources of energy. However, there are some challenges that need to be met before its real application.

In 1910, Porter inculcated the idea about the potential of microbes in generation of electricity [7]. Initially, it did not draw much attention. Later on, the advent of this technology was welcomed by the research communities [8,9] since it converts the wastage into the energy with no environmental footprint. Over the course of time, many advancements and modifications were done in the MFC technologies. PMFC was purposed with the idea of incorporating a plant at an anode region as the source of substrates for bacteria [10]. This technology comprises multidisciplinary areas ranging from the study of microbes, plants, electrochemistry and different engineering fields (Table 1). Therefore, exploration of these fields in PMFCs seems to be an essential to understand the relationship that exists among them. The best way to holistically understand the interrelationships that exist among these factors is to view a PMFC system as a biosystem that comprises biotic and abiotic components for production of biomass and bioenergy.

Biosystems comprise living and non-living components, interconnected to achieve a unified purpose with respect to food production, environmental preservation, economic development, and technological advancement. The photosynthetic process of converting solar radiation into carbohydrates and, finally, biomass is a series of interconnected

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Table 1
Multidisciplinary fields involved in PMFC research.

Field	Factor	Focal point
Plant science	Choice of suitable plants based upon morphology and physiology	Higher adaptation better rhizodeposition
Microbiology	Microbial strains in the rhizosphere-soil consortium	Better adapted electrically active microbes/electrogens
Chemical engineering	Favourable electrochemistry with possible fabrications of electrodes	Cost effective, less toxic, devoid of secondary pollutants configuration
Electrical engineering	Possible combination/stacking for maximization of the power output	Best combination of the individual cells with no leakage for scaling up
Environmental engineering	Wastewater treatment approach	Heavy metals removal, degradation of organics

transformations [11] and a classical example of a biosystem. In similar fashion, a PMFC arrests the root exudate from photosynthesis and converts it to bioelectricity with an aid of microbial metabolisms [10,12,13]. Plants are the primary producer of an ecosystem. Being autotrophs, plants utilize solar energy to produce biomass with the aid of a special pigment called chlorophyll in the green part of its leaves. However, 40% of their energy is consumed by the plants itself, with exudation of the remaining half to the rhizosphere. Microbe populations present in the soil around the rhizosphere break down the organics to yield electrons. PMFC exploits this phenomenon and traps the electrons released by the microbes in the anode region. When the electrons pass through a load and reach a cathode completing the circuit, electricity is produced, so called "bioelectricity" [10]. Electricity is thus generated by the redox gradient between two electrodes [14]. A PMFC can be viewed as an open loop type of biosystem and can be divided into two major structures: the *bio-control* and bio-*process* structures. The *bio-control* structure (plant) receives the external input signal (sunlight) to achieve voltage. The *bio-process* structure (microbial population) takes material resources (root exudates) and acts on them to produce the outputs (voltage). This structure is subject to disturbances, which may cause variations in the output and in the process, itself. In open-loop biosystems, the actuating signal (sunlight) can be altered thereby affecting the outputs (Fig. 1).

With the consideration of expanding researches in MFCs, few works have been reported in the field of PMFCs. Review papers with different flavours were delivered in recent years in terms of MFC technologies, such as methodology [15] configuration [16], substrates [17], microbes [18], applications [19], microfluidic cell [20], cellulosic MFC [21], constructed wetland [22], domestic wastewater treatment [23], and phototropic organism in an MFC [24]. However, only a couple of review papers were reported for PMFCs [25,26]. Therefore, the aim of this paper is to provide insight on the progress made on PMFCs. Factors affecting the system performances are critically analysed, challenges are presented and the future perspectives are shown. Furthermore, an overview of PMFC research is depicted in the tabular form. It is to be noted that any system, regardless of the name in the original work that encompasses plants for bioelectricity generation employing the MFC principle is treated as a PMFC in this paper.

2. Input signal

2.1. Light

Light intensity [27], quality [28], and photoperiodism [29] are the input signal that can affect the growth of plant and system performace of PMFCs. Effect of an illumination as a light cycle [30] and a power [31] has been studied in the photosynthehtic microbial fuel cell since it is directly linked to the metabolic activity of the microbes. There is an optimal light intensity requirememt for the microbial species and the operational conditions of a system [24]. In addition to this, in PMFCs, light plays an important role for photosynthesis resulting in the concurrent biomass and bioelectricity production. Besides the optimal conditions for the heterogenous microbial community in the rhizopshere, the role of light in maximization of the root exudates with high photosynthehtic activity is an important aspect of research in a PMFC. A few previous studies have proved the effect of light in the PMFCs' performance. For example, increment in light intensity maximized the achieved voltage [10]. Similarly, Kaku et al., reported that shading of plants can decrease the electric output in PMFCs due to inhibition of the photosynthesis accompanied with decline in rhizodeposition [13]. Moreover, addition of the acetate as a substrate increased the electric output in dark elucidating the role of light in triggering root exudates. *O. sativa* and *E. glabrescens* exhibited different times in achieving the maximum power in light phase i.e., 3–4 h and 6–8 h, respectively, in the biophotogalvanic cell. Differences in time for achievement in the maximum power was accounted for the physiology of plant such as synthesis of the organic compounds, transportation of compounds to the root, release of the exudates and absorption of the exudates by bacteria and release of the electrons [33]. Therefore, light is not only the limiting factor for power generation while plant physiology also affects the overall performances. Thus, plants having the physiology that can convert the photosynthetic matters in root exudates with the simultaneous absorption by the microbes are well suited to PMFCs since enhanced bioenergy harvest can be achieved. Nevertheless, identification of the optimum light intensity for an efficient photosynthesis, optimum microbial activity, and higher rhizodeposition are the factors that need to be researched intensively within PMFCs.

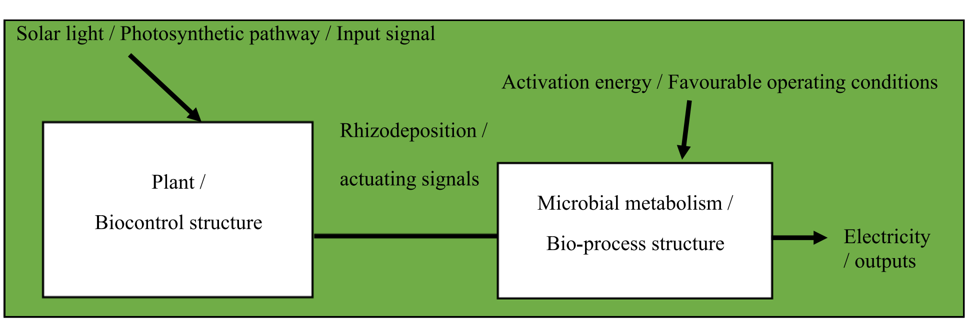

Fig. 1. PMFC as an open loop biosystem adapted from [11].