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Review article

Algal-microbial community collaboration for energy recovery and nutrient remediation from wastewater in integrated photobioelectrochemical systems

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A B S T R A C T

Integration of algae and cyanobacteria with microbial fuel cell bioelectrochemical systems (BES) can significantly improve energy recovery and nutrient remediation in wastewater treatment. One innovative option is an integrated photobioelectrochemical system (IPB). Algae can contribute to BES function as an organic feedstock to support bacterial growth, by assisting anode bacteria to generate electricity, by providing oxygen from photosynthesis as a cathode electron acceptor, and by removing N and P from effluent water. However, critical interactions among bacteria-algae communities are poorly understood and practical questions such as light and pH conditions and taxa selection need more research to optimize microbial interactions and promote IPB function. Only a few 'lab weed' algal and cyanobacterial taxa have been tried in IPB systems but algae offer additional metabolic flexibility such as mixotrophy, to further process organic carbon, and nutrient hyperaccumulation, which have yet to be examined for potential in wastewater IPB treatment systems. This review aims to serve as a guide for wastewater bioenergy engineers to address challenges in IPB systems, and identifies a need for more collaboration between algal biologists and engineers to optimize algal-microbial community collaboration and work towards improved sustainability of wastewater treatment.

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1. Introduction

Future sustainability of human activities on the planet presents the major crisis of the 21st century [1]. Reduction of energy consumption is critical for future sustainability and wastewater requires consideration, because wastewater treatment is an energy-intensive process that, for example, demands ~3% of the total electrical energy consumption in the U.S. [2]. Conventional wastewater treatment employs energy-intensive physical and chemical processes. New technological innovations to reduce energy demand and improve energy recovery are increasingly targeting the biological components of wastewater treatment [3–5].

Bioelectrochemical systems (BES) are promising alternatives to conventional technologies to improve the energy conversion efficiency of wastewater treatment [6]. The most basic BES is the microbial fuel cell (MFC), a system using heterotrophic bacteria as biocatalysts to oxidize the organic compounds in wastewater to produce electricity (Fig. 1) [7–9]. An MFC uses electricity-generating bacteria (electricigens) to directly transfer the electrons from organic matter via an anode electrode to the cathode electrode to react with electron acceptors (e.g., O_2), completing a circuit to achieve electricity generation (Fig. 1) [3,6]. Direct biological conversion of organic chemical energy into electricity enables MFCs to achieve higher energy conversion efficiency (~44%) than with anaerobic treatment (e.g., anaerobic digester) (~28%) [2,10]. Thus, MFCs can improve energy recovery to achieve more sustainable wastewater treatment. However, there are still some functional limitations to optimum performance of MFCs for energy recovery from and nutrient remediation of wastewater. For example, electricity generation at the cathode requires oxygen as an electron acceptor, so aeration to supply oxygen is commonly needed. Aeration is a major energy consumer of domestic wastewater treatment [11–13], so eliminating aeration will greatly reduce energy consumption in MFCs and move this technology towards net positive energy recovery [7].

To address the need for oxygen supply, algae and/or photosynthetic bacteria may be incorporated in BES. Photoautotrophs can use photosynthesis to produce oxygen as the electron acceptor for electricity generation, which has been demonstrated experimentally (Fig. 1) [14,15]. In addition to oxygen supply, photoautotrophs can also offer benefits including removal and potentially recovery of N and P macro-nutrients, removal of additional organic compounds and production of algal biomass that could be converted to biofuels or other value-added products [3,6,16–21]. Algae naturally grow well in wastewater, and their nutrient removal services also provide excellent motivation to consider integration of algae into BES [16–18]. The use of wastewater as a medium for algal growth for production of biomass for biofuels has been of interest for some time, with reduced costs of biofuel production utilizing a freely available source of freshwater and nutrients [20,22–24].

The integration of algae and BES has been investigated to improve the overall system performance over the past 7–8 years [17,25,26]. One significant representative is an integrated photobioelectrochemical system (IPB) (Fig. 1), to incorporate algae into BES to improve performance with the algae taking on three main functional roles in different IPB designs: 1) as an organic carbon substrate in the anode to support growth of electricigens for electricity generation [15,27–29]; 2) assisting electricigens to transfer electrons directly to the anode for boosting electricity generation [30–32]; and 3) assisting at the cathode to provide oxygen as an electron acceptor [33–35], and to remove nitrogen and phosphorus nutrients from effluent water coming from the anode [36–38]. Algae and bacteria form biofilms and close associations on electrode surfaces (Fig. 2) [14,15], and heterotrophic bacteria on the cathode surfaces can compete with the cathode for oxygen produced by photosynthetic cells, potentially causing reduction in electricity generation [26,39,40]. Nevertheless, algal-microbial communities can improve BES efficiency in certain applications and configurations [41].

To improve the IPB performance with incorporation of photosynthetic algae or cyanobacteria, we need a more detailed understanding of mechanisms and factors influencing microbial activities. The IPB performance is not only influenced by the system configuration and operation, but also by choice of taxa included, as well as conditions to promote algal growth and synergistic interactions between photoautotrophs and heterotrophs in the microbial communities. Relatively little is known about the impact of biological interactions within algal-microbial communities on the energy recovery and nutrient remediation efficiency in the IPB system. This review seeks to present our understanding about how algae might contribute to BES technology for wastewater remediation by reviewing research on the configurations and conditions for algal function to support BES, the algal taxa tested so far and the transformation of nutrients between compartments and biological components of these systems. This review is intended to provide background for phycologists interested in application of algae and cyanobacteria in IPB systems, and provide insights for BES researchers and engineers about how algal-microbial communities might function in BES technology. The downstream processing and uses of algae for biofuels production, for example, are covered extensively in other reviews [42–44]. Challenges and research needs for future application of algae in IPB will be identified, to help with the development of the technology integration.

2. System configurations

It is important to consider the configurations for integrated BES and algae systems which are most suitable to both accommodate algae or cyanobacteria, and also allow the photoautotrophs to optimize system performance. These configurations integrate BES with a photobioreactor (PBR) together to produce electricity utilizing the photosynthetic organisms to produce organic matter for fueling the BES or for oxygen produced from photosynthesis. Two major configurations are based on 1) the PBR externally linked to the BES components, defined as a coupled

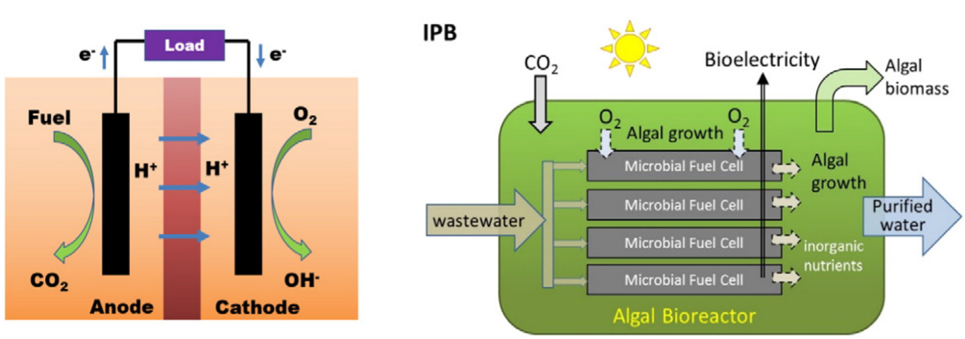

Fig. 1. Basic schematic of BES components and integrated photobioelectrical systems (IPB) system. *Left.* Principles of a microbial fuel cell. Fuel for bacterial growth at the anode is typically dissolved organic compounds in wastewater but algal biomass has been used as a carbon substrate. Oxygen is needed at the cathode as an electron acceptor. *Right.* Schematic of IPB system shows how the MFC function can be supported by algae in a bioreactor in contact with the cathode, providing oxygen from photosynthesis. Inorganic nutrients produced by the MFC can support growth of algae, and nutrient uptake by algae further purifies the wastewater.

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