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Modeling of microfluidic bio-solar cell using microalgae through multiphysics platform: A greener approach en route for energy production

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ABSTRACT

Due to the growing energy demands and increased concern over environmental deterioration and energy climate catastrophe, bio-energy based mechanisms had gained interest over recent years and had attained acknowledgment as the "greener" energy self-sustainable technologies of the future. A new micro-fluidic bio-solar cell modeling and their integration using COMSOL multi-physics have been proposed in order to convert solar energy into bioelectricity. *Synechocystis* PCC6803 is used as the microbial source due to its electrical property for generating electrons through an anodic chamber. Using COMSOL multi-physics platform, the microfluidic bio-solar cell was designed with five functioning layers. Each layer is been assigned with the suitable electrical/electrode properties of the polymer and the anodic chamber layer been assigned with the properties of the microalgae. Finally, the microfluidic bio-solar cell was modeled to create interfaces between optical and electrical physics in order to determine their material transport, heat transfer, electrochemical behavior, current density and voltage distribution behavior of the microfluidic bio-solar cell. The open circuit voltage of about 0.42 V is been obtained with 80% of absorption capacity. This modeling can be further developed into an extensible bio-solar panel by fabricating it using a microfluidic chamber for further application enhancement, which can replace inorganic solar cells with bio-solar cells for an eco-friendly environment with less production cost.

1. Introduction

The modern world faces high demand for energy in accordance with emerging energy challenges. It is expected to be a most dreadful scientific challenge for the researchers in the upcoming years towards the development of renewable and sustainable energy. By 2050 there will be a rapid increase in the global population, which is estimated to be around 10.6 billion. Further due to the confinement of the fossil fuel technology with the increasing cost and the growing affairs in terms of the adverse effects of the greenhouse gases especially in the emission of combustible carbon which is considered to be the major contributor to global warming, had engrossed researcher in finding out solutions for the depletion of the fossil fuel technology, carbon neutral sources and eco-friendly renewable energy resources and it also has become a key challenge for researcher ensuing research in the field of energy technologies. There are distinct types of alternate resources such as solar, geothermal, hydro, the wind. Each country follows its own ways of generating energy by using the above renewable energy resources. Among all, solar energy is the fastest emerging technology because of its incredibility and abundance. Therefore the application of the solar energy for the generation of electricity in terms of photovoltaic's, bio-solar cells or biofuels had gained the attention of the scientific research community since solar power is the major contributor of energy technology revolving around the photovoltaic cell application. The modern photovoltaic technology is based on Inorganic solar cells composed of silicon, which is highly superior in terms of efficiency. But nonetheless, this well-developed technology has some certain fundamental barriers in terms of cost and processing conditions. Hence a fundamental change is required to significantly improve the processing conditions and this was overcome by replacing silicon technology with organic solar cells (OSC). OSC are based on solution processing techniques which resulted in a reduction in cost and energy compensation time [1–4]. But these polymer modules suffered from less efficiency. These problems were resolved by using organic-inorganic metal halide perovskite

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semiconductors which derived higher efficiency at a low cost. Yet these perovskite solar cells experienced high environmental degradation due to the interaction of the perovskite materials with the moisture. To address these issues an Alternate greener version of solar cell termed as the bio-solar cell is been designed in order to gain insights in terms of reduction in environmental degradation and to avoid the depletion of the fossil fuel technology and they are based on the concept of bio-energy technologies. These technologies have drawn momentous research interest and had gained acknowledgment as the “Greener energy alternative of the future” because nature had harnessed solar energy technology very effectively via the photosynthetic process of electron generation [5]. The photosynthesis process acts as the base for all energy generation process including life and it is a distinct phenomenon occurring in many different organisms. This process can be improved by explicitly expanding the biological variations. The new bio-energy production technique involves the conversion of the solar energy into bioelectricity based on the natural system of photosynthesis process which has led to the discovery of bio-solar cells [6,7]. These bio-solar cells are otherwise known as the microbial fuel cells which involve in the production of bio-electricity based on the analysis of the photosynthetic biocatalytic reaction of the microorganism.

During photosynthesis, the microorganism captures solar energy in order to convert carbon dioxide and water into oxygen and carbohydrates. This generated organic matter is then finally used in their respiration process by regenerating carbon dioxide and water. At this time electrons are generated through the electron transport gateways and then they are discharged through the external electrical circuit. The proton has been released is then transferred from the anode to the cathode, where they re-associate with the electrons and oxygen to reform water. This process features as the Earth essential ecosystem because they require only sunlight, water, and carbon dioxide to generate electricity which is considered to be a superior trait when compared to the other feasible sources such as photovoltaic's or microbial fuel cell [8]. These bio-solar cells comprise of the photosynthetic microorganisms which don't require any organic fuel and this counteracts the need for an active feeding system and they are also capable of producing power throughout a day where the biotic components work in the conjugation with the abiotic components to attain self-sustainability [9]. Till date, prominent efforts were taken in demonstrating the photosynthesis activity of the various cyanobacteria strains or algae [10,11]. In spite of their enormous potential, they suffer from constant performance constraints and scale up a barrier. One of the considerable issues in the conventional bio-analyte cell is due to the disproportion of the device architecture configuration and the anodic layer for capturing sufficient solar energy and this is mainly because of the configuration of the dual chambered device [12]. Usage of anode materials with low electron transfer efficiency might also result in the poor correlation between the organism and the anodic material and a decrease in the power generation capacity [13]. Another challenge is the need to utilize an oxidant as an electron acceptor such as potassium ferricyanide [14]. Small scale bio-solar cells are considered to have larger power density when compared with larger units [15]. Hence these smaller units can be arranged and connected as the multiple units in order to produce higher energy outputs and only a small part of the research group had shown interest in scaling up from macro-sized bio-solar cell to macro regime. In this work, micro-fluidic bio-solar cells were designed using five functioning layers as shown in Fig.1. Each layer is been assigned with the suitable electrical/electrode properties of their corresponding polymer materials according to their working function and the anodic chamber layer is been assigned to the properties of cyanobacteria so that it acts as the particular strain. Finally, the bio-solar cells were modeled to create interfaces between the optical and the electrical physics in order to determine their material transport, heat transfer, electrochemical behavior, current density and voltage distribution behavior of the microfluidic bio-solar cell.

2. Bioanalyte reactions

Cyanobacteria are considered to be the prime species in the new adobe because of their massive availability in all over nature. They have the capability of colonizing all over the environmental divisions and in delivering the photo-energy as a floor for other habitat. They have the competency of fixing atmospheric CO_2 by converting the solar energy into the bioenergy medium. This route of transforming solar energy into bioenergy resources paves the way for harvesting effective forms of eco-friendly energy resources. Cyanobacteria can withstand effectively to intense environmental threat starting from the alkaline hot spring condition to the polar zone making them aggressive towards other life patterns. These adaptable groups of photoautotrophic bacteria can be used to design bio-cells and to create interfaces between the microorganisms. Hence they are known as the primary producer of the biomass on the earth. They have a significant metabolic functionality of intersecting photosynthetic reactions with the respiratory electron transport chains which make them unique from other forms of organisms.

They are mostly found in alkaline regions and can grow at a temperature of up to 74 °C [16]. True psychrophilic cyanobacteria are less in numbers and can metabolize even at near 0 °C, but they need an optimum temperature of about 15 °C to grow [17]. It has been reported that the filamentous cyanobacteria can withstand even at the high acidic environment with pH as low as 2.9. It has also been investigated that cyanobacteria can survive in an extremely harsh alkaline environment with pH as high as 13 [18]. These photosynthetic microorganisms have the capacity of thriving even under higher solar and UV radiations [19]. Halotolerant cyanobacteria are a type of bacteria present in the coastal region which can colonize even in the euryhaline conditions having the competency to grow in the unified salt circumstances [20]. Cyanobacteria capability to grow photo autotrophically has made it appear as one of the significant criteria to use this bacteria in the application of the bioenergy production technology for generating electricity from the solar energy in a self-sustainable way. They are used in this application because of their resistance towards organic contaminants and high salt concentration, ability to survive under conflicting environmental situations and their competency to develop stable bio-cells for the generation of the bioelectricity.

The electrogenic attitude of the cyanobacteria is well documented. Tanaka et al. investigated a bio-electrochemical based system and generated a current output involving cyanobacteria as a bacterial source and 2-hydroxy-1, 4-naphthoquinone (HNQ) as an artificial redox mediator operating under anaerobic conditions [21]. Later on, *Synechococcus* sp., was studied as the catalyst using HNQ as a redox mediator achieved an increase in cell voltage; upon illumination, a current output of about 230 mA was attained. But however, this resulted in less columbic yield [22]. The electron transport property of the *Synechococcus* sp. PCC7942 was examined using 1, 4-Benzoquinone (BQ) and 2, 6-dimethyl-1, 4-benzoquinone (DMBQ) as electron acceptors in the photosynthetic system and attained a current density of about 10 mA/cm^2 [23]. To improve the current density two mediators such as ferricyanide and an osmium based polymer was used. Further *Lyptolyngbia* sp. (CYN82) were used as the bacterial strain, which was immobilized using graphite electrodes resulted in a maximum power generation of about 48.2 mA/cm^2 [24]. An elemental design based on *Nostec* sp. and carbon nanotube as donor and laccase/CNT as the cathode were reported with the maximum current density of about 250 mA/m^2 and this was improved by the addition of the 1,4-benzoquinone as the redox mediator resulting in current density of about 2300 mA/m^2 and a power density of about 100 mW/m^2 [25]. Later on *Rhodopseudomonas palustris* was used as the photosynthetic bacteria and generated a maximum power density of about 5.26 mW/cm^2 with an open circuit voltage of about 0.089 V [26]. *Spirulina platensis* was investigated in a parallel and serial mode and yielded a maximum open circuit voltage of about 450 mV and 310 mV [27]. Native *Nostoc* sp.,