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A comprehensive overview on electro-active biofilms, role of exo-electrogens and their microbial niches in microbial fuel cells (MFCs)

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HIGHLIGHTS

- Role of exo-elctrogens in MFC are reviewed.
- Advanced molecular techniques for the identification of electrogens are tabulated.
- Biofouling is major event to be considered towards the success of MFC technologies.
- Back washing of membrane and anti-foulant usage are suggested to avoid biofouling.

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ABSTRACT

Microbial fuel cells (MFCs) are biocatalyzed systems which can drive electrical energy by directly converting chemical energy using microbial biocatalyst and are considered as one of the important propitious technologies for sustainable energy production. Much research on MFCs experiments is under way with great potential to become an alternative to produce clean energy from renewable waste. MFCs have been one of the most promising technologies for generating clean energy industry in the future. This article summarizes the important findings in electro-active biofilm formation and the role of exo-electrogens in electron transfer in MFCs. This study provides and brings special attention on the effects of various operating and biological parameters on the biofilm formation in MFCs. In addition, it also highlights the significance of different molecular techniques used in the microbial community analysis of electro-active biofilm. It reviews the challenges as well as the emerging opportunities required to develop MFCs at commercial level, electro-active biofilms and to understand potential application of microbiological niches are also depicted. Thus, this review is believed to widen the efforts towards the development of electro-active biofilm and will provide the research directions to overcome energy and environmental challenges.

1. Introduction

Conservation and enhancing our resource base (water and energy) is the main aim of sustainable development to balance our economic growth and environmental needs. Currently a challenging issue is to meet energy requirement round the globe which unfortunately is at higher side as compared to its availability. It is

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Abbreviations

BESs	Bioelectrochemical Systems
MES	Microbial electro-synthesis
CO_2	Carbon dioxide
CO	Carbon monoxide
EET	Extracellular electron transport
MFC	Microbial fuel cells
MEC	Microbial electrolysis cell
V	Voltage
mV	Millivolt
e	Electrons
H^+	Protons
COD	Chemical oxygen demand
VSS	Volatile suspended solids
mMC d^{-1}	Millimolar of carbon per day
FTHFS	Formyl tetrahydrofolate synthetase
FAME	Fatty acid methyl ester
QCM	Quartz crystal microbalance
c-Cyts	c-type cytochromes
MET	Mediated electron transfer
FISH	Fluorescence in situ hybridization
T-RFLP	Terminal-restriction fragment length polymorphism
ARISA	Automated ribosomal intergenic spacer analysis
qPCR	Quantitative RT-PCR
SSCP	Single strand conformation polymorphism
PCR-DGGE	Polymerase chain reaction denaturing gradient gel electrophoresis

well known that source of energy is usually obtained after combustion of fossil fuels and is estimated in near future will be depleted (Shafiee and Topal, 2009; Saratale et al., 2013). Industrial advancement, increase in population and lack of energy sources are the major reasons which boosts the development of alternative sources of power generation. Bioelectrochemical systems (BESs) are one of the emerging sustainable technologies which are capable of producing energy from wastewater. The utilization of BESs in the treatment of wastewater also assists to control pollution and economy of the treatment system. Beside the electrical energy generation, bioremediation of waste, biosensing and the chemicals production are also major applications of BESs (Aulenta et al., 2007; Kumlanghan et al., 2007; Rabaey and Rozendal, 2010). BESs has diverse applications and on the basis of their function they can be classified as microbial fuel cells (MFCs) for bioelectricity production, bioelectrochemical treatment systems (BET) mainly for wastewater treatment, bioelectrochemical systems (BESs) for the synthesis of syngas and value added biochemical production and microbial electrolysis cells (MECs) mainly for H_2 production with simultaneous wastewater treatment (Butti et al., 2016; Kadier et al., 2016; Logan and Rabaey, 2012; Pant et al., 2012). This review will be focused on the biofilm formation and the effects of operating and biological parameters on the biofilm formation and their microbiological niches. We also highlight the role of exo-electrogens in electron transfer and biofilm development in MFCs. Further discussions about the molecular techniques used in the microbial community analysis of electro-active biofilms have been addressed. Finally, it also includes their future needs and the way forward for developing MFCs and the electro-active biofilms for the commercial applications. This article is expected to be useful to understand the factors, challenges for electro-active biofilms and the role of exo-electrogens in the MFCs technology in next-generation.

2. Microbial fuel cells

Advances made in MFCs have gained many attention due to its unique advantages in wastewater treatment and energy production by applying mild operational condition, high electric efficiency and less sludge production (Hu et al., 2017; He et al., 2017; Gajda et al., 2017; Logan et al., 2006; Lovley, 2008). Normally MFCs transform the organic matter into electrical energy and the reaction is catalysed by microorganisms. The microorganisms can be defined as biocatalyst. MFCs devices have been extensively studied in a range of single, double, or triple chamber configurations (Gude, 2016; He et al., 2017; Logan et al., 2008.) Usually, MFCs designed with two chambers including anaerobic anode and aerated cathode. An anode was used to accept the electrons from microbial culture which were moved to an electron acceptor through cathode. The reaction takes place under anoxic conditions (Logan and Rabaey, 2012).

A semipermeable membrane or salt bridge separates the anode and cathode compartments. Here, the objective of separation wall is to mitigate and allow the oxygen to diffuse from the cathode to the anode compartment. However, the shuttling of the protons that are generated from the anode electrode to cathode electrode is mediated through the membrane. As compared to other membranes, proton exchange membrane (PEM) have been used in many studies considering its high conductivity to protons and lesser inner resistance (Zhang et al., 2009a,b). Anaerobic respiration takes place in anode compartment which generate electrons and protons (Venkata Mohan et al., 2007). The interaction of proton, electron and dissolved oxygen at cathode results in water formation by reduction reaction. The electric energy generates from the voltage and the current is produced in the cathode chamber due to the potential difference of respiratory system and electron acceptor (Lovley, 2006). Different mechanisms have been discussed in earlier studies regarding electron transport from microbes to the electrodes i.e., through microbial cell, via cytochromes bound to cell membrane or conductive pili (Fig. 1) (Kalathil and Pant, 2016; Bond and Lovley, 2003; Busalmen et al., 2008; Park and Zeikus, 2000; Schröder et al., 2003).

Power generation has been specified by fungi, microalgae, yeast and bacteria from phylum *Proteobacteria*, *Acidobacteria* and *Firmicutes*. Due to the enriched degradable protein and carbohydrates, the microalgae biomass has been used as a substrate in MFCs (Singh and Wahid, 2015; Wang et al., 2012). *Geobacter* spp., *Shewanella* spp., *Rhodoferax ferrireducens*, *Aeromonas hydrophila*, *Pseudomonas*

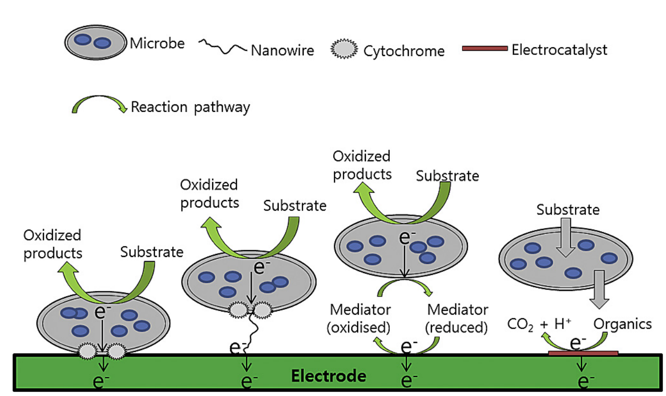

Fig. 1. Different electron transfer mechanisms from microbes to electrode (modified from Patil et al., 2012).