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Review

New insights in photosynthetic microbial fuel cell using anoxygenic phototrophic bacteria

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ABSTRACT

Anoxygenic phototrophic bacteria (APB) pay a key role in biogeochemical cycles, and it can convert light energy to chemical energy by photosynthesis process. Photosynthetic microbial fuel cell (photo-MFC) is regarded as a promising energy-harvesting technology, which is also applied to environment treatment in recent years. The previous studies show that photo-MFC with APB have higher power putout than other bioelectrochemical systems. However, photo-MFC with APB is not reviewed due to some limited factors in the development process. In this review, photo-MFC with APB is treated according to its electron transfer pathways, the current understanding, APB strains, application, influence of substrates, and economic assessment. Meanwhile, knowledge of photosynthesis components and electron transfer pathways of APB is crucial for developing new energy and easing the serious energy crisis. Moreover, some new insights (the optimization of light source and self-sustaining bioelectricity generation) are proposed for the future explorations.

1. Introduction

Photosynthesis is one of the important energy conversion pathway on earth, and it play a key role in the biogeochemical cycles. In addition to plants, phototrophic microorganisms are regarded as the primary mediator for photosynthesis. Researchers have explored the reactions of photosynthetic process in the organisms for the past century, and they think that the mechanism of action will contribute to the future new energy development. However, how to exploit and utilize the energy from the organisms? The problem has become a hotspot in recent decades for the energy crisis.

Phototropic prokaryotes belong to bacteria or archaea that can convert light energy to chemical energy by photosynthesis process (Hallenbeck, 2017). Currently, phototropic prokaryotes are mainly divided into two categories, oxygenic and anoxygenic phototrophic bacteria (OPB and APB) (Fig. 1). Cyanobacteria are deemed as the major member of OPB, which are also the typical photoautotrophs that obtain carbon from atmospheric carbon dioxide (Dvořák et al., 2017). The metabolic process does not produce oxygen as a byproduct of the reaction in APB, which chiefly contain purple bacteria (BChl a and b), green bacteria (BChl c and d) and heliobacteria (BChl g) based on the different bacteriochlorophylls (BChl) (Wang-Otomo, 2016). Because of its unique properties, APB display the promising applications in many fields, such as aquaculture production (e.g. fish, shrimp), new energy development (e.g. hydrogen, bioelectricity), environmental modification (e.g. wastewater treatment), medical field (e.g. mycoprotein) and so on (Hallenbeck and Liu, 2016; Meng et al., 2017a; Meng et al., 2017b; Sasaki et al., 2005; Wang et al., 2014; Wang and Liao, 2005). Although APB have been applied in such fields, the most studies still focus on environmental treatment and new energy development. However, researchers are exploring a device that can treat wastewater and produce bioenergy at the same time in recent decades.

The device is photosynthetic microbial fuel cell (photo-MFC), which can use phototrophic prokaryotes to convert light energy into electricity through photosynthesis process. Photo-MFC is considered as the most promising energy-developed equipment in the future, which not only treat wastewater but also produce bioelectricity. Therefore, one of the impact factors on photo-MFC is the choice of mediator (microorganisms). Currently, cyanobacteria (e.g. *Spirulina platensis*, *Synechocystis* PCC-6803, *Nostoc* sp.) have been applied to MFC system widely (Figueredo et al., 2015; Fu et al., 2009; Lee and Choi, 2015; Ma et al., 2012). The bioelectrochemical systems based on cyanobacteria are called as biophotovoltaics (BPVs), which generate bioelectricity through the light-driven oxidation of water that occured in an oxygenic photosynthetic reaction center (Sawa et al., 2017; Wei et al., 2016). Further studies have been reviewed by some researchers (Mccormick

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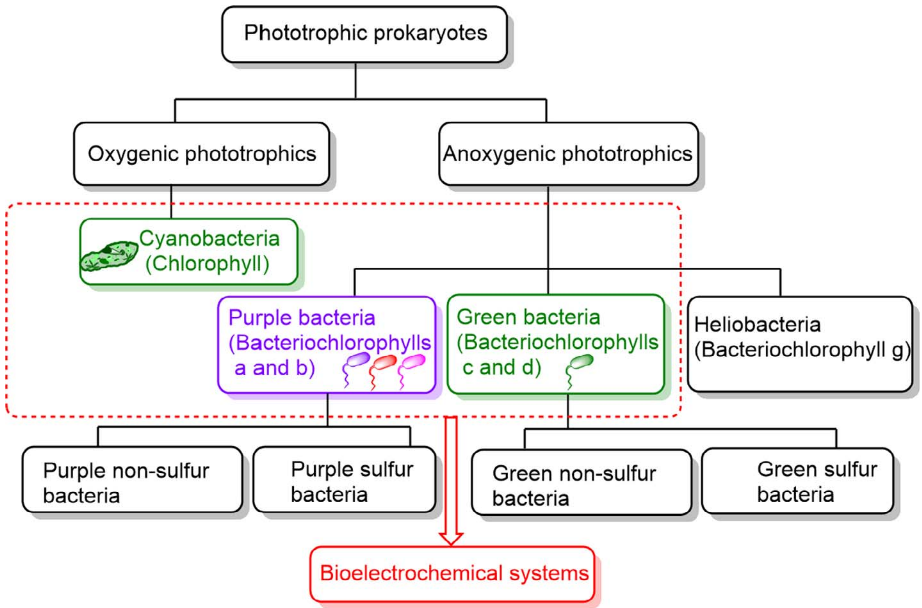

Fig. 1. The category of phototrophic prokaryotes.

et al., 2015; Rosenbaum et al., 2010; Wang et al., 2014; Xiao and He, 2014). However, the first reported bioelectricity generation with phototrophic prokaryote is not cyanobacteria but APB. Berk and his team explore the bioelectrochemical energy conversion by using the resting cells of *Rhodospirillum rubrum* for the first time in 1964 (Berk and Canfield, 1964). Recently, some researchers are trying to achieve the self-sustained bioelectricity generation by photo-MFC with APB (Qi et al., 2018). Although photo-MFC with APB have been proposed for many years, the studies have not attracted more attention. The main reason is that the previous reports focus on the bioelectricity generation performance of different APB chiefly. Therefore, a targeted review should be displayed for the future development of photo-MFC with APB.

The aim of this review is to summarize the recent studies in photo-MFC system with APB, and provide some new insights. Firstly, the review will give the current understanding of photo-MFC, and display the constructed devices (Section 2). Secondly, the article will summarize the APB strains that are used in photo-MFC, and review the performance of photo-MFC using APB (Section 3). Thirdly, the paper gives an economic assessment of traditional MFC and photo-MFC with APB (Section 4). Fourthly, the article will analyze the photosynthesis components and electronic conversion process of APB from previous studies (Section 5). The part contents not only provide the present understanding of microbial electron transfer in photo-MFC system with APB, but also give the challenges in future studies. Finally, the review will give some new insights for the future exploration (Section 6).

2. The current understanding of photo-MFC

The traditional photo-MFC is made up of two chambers, which are separated by proton exchange membrane. According to the different cathode, it is usually divided into two representative types. One is the reduce electron acceptor (ferricyanide ($[Fe(CN)_6]^{3-}$) or permanganate (MnO_4^{-})), and the other is catalyzer (platinum (Pt) or Pt black-catalyst materials). Fig. 2a display the schematic diagram and digital photos of a traditional dual-chamber photo-MFC device using ferricyanide as electron acceptor in cathode. However, the device is only applied to laboratory investigation due to the potential environmental issues (Jang and Kim, 2004; Wei et al., 2012). Therefore, the air-cathode based on catalyst materials draw wide attention for the practical engineering (Bosch-Jimenez et al., 2017; Yang et al., 2017a; Yang et al., 2017b). The catalyst materials are mainly used to restrain the overpotential for oxygen reduction (Cirik, 2014; Sangeetha and Muthukumar, 2013). Fig. 2b shows the schematic diagram and digital image of a real Photo-MFC device using an air cathode. Moreover, with the optimization of art construction, some single chamber and micro photo-MFC are also proposed in recent years (Chandra et al., 2015; Lai et al., 2017; Wang et al., 2011). For application, photo-MFC with APB not only can treat wastewater, but also generate bioelectricity and APB single cell protein.

In fact, the current classification of photo-MFC mainly contain three devices: (1) sub-cellular photo-MFC; (2) cellular photo-MFC; (3) complex cellular photo-MFC (Mccormick et al., 2015). Sub-cellular photo-MFC system is that the purified APB photo-components are directly attached to the electrode surface. Janzen et al. firstly report the system in 1980 (Janzen and Seibert, 1980). They isolate the bacterial photosynthetic RC from *Rhodopseudomonas sphaeroides*, which are directly attached onto the surface of an SnO_2 electrode for bioelectricity generation. The photosynthetic RC complexes based on light-induced charge separation process can generate 70 mV of photovoltages and 0.3 $\mu A/cm^2$ of photocurrents in an external circuit. The most common cases of cellular photo-MFCs are those that utilize the living APB to directly generate bioelectricity under anaerobic conditions. Cellular photo-MFCs are widely used due to the self-repair and reproduction property of whole cells in recent years (Table 1). The complex cellular photo-MFC is mainly made up of two parts: producer and consumer, and it contains different form: algae and heterotrophic bacteria, algae and APB. However, the previous studies have not covered the interaction of heterotrophic bacteria and APB. Recently, the interaction effect have been proposed for the better understanding of biogeochemical cycles (Benomar et al., 2015). Therefore, the future study probability focuses on the interaction of heterotrophic bacteria and APB in photo-MFC.

3. Photo-MFC using APB

The different APB have different metabolic pathways. It can be applied either to the anode or to the cathode. APB can degrade organic matters for bioelectricity generation in anode, and it also can be used as the electron acceptor in cathode.