Photosynthesis-Assisted Energy Generation

From Fundamentals to Lab Scale and In-Field Applications

Edited by
Sathish-Kumar Kamaraj • Iryna Rusyn

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Preface

Sustainable renewable energy technologies are gaining prominence. The biological basis for sustainable renewable energy is the most appealing priority on that list. Sustainable photosynthesis-assisted power generation is an intriguing renewable energy generation system, which generally exploits the light-harvesting systems of phototrophic prokaryotes (oxygenic phototrophic-cyanobacteria and anoxygenic phototrophic-purple, green, and heliobacteria) and higher plants in biological systems. This may effectively capture and transform solar energy, resulting in anabolism and catabolism activity and ensuring biological system growth and development. The conversion of organic material into electricity using biocatalysts in microbial energy-generating systems such as microbial fuel cells is an emerging renewable energy generation systems. The integration of these efficient energy generation systems with photosynthetic biological systems opens up new possibilities in the sustainable renewable energy industries. The first part of the book introduces the essence of getting bioelectricity through photosynthesis-assisted systems, describing their fundamentals and basic operating principles. Direct electronic transfer (DET) and indirect electronic transfer (IET), including abiotic factors, are highlighted as key links in power generation. The section provides insights into the diversity and importance of both technological and biological components of photosynthesis-assisted power-generating systems. Functional fundamental materials such as electrodes, photocatalytic and membranes, as well as their structural design, are recognized as having a significant impact on the efficiency and power production of photosynthesis-assisted systems. The possibilities, constraints, and significant sustainability factors for photosynthetic microbial fuel cells are addressed. The diversity of exploited plants, including C3, C4, and CAM plants, as well as wetland and drought-resistant plants, is assessed, as is their critical impact on the performance of photosynthesis-assisted power-generating systems. The second part of the book presents an overview of the diversity of photosynthetic species used in photosynthesis-assisted power generation, including anoxygenic photosynthetic bacteria as well as oxygenic photosynthetic organisms such as cyanobacteria, microalgae, bryophytes, and other plants. Electrogenic microalgae are studied, as well as the impact of biomass weight and light intensity, temperature, and pH on the performance of photosynthetic microbial fuel cells. Purple photosynthetic bacteria dry-surface biofilms are clarified. Recent research on bryophytes as a prospective object of photosynthesis-assisted power-generating technology is presented due to their great stress tolerance and survival in a wide range of temperature conditions. The effect of plant species on the efficiency of plant microbial fuel cells (PMFCs) is explored, as well as the potential of wetland and drought-resistant plants for photosynthesis-assisted power generation. The third part of the book highlights advancements and recent trends in photosynthesis-assisted microbial fuel cells to power various types of low-energy-consuming devices and IoT: as a power supply for real-time LED and digital clocks, IoT-based WSN sensor systems, powering batteries and partially loading a mobile phone, and so on. Because of their synergistic interrelationships, ammonium and phosphorus treatment with hybrid photoautotrophic algal-assisted MFCs presents an effective sustainable technology for the elimination of organic matter and the removal/recovery of nutrients from different wastes with simultaneous zero-waste bioenergy recovery. Photo-bioelectrochemical fuel cells for antibiotics and dye removal with simultaneous power generation have only recently begun to emerge, but they have made great progress. PBFC systems have a high power generation capacity and can eliminate up to 99–100% of antibiotics and dyes, which is the topic of this section. The progress of PMFC applications for bioremediation as well as plant health monitoring and biosensing is presented. The book also discusses the challenges of obtaining bioelectricity on green roofs in various climatic conditions, such as northern countries with frosty winters and southern countries with arid climates, which both provide biosensing and climatic benefits by reducing urban heat island temperatures using various types of photosynthesis-based microbial fuel cells. The prospect of agriculture-based crops in PMFC for futuristic sustainable protected agriculture is also considered. Finally, the most critical features of photosynthesis-assisted power generation sustainability are revealed. The topics encompassed in this discussion include renewable energy sources, the management of liquid effluents and solid residues in photosynthesis-assisted power generation, the environmental implications of bioelectrochemical systems, cost challenges, and the transition to a practical scale, as well as social considerations. With this in consideration, this book delves into the different distinct light-harvesting biological systems for energy generation, from principles to practical challenges ranging from the lab scale to in-field application.

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Part I

The Basic Principle and Fundamentals of Photosynthesis-Assisted Power Generation

The part introduces the essence of obtaining bioelectricity by the photosynthesis-assisted systems presenting their fundamentals and basic principles of operation. Electron transfer mechanisms as an important link in power generation, the latest current data of their various types, direct electronic transfer (DET), and indirect electronic transfer (IET), including through abiotic elements, are discussed. Insights into the diversity and importance of both technological and biological components of photosynthesis-assisted power generation systems are revealed in this section. Functional basic materials such as electrodes, photocatalytic and membranes, and also their structural design that has some of the crucial effects on efficiency and power output of the photosynthesis-assisted systems are highlighted. Opportunities, limitations, and considerable sustainable parameters for photosynthetic microbial fuel cells are clarified. The diversity of exploited plants, C3, C4, and CAM plants, wetland and drought-resistant plants, and their essential impact on the performance of photosynthesis-assisted power generation systems are evaluated.

1

Introduction to Electron Transfer Mechanisms in Photosynthesis-Assisted Power Generation

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1.1 Introduction

Electron transfer mechanisms (ETMs) are chains where microorganisms generate energy during their activities and this energy can be harnessed by bioelectrochemical systems. Microorganisms regulate their ETMs so that electrons from a donor are transferred to an available electron acceptor, which maximize their energy gain (Patil et al., 2012).

Bioelectrochemical systems, also known as plant microbial fuel cells (PMFC), are composed of two electrodes (anode and cathode) and an electrolyte. These systems utilize microorganisms that are either attached to one or both electrodes to catalyze the oxidation reaction at the anode and/or reduction reaction at the cathode (Hamelers et al., 2010).

Bioelectrochemical systems have the ability to transfer electrons bidirectionally between biotic and abiotic components, where redox-active microorganisms or biomacromolecules catalyze the exchange process. PMFCs work through the ETM that occurs in bioelectrochemical systems, where microorganisms transport electrons to a final acceptor, known as the anode. These electrons then pass through an external circuit to reach the cathode, and protons migrate through ions dissolved in the electrolyte to reach the cathode; this process closes the circuit and generates electrical energy and removes the organic matter. MFCs can be used to generate hydrogen, known as microbial electrolysis cells, for the

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generation of solar energy, known as microbial solar cells, and microbial plant cells (photosynthesis) (Kumar et al., 2017).

The aim of this chapter is to describe the mechanism of electron transfer in PMFCs, occurring mainly at the anode and cathode of the systems, and the role of microorganisms working in the systems, as well as the various technologies that utilize the electron transport chain.

1.2 Electron Transfer Mechanism

A conventional microbial fuel cell (MFC) is composed of an anode and cathode chamber, which are separated by proton exchange membranes. The MFC generates its energy from the oxidation of organic matter by bacteria at the anode, and with the reduction of oxygen at the cathode (Logan et al., 2005).

The key advantages of biological fuel cells, in comparison to conventional fuel cells, are the mild operation conditions (ambient temperature and near-neutral pH) and the virtually unlimited range of potential fuels, for the oxidation of which we lack suitable electrocatalysts (Schröder, 2007).

Microorganisms are not evolutionarily designed to dispense energy to power a fuel cell—the majority of relevant redox processes take place within the microbial cells, and it is a great challenge and a major research issue to find means to efficiently divert electrons from the metabolism to the anode of the fuel cell. Various approaches have been proposed. They differ in the nature and the mechanism of the electron transfer from the microorganism to the fuel cell anode (Schröder, 2007).

Respiration in bacteria is a versatile process that involves multiple metabolic networks acting as conduits for electron flow to a terminal electron acceptor (TEA). Microorganisms harvest electrons from organic and/or inorganic molecules present in their environment and transfer these to specialized electron transport chains during cellular respiration. Electrons are ferried by the carrier proteins of the electron transport chain to the TEA for the purpose of generating energy via the creation of a transmembrane ion gradient for ATP synthesis. TEAs run the gamut from oxygen to organic carbon-based molecules in the case of fermentation, and inorganic molecules such as sulfate and nitrate. In the case of oxygen, its high redox potential, easy uptake into the cell, and abundance in the atmosphere makes it a natural TEA for the majority of living organisms. In anaerobic environments, the cells depend on alternative TEAs for energy generation. Molecules such as nitrate and sulfate in dissolved form can be ingested into the cell and used for the energy generation process. However, many anaerobic environments do not possess sufficient reserves of soluble TEAs. In such cases, microbes adapt by extending their redox circuitry across the cell membrane and accessing TEAs for the final discharge of electrons. This phenomenon, called the extracellular electron transfer (EET), requires special mechanisms and