



Photosynthesis-Assisted Energy Generation

From Fundamentals to Lab Scale and
In-Field Applications

Edited by
Sathish-Kumar Kamaraj · Iryna Rusyn

WILEY

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Published by John Wiley & Sons, Inc., Hoboken, New Jersey.

Published simultaneously in Canada.

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Library of Congress Cataloging-in-Publication Data

Names: Kamaraj, Sathish-Kumar, editor. | Rusyn, Iryna, editor.

Title: Photosynthesis-assisted energy generation : from fundamentals to lab scale and in-field applications / edited by Sathish-Kumar Kamaraj, Iryna Rusyn.

Description: Hoboken, New Jersey : Wiley, [2024] | Includes index.

Identifiers: LCCN 2023053436 (print) | LCCN 2023053437 (ebook) | ISBN 9781394172306 (hardback) | ISBN 9781394172313 (adobe pdf) | ISBN 9781394172320 (epub)

Subjects: LCSH: Photosynthesis. | Electric power production.

Classification: LCC QK882 .P37 2024 (print) | LCC QK882 (ebook) | DDC 572/.46—dc23/eng/20231219

LC record available at <https://lcn.loc.gov/2023053436>

LC ebook record available at <https://lcn.loc.gov/2023053437>

Cover Design: Wiley

Cover Image: Courtesy of author

Contents

List of Contributors xv
Preface xxi
Acknowledgments xxiii

Part I The Basic Principle and Fundamentals of Photosynthesis-Assisted Power Generation 1

**1 Introduction to Electron Transfer Mechanisms in
Photosynthesis-Assisted Power Generation 3**
Nancy González Gamboa

1.1 Introduction 3
 1.2 Electron Transfer Mechanism 4
 1.2.1 Electron Transfer at the Anode 5
 1.2.2 Electron Transfer at the Cathode 6
 1.3 Photosynthesis in the Electron Transfer Mechanism 8
 1.3.1 Anodic Electrode 10
 1.3.2 Cathodic Electrode 10
 1.4 Technologies In Which the Photosynthesis Process Can Be Applied
for Energy Generation 12
 1.5 Future Vision of the Use of Photosynthesis in Energy Generation 15
 1.6 Conclusion 17
 References 18

**2 Role of Functional Materials Involved in the Photosynthesis-Assisted
Power Generation 21**
*Manoj K. Srinivasan, Pratima B. Jayarm, Ravichandiran Ragnath,
Briska Jifrina Premnath, Nalini Namasivayam, and Sathish-Kumar Kamaraj*

2.1 Introduction 21
 2.2 Plant-Mediated Microbial Fuel Cells 23

2.2.1	Basic Concept of PMFCs	23
2.2.2	Plants and Their Bioelectricity Generation Capabilities	25
2.3	Applications of PMFC technology	27
2.4	Development of Electrodes and Membranes for Plant Microbial Fuel Cells	28
2.4.1	Progress in Electrode Materials	29
2.4.1.1	Progress in Anode Materials	30
2.4.1.2	Progress in Cathode Materials	34
2.4.2	Development of Membranes for PMFC Performance	37
2.5	Challenges and Future Perspective	41
2.6	Conclusion	42
	References	43
3	An Overview of the Non-noble Electrocatalysts as Air Cathodes in Biocells	57
	<i>Omar Francisco G. Vazquez and Ma. Del Rosario M. Virgen</i>	
3.1	Introduction	57
3.2	Operation and Structure of the Aerated Cathode	59
3.2.1	Advantages of Aerated Versus Non-aerated Cathodes	60
3.2.2	Oxygen Reduction Reactions and Electron Transport	60
3.3	Importance of Materials in the Construction of Catalytic Electrodes for Hydrogen Reduction	62
3.3.1	Use of Noble Metals as Catalytic Materials and Their Performance	62
3.4	Disadvantages of Noble Metal Electrocatalysts	63
3.4.1	Synthesis	63
3.4.2	Economy	65
3.4.3	Performance	65
3.5	Synthesis of Non-noble Electrocatalysts and Their Performance	65
3.5.1	Metals	65
3.5.2	Carbonaceous	66
3.5.3	Amalgams	67
3.5.4	Carbides	68
3.5.5	Nitrides	69
3.5.6	Oxides	70
3.6	Conclusions and Perspectives	70
	References	71
4	Configurations of Plant-Based Microbial Fuel Cell System and Its Impact on Power Density	77
	<i>Mohnish M. Borker</i>	
4.1	Introduction	77
4.2	Operating Principle	78

4.3	PMFC Configurations	79
4.3.1	Open Circuit Voltage (V_{oc})	81
4.3.2	Polarization Curves	81
4.4	Cylindrical PMFC	82
4.5	Conclusion	85
	References	86
5	The Critical Impact of Photosynthetic Pathway of Plants on the Performance of PMFC	87
	<i>Julio C. Gómora-Hernández, Nicolas Flores-Álamo, L.A. Díaz-Colín, S. Ventura-Cruz, and Miriam J. Jiménez-Cedillo</i>	
5.1	Introduction	87
5.2	Brief History of PMFC	89
5.3	Conformation of Conventional PMFC, Electrode Materials, and Basic Elements	90
5.4	Bacterial Community	92
5.5	Rhizodeposition Process and Photosynthetic Pathways	94
5.6	The Role of C3, C4, and CAM Plants in PMFC	97
5.7	The Role of Wetland and Drought-resistant Plants in PMFC	109
5.8	Trends and Future Perspectives	110
5.9	Conclusions	111
	Acknowledgments	112
	References	112
	Part II The Diversity of Photosynthesis-Assisted Power Generation	125
6	Insights on Algae-based Microbial Fuel Cells	127
	<i>Nivedha Jayaseelan, Vennila Lakshmanan, Kanimozhi Kaliyamoorthi, Olikkavi Subashchandrabose, Tani Carmel Raj, and Sathish-Kumar Kamaraj</i>	
6.1	Introduction	127
6.2	Algae-based Microbial Fuel Cells (AMFCs)	129
6.2.1	Microbial Carbon Capture Cells (MCCs)	129
6.2.2	Sediment Microbial Fuel Cells (SMFC)	131
6.3	The Implementation of Algae in MFCs	132
6.3.1	MFCs with algae-assisted cathodic compartment	132
6.3.2	Biomass-derived Algae as a Substrate in the Anodic Compartment	135
6.4	The Wastewater Treatment Using Algae-assisted MFCs (AMFCs)	137
6.4.1	COD Reduction in Algae-based MFC with the Use of Algal Biomass	137

- 6.4.2 The Removal of Nitrogen and Phosphorus Utilizing AMFCs at the Cathode 139
- 6.4.3 The Recuperation of Compounds with Value-added Microorganisms Based on Algae 139
 - 6.4.3.1 Formation of Photosynthetic Biofilm on the Cathode 139
- 6.4.4 Carbon Dioxide (CO₂) Removal by the Use of MFCs with Algae-assisted Cathodes 140
- 6.5 Photosynthetic Algae Microbial Fuel Cell (PAMFC) 140
 - 6.5.1 Reactor Design – PAMFCs 141
 - 6.5.2 Photosynthesis-related Factors Influencing Reactor Performance 142
 - 6.5.2.1 Effect of Light on AMFCs 142
 - 6.5.2.2 Genetic Modification of Algae for Improved Photosynthesis 143
- 6.6 Conclusion 143
 - References 144

7 An Overview of Photosynthetic Bacteria-Based Microbial Fuel Cells 153

Kuppurangan Gunaseelan, Moogambigai Sugumar, and Selvaraj Gajalakshmi

- 7.1 Introduction 153
- 7.2 Ecology, Metabolism, and Extracellular Electron Transport in OPB and APB 155
 - 7.2.1 Oxygenic Photoautotrophs-Based Microbial Fuel Cells 156
 - 7.2.2 Anoxygenic Photoautotrophic Bacteria-Based Microbial Fuel Cells 159
- 7.3 Advantages of the APB over Algae and Cyanobacteria 162
- 7.4 Optimization of Light Source for Sustainable Electricity Production 163
 - 7.4.1 Source of Light 164
 - 7.4.2 Photoperiod 165
 - 7.4.3 Light Intensity 166
- 7.5 Governing Factors and Bottlenecks of Photosynthetic Bacteria-Based Microbial Fuel Cells 167
- 7.6 Conclusion 168
 - References 168

8 The Development of Bryophyte Microbial Fuel Cell Systems 177

Iryna Rusyn, Wilgince Apollon, and Soumya Ghosh

- 8.1 Introduction 177
 - 8.1.1 Physiological Peculiarities of Mosses as an Object for Electro-biotechnology 178

8.2	Moss-Driven Microbial Fuel Cells	180
8.3	Indoor Application of Moss-PMFC	184
8.4	Bryophyte PMFC as a Source of Photosynthesis-Associated Energy Generation on Green Roofs	185
8.4.1	Eco-environmental Value of Green Roofs	185
8.4.2	Comparative Analysis of Bryophyte-PMFC with other ones using on Green Roofs	186
8.5	Perspectives of Bryophyte PMFC	189
8.6	Conclusions	190
	References	190
9	Duckweeds as Biocatalysts in Plant-based Biofuel Cell	199
	<i>Yolina Hubenova and Mario Mitov</i>	
9.1	Introduction to Plant-based Microbial Fuel Cells	199
9.2	Biofuel Cells Using Aquatic Higher Plants as Anodic Biocatalysts	200
9.2.1	Structure of the Duckweeds	201
9.2.2	The Electrical Parameters Achieved by Plant Biofuel Cells (P-BFC)	202
9.2.3	The Generated Current by P-BFC Depends on the Light Source	204
9.2.4	The Rootles <i>Wolffia globosa</i> in Plant-based Biofuel Cell	205
9.3	Influence of the Electrode Polarization on the Plants' Metabolism	208
9.3.1	The Change in the Protein Content	208
9.3.2	Synthesis, Accumulation, and Degradation of Carbohydrates	209
9.3.3	Formation and Degradation of the Phytates	211
9.4	Components of Photosynthetic Systems Involved in the Direct EET to the Anode	212
9.5	Future Challenges and Concluding Remarks	216
	Acknowledgments	217
	References	218
10	Low Power Voltage Acquisition System for Photosynthesis-Based Microbial Fuel Cells	221
	<i>Victor A. Maldonado-Ruelas, Raúl A. Ortiz-Medina, Sathish-Kumar Kamaraj, Wilgince Apollon, and Marco A. Vázquez-Gutierrez</i>	
10.1	Low Power Sources	221
10.1.1	Photosynthesis-Based Microbial Fuel Cells	222
10.1.2	Potential Difference	222
10.1.3	Power and Energy	224
10.2	Voltage Acquisition System	224
10.2.1	Analog Instrumentation	225

10.2.1.1	In Parallel (Independent PMFC)	225
10.2.1.2	Multiplexed (PMFC Dependent)	225
10.2.2	Acquisition System Design	225
10.2.2.1	Input Impedance Coupler	227
10.2.2.2	OFF-SET Added to Suppress Input Signal Polarity	227
10.2.2.3	Adjustable Gain Amplifier	227
10.2.2.4	Output Voltage Limiter	228
10.2.2.5	Bass-Pass Filter to Eliminate High-Frequency Noise	228
10.2.2.6	Output Impedance Coupler	228
10.2.3	Physical Implementation and Operation Tests	228
10.2.4	Programing of Digital Platform	229
10.2.5	Operation of the Integrated Voltage Acquisition System	231
10.3	Field Application of the Acquisition System	232
10.3.1	Prickly Pear	232
10.3.2	<i>Plectranthus hadiensis</i> (Vaporub)	232
10.3.3	<i>Stevia</i>	235
10.4	Conclusions	235
	References	236

Part III Lab-Scale and Infield Application of Photosynthesis-Based Microbial Fuel Cells 239

11	Plant-Based-Microbial Fuel Cells for Bioremediation, Biosensing, and Plant Health Monitoring	241
	<i>Roshan Regmi, Vinh Nguyen, and Ranjita Sapkota</i>	
11.1	Introduction	241
11.2	Bioelectricity Generation Using a Plant-based Microbial Fuel Cell	242
11.3	PMFCs for Bioremediation	243
11.4	PMFCs for Control of Biogas Emission	245
11.5	PMFCs-based Sensors	247
11.6	PMFCs for Plant Health Monitoring	247
11.7	Design Criteria for Plant-based Microbial Fuel Cells	248
11.7.1	Anode	248
11.7.2	Cathode	249
11.7.3	Single Chamber PMFCs	249
11.7.4	Dual Chamber PMFCs	250
11.7.5	Reactor Design	250
11.8	Conclusion and Recommendation	251
	References	253

- 12 Progress and Recent Trends of Application of Low-energy Consuming Devices and IoT Based on Photosynthesis-assisted Power Generation 261**
Edith Osorio-de-la-Rosa, Mirna Valdez-Hernández, Rosa M. Woo-García, and Javier Vázquez-Castillo
- 12.1 Introduction 261
 - 12.2 Promising Plants for Use as Energy Sources 263
 - 12.3 Understanding Energy Harvesting 267
 - 12.4 Low-consumption Electronic Devices for IoT Applications 268
 - 12.4.1 Bluetooth® Low Energy 270
 - 12.4.1.1 Bluetooth 4.0 270
 - 12.4.1.2 Bluetooth 5.0 273
 - 12.5 Precision Agriculture 275
 - 12.6 Conclusion and Future Perspectives 277
 - References 278
- 13 Problems of Improving Organics, Ammonium and Phosphorus Treatment with Algal-assisted MFCs 285**
Nguyen Trung Hiep
- 13.1 Introduction 285
 - 13.2 Components and Designs of Algal-assisted MFCs 286
 - 13.2.1 Components of A-MFCs System 286
 - 13.2.1.1 Electrodes 286
 - 13.2.1.2 Proton Exchange Membrane (PEM) 287
 - 13.2.1.3 Anolyte and Catholyte 287
 - 13.2.2 Designs of A-MFCs System 287
 - 13.2.2.1 Single-chambered Algae-MFCs 287
 - 13.2.2.2 Dual-chambered Algae-MFCs 289
 - 13.2.2.3 Triple-chambered Algae-MFCs 290
 - 13.3 Factors Influencing the Performance of the Algal-assisted MFCs System 291
 - 13.3.1 Algal Species 291
 - 13.3.2 Microbial Community 293
 - 13.3.3 Light Therapy 294
 - 13.3.4 Temperature 295
 - 13.3.5 pH 296
 - 13.3.6 Organic Loading Rate (OLR) 297
 - 13.3.7 Hydraulic Retention Time (HRT) 298
 - 13.4 Limitations and Future Perspectives of A-MFCs 299
 - 13.4.1 Limitations 299

- 13.4.2 Future Perspectives 300
- 13.5 Conclusion 301
- References 301

14 Development and Achievements of Photo-bioelectrochemical Fuel Cell (PBFC) in Metal, Antibiotics, and Dyes Removal 311

Anwasha Mukherjee

- 14.1 Introduction 311
- 14.2 Microorganisms Involved in Metal, Antibiotic and Dye Removal 313
- 14.3 Mechanism of Toxic Compounds Removal Through Photo-Bioelectrochemical Fuel Cell (PBFC) 316
 - 14.3.1 Mechanism of PBFC 316
 - 14.3.2 Various Configurations of PBFC for Toxic Compound Removal 317
 - 14.3.2.1 Bioanode–Photocathode System 317
 - 14.3.2.2 Photoanode–Biocathode System 318
 - 14.3.2.3 Biophotoanodic System 318
 - 14.3.3 Various Materials Involved in PBFC Structure 319
 - 14.3.4 Photoelectrode-Microbe Interaction 320
- 14.4 Recent Developments in PBFC for Metal, Antibiotics, and Dye Removal 322
- 14.5 Challenges and Future Outlook 326
- 14.6 Conclusion 328
- References 329

15 Agriculture-based Crop in PMFCs for the Futuristic Sustainable Protected Agriculture 337

Divya Shanmugavel, Omar Solorza-Feria, and Sathish-Kumar Kamaraj

- 15.1 Introduction 337
- 15.2 Challenges for Agriculture 339
- 15.3 Development of Plant Microbial Fuel Cells 341
- 15.4 Agriculture-Based Crops in PMFCs 343
 - 15.4.1 C3 Photosynthetic Plant 344
 - 15.4.1.1 *Oryza sativa* 344
 - 15.4.1.2 *Vigna radiata* 345
 - 15.4.1.3 *Solanum lycopersicum* 345
 - 15.4.1.4 *Stevia rebaudiana* 346
 - 15.4.2 C4 Photosynthetic Plant 346
 - 15.4.2.1 *Zea mays* 346
 - 15.4.3 CAM Photosynthetic Plant 347
 - 15.4.4 *Opuntia* species 347

- 15.5 Development of Green Energy System to Promote Sustainable Agriculture 350
- 15.6 Conclusion 351
- References 351

Part IV Sustainable Issues Associated with Photosynthesis-Assisted Power Generation 357

16 An Overview of Sustainable Issues Associated with Bio-Assisted Power Generation Systems 359

Lakshmiathy Muthukrishnan, Sathish-Kumar Kamaraj, Manuel Sánchez-Cárdenas, and Luis Antonio Sánchez-Olmos

- 16.1 Introduction – Paradigm Shift toward Sustainability 359
- 16.2 Sustainable Systems 360
 - 16.2.1 Exploring the Bio-catalytic and Self-Assembly Characteristics 360
 - 16.2.2 Self-Repair and Replication, Energy Harvesting, and CO₂ Fixation and Chemosynthesis 361
- 16.3 Challenges and Motivations 363
- 16.4 Biological Solution 365
- 16.5 Life Cycle Assessments (LCA) 366
- 16.6 Composite Sustainability Indices (CSI) 367
- 16.7 Construction of a CSI 368
- 16.7.1 Selection, Judgment, and Data Collection 369
- 16.8 The Concept of Biorefinery and their Applications 370
- 16.9 Biorefinery Technology 371
 - 16.9.1 Pathways 372
 - 16.9.2 Thermochemical Pathway 373
 - 16.9.3 Combustion 374
 - 16.9.4 Carbonization 374
 - 16.9.5 Pyrolysis 374
 - 16.9.6 Gasification 375
 - 16.9.7 Liquefaction 375
 - 16.9.8 Biochemical Pathway 376
 - 16.9.9 Step by Step Chemical Conversion 376
- 16.10 Circular Economy 376
- 16.11 Limitations 378
- 16.12 Conclusions 378
- References 380

Index 385

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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.

Acknowledgments

First, we want to thank God for blessing us with good health and the ability to edit this book. Our deepest gratitude goes to Wiley for believing in our work and accepting our book for publication. We thank all the authors who responded to the suggestion for cooperation and their excellent work. Thanks to everyone who helped make this book a reality – the authors, the reviewers, and everyone in between. We are grateful to the many publishers and authors who permitted us to use their work, especially the figures and tables.

Sathish-Kumar Kamaraj would like to express his gratitude to the Director General of Instituto Politécnico Nacional (IPN) and the Director of Centro de Investigación en Ciencia Aplicada y Tecnología Avanzada, Unidad Altamira (CICATA Altamira), for their constant support and facilities in promoting the research activities. Thanks for the project SIP:20231443, Secretaría de Investigación y Posgrado (SIP) – IPN. Further extensions to the funding agency of the National Council of Humanities, Sciences and Technologies (CONAHCyT – México) and the Secretary of Public Education (SEP – México). He extended his gratitude to Mrs. Mounika Kamaraj and Bbg. Aarudhraa for the family support.

Iryna Rusyn thanks God for the opportunity to work on this book during the difficult wartime in Ukraine and would like to express her gratitude to the family Mr. Oleksandr and Lukyan for their support.

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

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