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Applications and perspectives of phototrophic microorganisms for electricity generation from organic compounds in microbial fuel cells

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ABSTRACT

There is an increasing interest to integrate phototrophic microorganisms into microbial fuel cells (MFCs) to assist electricity generation. In general, this integration can be accomplished in three ways: (1) phototrophic microorganisms function as or provide a substrate for supplying electrons; (2) photoheterotrophic microorganisms catalyze the anode reaction; and (3) photoautotrophic microorganisms provide oxygen as an electron acceptor to the cathode reaction. Direct use of phototrophic microorganisms for electricity production in MFCs faces significant challenges, because of the complex composition of microbial cells and their resistance to hydrolysis, and low conversion efficiency to electric energy by MFCs. Proper pretreatment using chemical or biological methods may improve degradability of microbial cells. Some purple nonsulfur bacteria exhibit strong electrochemical catalysis of organic compounds in the anode of an MFC, and the effect of illumination on the catalytic performance needs further investigation. Electricity generation via syntrophic relationship between photosynthetic microorganisms (providing organic compounds) and heterotrophic bacteria (oxidizing organics) in the anode is generally low due to low concentration of the electron donors and adverse effect of oxygen as a result photosynthesis on anode activities. It is promising to apply photosynthetic microorganisms in the cathode with multiple functions of oxygen supply, nutrient removal and biomass production. To address some of the challenges, two paradigms are proposed to encourage further investigation and development of effective processes with strong synergy between phototrophic microorganisms and MFCs.

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1. Introduction

Microbial fuel cells (MFCs) are an emerging technology that takes advantage of microbial interaction with solid electron acceptors/donors to convert organic compounds into electricity, which is then used to produce energy and other value-added compounds [1,2]. In the past decade, MFCs have been intensively studied from the aspects of configuration/operation, microbiology, electrochemistry, and application [3,4]. MFCs are modified to have additional functions such as hydrogen production and/or desalination, and the modified devices include microbial electrolysis cells (MECs) [5] and microbial desalination cells (MDCs) [6]. The potential applications of MFCs include wastewater treatment, remote power source for sensors, production of value-added compounds through electrochemical or electrosynthetic processes, and a research platform for understanding fundamental microbial respiration. One attractive feature of MFCs is direct conversion of the low-grade substrates such as wastewater into electricity, which is promising for sustainable water/wastewater treatment with a low carbon footprint. MFCs are capable of degrading various organic compounds including industrial and domestic wastewaters [7], its scale has been enlarged from milliliter to several hundred liters [8], and the long-term performance outside the laboratory has been examined [9]. However, the low efficiency (e.g., organics to electricity) is a great challenge for MFC development, and it is recognized that it will be beneficial to couple MFCs with other technologies to improve the efficiency, for example, MFCs can be integrated into a regular treatment process [10], and MDCs can be linked to either reverse osmosis or forward osmosis [11,12].

Among those integrations, phototrophic systems such as algal bioreactor is of particular interest for MFCs, because of the multiple benefits such as providing dissolved oxygen, nutrient removal, and biomass production [13]. Algal treatment of wastewater has a long history [14], especially in removing nutrients and heavy metals. The algal biomass produced from bioreactors can be used to produce biofuels such as biodiesel [15,16]. Producing algal biomass with wastewater provides an economically feasible biofuels option, benefiting from existing resources and infrastructure at wastewater treatment plants [17]. Algal bioreactors have been well studied for practical biomass harvest [18] and for removing nutrients from wastewater [19].

Integrating phototrophic microorganisms into MFCs occurred in the past 5–6 years with increasing interests in MFC technology [20,21], and there has been active research in microbiology and system development. Table 1 summarizes the major species (or mixed culture) of phototrophic microorganisms applied in MFCs. The objectives of this review are to provide an overview of current status of research in MFCs (including modified MFCs such as MDCs) containing phototrophic microorganisms and to analyze the challenges and perspectives of this biotechnology. It should be noted that the MFCs discussed here are different from some “photo-bioelectrochemical cells”, “photo-MFCs”, or similar processes in which the source of electrons is water [22]; in an MFC, electrons come from oxidation of organic compounds (including biomass of photosynthetic microorganisms). Thus, any work that performs water oxidation in the anode is excluded from this review, because they are different from typical “microbial fuel cells”, which requires the addition of organic compounds. In addition, this review does not include the photo MFCs based on plants.

2. Algal biomass as a substrate

Photosynthetic activities accumulate biomass, which can be used as an energy source via further conversion such as anaerobic digestion [23]. Likewise, algal biomass can also be used as a substrate for electricity generation in MFCs, either in living cells (cultivated or naturally occurred) or dry mass.

Table 1
Phototrophic microorganisms used in the MFC research.

Function	Species	MFC structure	References
Substrate	*Microcystis aeruginosa, Chlorella vulgaris*	Two chamber	[26]
Substrate	*Chlamydomonas reinhardtii*	Single chamber	[35]
Substrate	*Arthrospira maxima*	Two chamber	[34,44]
Substrate	*Chlorella vulgaris, Ulva lactuca*	Single chamber	[27]
Substrate	Scenedesmus	Two chamber	[28,71]
Substrate	*Laminaria saccharina*	Two chamber	[37]
Substrate	*Scenedesmus obliquus*	Two chamber	[30,32]
Substrate	*Chlorella vulgaris, Dunaliella tertiolecta*	Two chamber	[31]
Substrate	*Cyanobacteria*	Single chamber	[25,39]
Substrate	Mixed algae	Two chamber	[24,33,38]
Assisting Anode	*Chlorobium limicola*	Two chamber	[56]
Assisting Anode	*Rhodobacter sphaeroides*	Single chamber	[52]
Assisting Anode	*Rhodopseudomonas palustris*	Single chamber	[43]
Assisting Anode	*Rhodopseudomonas palustris*	Two chamber	[44]
Assisting Anode	*Chlamydomonas reinhardtii*	Single chamber	[55]
Assisting Anode	Mixed algae	Single chamber	[47,48,54]
Assisting Anode	Mixed culture	Two chamber	[46,49]
Assisting Cathode	*Chlorella vulgaris*	Two chamber	[58,61,64,65,69–71,73,74]
Assisting Cathode	*Chlorella vulgaris*	Three chamber	[63]
Assisting Cathode	*Chlorella vulgaris*	Single chamber	[72]
Assisting Cathode	*Desmodesmus sp.* A8	Two chamber	[60]
Assisting Cathode	*Microcystis aeruginosa* IPP	Two chamber	[68]
Assisting Cathode	Mixed culture	Two chamber	[57,59,62,66,78,79]