EFFECT OF AERATION AND ANODE MATERIAL ON THE BIOELECTRICITY GENERATION OF FLOATING MICROALGAE BIOPHOTOVOLTAIC DEVICE

CHIN JIA CHUN

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School of Mechanical Engineering
Faculty of Engineering
Universiti Teknologi Malaysia

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ABSTRACT

A biophotovoltaic (BPV) system is a developing renewable energy technology that promises carbon-free electricity generation from solar energy by utilizing photosynthetic exoelectrogenic microorganisms. However, further development of this novel technology is restricted by its relatively low power output. The problem could be solved by directly acquiring the bioelectricity from floating microalgae instead of forming thin biofilms on the anode surface. One technical concern is that previous studies emphasized the composition of anode materials and biofilm formation in the BPV devices, whereas there are limited studies regarding the bioelectricity generation of BPV devices with well-mixed microalgae cultivation medium. Therefore, the objectives of this research are to determine the effects of various anode materials on the bioelectricity generation of BPV devices in natural and aeration modes; and to determine the effects of aeration on bioelectricity generation in BPV devices with free surface and multiphase flow cultures. The methodology starts with voltage output measurement under gradually rising external load to form a polarization curve for each BPV device, with various anode materials of graphite, aluminium, indium tin oxide (ITO)-coated glass, and ITO-coated plastic in natural conditions and aeration mode. The result shows that graphite anode has poor absorption of electrons released by *Spirulina (Arthrospira) platensis* and aluminium anode dissolved into the culture medium and became an extra electron source. ITO-based BPV devices have comparable good performance among other electron materials. However, the devices experience significant power overshoot phenomena and have a low peak power output under natural conditions. In aeration mode, the peak power output of ITO-coated glass-based BPV devices increased to 0.659±0.009 mW/m^2 as compared with 0.118±0.003 mW/m^2 in natural conditions. In turbidity test, aeration prevented the formation of biofilms and sedimentation and produced a multiphase flow solution. In conclusion, aeration significantly alleviated the power overshoot phenomenon and enhanced the peak power output of ITO-coated glass-based and plastic-based BPV devices by 458.47% and 244.65%, respectively. The findings are expected to contribute to further understanding of the correlation of the selected parameters with regards to power generation of the BPV devices.

ABSTRAK

Sistem biofotovoltaik (BPV) adalah teknologi tenaga boleh diperbaharui yang sedang berkembang yang menjanjikan penjanaan elektrik bebas karbon daripada tenaga suria dengan menggunakan mikroorganisma eksoelektrogenik fotosintetik. Walau bagaimanapun, perkembangan selanjutnya teknologi baru ini dibatasi oleh pengeluaran kuasanya yang agak rendah. Masalahnya dapat diselesaikan dengan secara langsung dengan memperolehi bioelektrik dari mikroalga terapung dan bukannya membentuk biofilem nipis di permukaan anod. Satu kebimbangan teknikal adalah bahawa kajian sebelumnya menekankan komposisi bahan anod dan pembentukan biofilem dalam peranti BPV, sedangkan hanya terdapat kajian terhad mengenai penjanaan bioelektrik peranti BPV dengan medium penanaman mikroalga yang bercampur dengan baik. Oleh itu, objektif penyelidikan ini adalah untuk menentukan kesan pelbagai bahan anod pada penjanaan bioelektrik peranti BPV dalam mod semula jadi dan pengudaraan; dan untuk menentukan kesan pengudaraan terhadap penjanaan bioelektrik dalam peranti BPV dengan budaya aliran permukaan bebas dan pelbagai fasa. Metodologi bermula dengan pengukuran pengeluaran voltan di bawah beban luaran yang meningkat secara beransur-ansur untuk membentuk lengkung polarisasi untuk setiap peranti BPV, dengan pelbagai bahan anod seperti grafit, aluminium, kaca bersalut indium timah oksida (ITO), dan plastik bersalut ITO dalam keadaan semula jadi dan mod pengudaraan. Hasilnya menunjukkan bahawa anod seperti grafit mempunyai penyerapan elektron yang lemah yang dikeluarkan oleh *Spirulina (Arthrospira) platensi* dan anod aluminium yang terlarut ke dalam medium kultur dan menjadi sumber elektron tambahan. Peranti BPV berasaskan ITO mempunyai prestasi yang baik yang setanding dengan bahan elektron lain. Walau bagaimanapun, peranti mengalami fenomena lajakan kuasa yang ketara dan mempunyai output kuasa puncak yang rendah di bawah keadaan semula jadi. Dalam mod pengudaraan, pengeluaran kuasa puncak peranti BPV berasaskan kaca bersalut ITO meningkat kepada 0.659±0.009 mW/m^2 berbanding 0.118±0.003 mW/m^2 dalam keadaan semula jadi. Dalam ujian kekeruhan, pengudaraan menghalang pembentukan biofilem dan pemendapan serta menghasilkan penyelesaian aliran multifasa. Kesimpulannya, pengudaraan mengurangkan fenomena lajakan kuasa dengan ketara dan meningkatkan pengeluaran kuasa puncak peranti BPV berasaskan kaca dan berasaskan plastik bersalut ITO, masing-masing sebanyak 458.47% dan 244.65%. Penemuan ini dijangka menyumbang kepada pemahaman lanjut tentang korelasi parameter yang dipilih berkenaan dengan penjanaan kuasa peranti BPV.

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LIST OF ABBREVIATIONS

ATP	-	Adenosine Triphosphate
BES	-	Bioelectrochemical System
BPV	-	Biophotovoltaic
EET	-	Extracellular Electron Transmission
EFC	-	Enzymatic Fuel Cell
FTO	-	Fluorine-doped Tin Oxide
ITO	-	Indium Tin Oxide
MEC	-	Microbial Electrolysis Cell
MES	-	Microbial Electrosynthesis
MFC	-	Microbial Fuel Cell
MOF	-	Metal Organic Frameworks
NADPH	-	Nicotinamide Adenine Dinucleotide Phosphate
OECD	-	Organization for Economic Co-operation and Development
PAR	-	Photosynthetically Active Radiation
PBR	-	Photobioreactor
PC	-	Plastocyanin
PEM	-	Proton Exchange Membrane
PMFC	-	Photosynthetic Microbial Fuel Cell
POME	-	Palm Oil Mill Effluent
PQ	-	Plastoquinone
PSI	-	Photosystem I
PSII	-	Photosystem II
PV	-	Photovoltaic
RGO	-	Reduced Graphene Oxide
TSS	-	Total Suspended Solids

LIST OF SYMBOLS

TW	-	Terawatt
g	-	Gravity Acceleration
c_i	-	Conservative quantity
C_{i0}	-	Initial condition of conservative quantity
Ω	-	Domain inside the boundary
u	-	Fluid velocity
De	-	Dynamic value
$R(c_i)$	-	Reaction kinetics of the reacting species
$S(c_i)$	-	Temporal changes of the reacting species
ρ	-	Density of the fluid
ρ_w	-	Density of the medium
ρ_s	-	Density of the dry cell
k	-	Volume friction.
f	-	Body forces
v	-	Kinematic velocity
V	-	Actual Open Circuit Voltage
V_{rev}	-	Theoretical Potential
V_{irrev}	-	Potential Loss
v_{act_an}	-	Anodic Activation Loss
v_{act_cath}	-	Cathodic Activation Loss
v_{ohmic}	-	Ohmic Loss
V_{conc_an}	-	Anodic Concentration Loss
V_{conc_cath}	-	Cathodic Concentration Loss
R	-	Universal Gas Constant
T	-	Absolute Temperature
α	-	Charge Transfer Coefficient
F	-	Faraday's Constant
i	-	Current Density
i_o	-	Reaction Exchange Current Density
p	-	Number of Exchange Protons per Mole of Charged Species

R_{ohmic}	-	Total Effective Resistance
R_{elec}	-	Electronic Resistance
R_{ionic}	-	Ionic Resistance
d^m	-	Membrane Thickness
d_{cell}	-	Electrode Distance
k^m	-	Conductivity of Membrane
k^{aq}	-	Conductivity of Medium
E_{630}	-	Value of Absorbance at Wavelength 630 nm
E_{652}	-	Value of Absorbance at Wavelength 652 nm
E_{665}	-	Value of Absorbance at Wavelength 665 nm
Chl-a	-	Concentration of Chlorophyll a
vol	-	Volume of Solvent
VOL	-	Volume of Sample
L	-	Path Length of the Cuvette
CD	-	Current Density
PD	-	Power Density

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CHAPTER 1

INTRODUCTION

1.1 Background

Elevating population growth and rapid urbanization have led to a rising demand for new energy resources. Global Energy and CO2 Status Report 2018 reported that annual global energy consumption had increased by 2.3% because of continued economic growth of 3.7% in 2018 (IEA Publication., 2019). International Energy Outlook 2019 estimated there will be more than 50% increase in global energy consumption from 2018 to 2050 due to the continuous development of non-OECD (Organization for Economic Co-operation and Development) countries (U.S. Energy Information Administration., 2019). According to BP Statistical Review of World Energy 2021, the current reserves-to-production ratios of natural gas and crude oil reserves in 2020 would account for another 48.8 years and 50 years of current production, respectively (BP p.l.c.., 2021). Considering this prospect, it is necessary to discover new energy sources in order to support continuous human development and inhibit a foreseeable global energy crisis.

Malaysia possesses enormous tropical sunshine, a long coastline, an enormous diversity of algae, and sufficient infrastructure (Phang, 2018), all of which are suitable for the development of algal industry. Cyanobacteria, a type of algae, have gained much attention in recent years because of their economic value in agriculture, nutraceuticals, effluent treatment, biofuel production, and various secondary metabolite productions (Lau et al., 2015). The abundance of this natural resource is an opportunity to have a place in the global algae market. Malaysia is targeting to develop international-level seaweed industry, with 150 000 metric tons of annual production of high-quality seaweed industry, which is expected to bring in RM 1.45 billion of economic income by the year 2020 (Olanrewaju et al., 2016). The rapid development of the algae industry in Malaysia is proven by the opening of the world's largest microalgae cultivation facility on August 27th, 2019, in Kuching, Sarawak, as shown in Figure 1.1. The facility is jointly organized by Chitose Group, Sarawak Biodiversity Centre, and Mitsubishi Corporation.

Figure 1.1 World largest algal culturing facility

A bioelectrochemical system (BES) is a developing bioelectric-generated technology that ensures sustainable energy supplements. BESs generate electricity either by acquiring power supply from wastewater, through the chemical reactions between exoelectrogenic microbes and solid electrodes, or by utilizing the electrons released by photosynthetic exoelectrogenic microorganisms, including microalgae and cyanobacteria. There are several types of BES, including but not limited to Microbial Fuel Cell (MFC), Biophotovoltaic (BPV), Microbial Electrolysis Cell (MEC), Microbial Electrosynthesis (MES), and Enzymatic Fuel Cell (EFC) (Bajracharya et al., 2016).

Biophotovoltaic (BPV) is an emerging renewable energy technology that utilizes natural photosynthesis of exoelectrogenic microorganisms for bioelectricity generation. During photosynthesis, exoelectrogens release electrons extracellularly to insoluble electron acceptors, such as electrode of the power plant (Patil et al., 2012). BPV device is one type of bioelectrochemical system other than microbial fuel cells (MFCs). MFCs utilize dark fermentation of anodic respiring bacteria to degrade the organic substances, in the presence of an external mediator (Chandra et al., 2017). Comparatively, BPV device simplifies the system by eliminating the need for application of external microbes in the power generation process (Tschortner & Kromer, 2019), and still functions well due to the photolysis of water by photosynthetic exoelectrogenic microorganisms in the anode (Chandra et al., 2017). BPV device functions continuously under sustainable supplement of sunlight and water, which are the most popular natural resources, and offer negative carbon footprint (Thong et al., 2019). It makes BPV device a potentially new electrical energy source besides fossil fuels. Figure 1.2 illustrates the working mechanism of the BPV device (Soni et al., 2016).

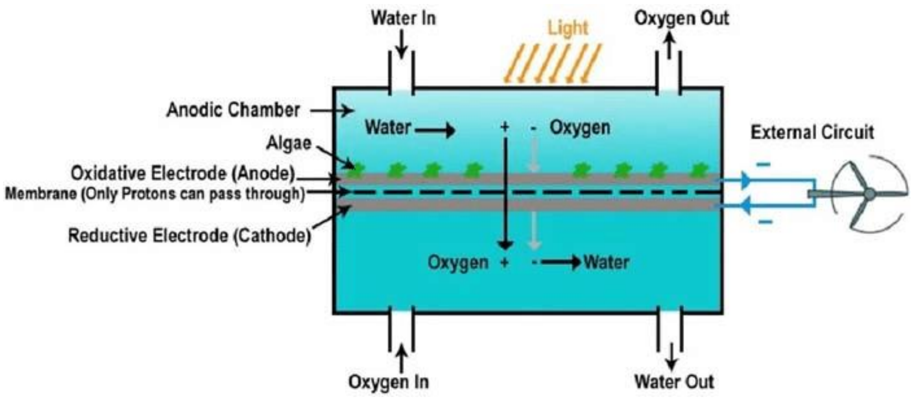

Figure 1.2 BPV system (Soni et al., 2016)

Biofilm-BPV devices can provide considerable power output, but it needs a large surface area to grow thin electrically productive biofilms. In other words, it needs abundant land resources to support megawatt-scale power supplements of such a system. Therefore, it is not a good choice for large-scale application of BPV. Suspension-BPV devices obtain bioelectrical energy from well-mixed and multiphase flow microalgae culture directly, and it could be installed as a value-added product in algal cultivation facilities. It is a potential solution to minimize the requirement of BPV devices on land resources. The applicability of BPV devices can be further improved by installing the system on the ocean surface. Costello et al. (2010) declared that the ocean covered 70.55% of the Earth's surface, which had a total area of 360.663 x 10^6 km^2. A floating BPV devices occupy spacious offshore area and utilizes microalgae culture as the power source, to minimize the acquisition of precious land resources.

1.2 Problem Statement

A biophotovoltaic (BPV) system is an emerging photo-bio-electrochemical technology that promises bioelectricity generation through the photosynthesis of exoelectrogenic microorganisms. By referring to previous studies, most BPV devices produce a limited bioelectrical energy in a range of 10^{-3} W/m^2 (Ng et al., 2014; Li et al., 2015; Liu et al., 2017; Ng et al., 2017; Bateson et al., 2018; Ng et al., 2018; Senthilkumar et al., 2018; Karthikeyan et al., 2020). The electrical power production of BPV devices, on the other hand, is relatively low, and this has become a significant challenge for this new technology. Sufficient supply would require large-scale BPV farms for megawatt applications, which may not be economically viable. A possible solution is to acquire bioelectricity from well-mixed microalgae culture, as it benefits the system in terms of volume. Moreover, it enables combination with an algae pool or floating photobioreactor. One technical concern is that previous studies focused on the absorption of electrons from cultivated biofilm, whereas bioelectricity generation by aerated microalgae culture under different anode materials still has research value. Hence, cell performance by well-mixed anodic microalgae culture under different anode materials is a crucial decision-making factor of suspension-BPV devices. In this study, the devices were aerated to create a well-mixed and multiphase flow microalgae culture. Therefore, the experiment was conducted to investigate the bioelectrical power generation of BPV devices in natural and aeration conditions from using four different anode materials, namely graphite, aluminium, indium tin oxide (ITO)-coated glass, and ITO-coated plastic.

1.3 Research Questions

The questions of the research are :

(a) What is the effect of key parameters on the bioelectricity generation of BPV devices?

(b) What effect does aeration-induced fluid motion have on a BPV device from its static state?

1.4 Research Objectives

The objectives of the research are :

(a) To determine the effects of various anode materials on the bioelectricity generation of BPV devices in natural and aeration modes.

(b) To determine the effects of aeration on bioelectricity generation in BPV devices with free surface and multiphase flow cultures

1.5 Scope of Study

The scope of the study involves anode materials and aeration for the experiment to be completed. Four types of anode materials, including graphite, aluminium, ITO-coated glass, and ITO-coated plastic, will be applied in the experiment. The performance of different anode-based BPV devices under natural conditions and aeration mode will be determined. Environmental parameters, including temperature and light intensity, will be measured throughout the experiment. The duration of experiment will range from four days to fourteen days. The voltage output of BPV devices will be determined at different resistances. The current density and power density of the devices will be calculated and used to plot the polarization curves. Researchers should know the effect of selected key parameters on the performance of BPV devices through the polarization curves.

1.6 Significances of Study

The research findings will be indispensable in assessing the effect of aeration on the bioelectricity generation of different anode-based BPV devices from their static state. This research studies aeration-induced multiphase flows in the cyanobacteria medium with free surface and its interaction effects with the bioelectricity generation of aerated-BPV devices. Most previous studies focus on the influence of biofilms or electrode materials on the bioelectricity generation of the BPV devices, and this is the first study providing a comparison between static and aerated BPV devices. It is hypothesized that indium tin oxide (ITO) films are suitable materials for electron transmission in both aerated and non-aerated BPV devices. Compared to natural conditions, aeration enhances the performance of BPV devices.

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LIST OF PUBLICATIONS

Indexed Conference Proceedings

1. **Chin, J. C.**, Chong, W. W. F., Lee, K. Q., Ng, C. Y., Lee, K. M., Tey, W. Y., & Kang, H. S. (2021). Interaction of Wave-Induced Motion and Bioelectricity Generation for Floating Microalgal Biophotovoltaic System. *Lecture Notes in Civil Engineering*, 266–273. https://doi.org/10.1007/978-981-33-6311-3_31 **(Indexed by Scopus)**

2. **Chin, J. C.**, Khor, W. H., Chong, W. W. F., Wu, Y. T., & Kang, H. S. (2022a). Effects of anode materials in electricity generation of microalgal-biophotovoltaic system - part I: Natural biofilm from floating microalgal aggregation. *Materials Today: Proceedings*. https://doi.org/10.1016/j.matpr.2022.03.138 **(Indexed by Scopus)**

3. **Chin, J. C.**, Khor, W. H., Ng, F. L., Chong, W. W. F., Wu, Y. T., & Kang, H. S. (2022b). Effects of anode materials in electricity generation of microalgal-biophotovoltaic system – part II: Free-floating microalgae in aeration mode. *Materials Today: Proceedings*. https://doi.org/10.1016/j.matpr.2022.03.576 **(Indexed by Scopus)**