NEWPORT INTERNATIONAL JOURNAL OF SCIENTIFIC AND EXPERIMENTAL SCIENCES (NIJSES)

Volume 6 Issue 3 Page 238-248, 2025

©NIJSES PUBLICATIONS
Open Access

ONLINE ISSN:2992-5819
PRINT ISSN:2992-6149

https://doi.org/10.59298/NIJSES/2025/63.238248

Microbial Electro-Biotechnology: Integrating Microbes with Bioelectrochemical Systems

Chukwudi Anthony Ugwuanyi

Department of Applied Microbiology Ebonyi State University Nigeria
Email:ugwuanyitony@gmail.com

ABSTRACT

Microbial electro-biotechnology is an emerging interdisciplinary field that integrates microorganisms with bioelectrochemical systems (BESs) such as microbial fuel cells (MFCs), microbial electrolysis cells (MECs), and microbial electrosynthesis systems. These systems exploit the capacity of electroactive microorganisms to catalyze extracellular electron transfer processes, thereby coupling microbial metabolism with electrical current generation, hydrogen production, or pollutant remediation. Fundamental advances in the understanding of bioanodes, biocathodes, electrode materials, and electron transfer mechanisms have enabled applications in wastewater treatment, energy recovery, bioremediation, biosensing, and integration with renewable energy systems. Despite their promise, large-scale adoption remains constrained by technical and economic barriers, including limited power output, material costs, and reactor complexity. Recent innovations in nanomaterials, reactor design, microbial consortia engineering, and hybridization with solar and wind energy highlight the potential of microbial electro-biotechnology as a sustainable pathway for energy production, waste valorization, and environmental remediation.

Keywords: Microbial electro-biotechnology; Bioelectrochemical systems (BESs); Microbial fuel cells (MFCs); Microbial electrolysis cells (MECs) and Extracellular electron transfer (EET).

INTRODUCTION

Microbial electro-biotechnology is an interdisciplinary field that combines microbial technology with bioelectrochemistry. It is based on the integration of microbes with bioelectrochemical systems such as microbial fuel cells, microbial electrolysis cells, or microbial electrosynthesis systems [1]. These systems exploit the ability of microorganisms to catalyse the conversion of chemical energy into electrical or chemical energy by exchanging electrons with solid electron acceptors or donors. The concept of microbial electrochemistry has attracted growing interest during the past two decades owing to its environmental, industrial and sensor applications [2]. The design and operation of bioelectrochemical systems, together with the classification and characteristics of the most common electroactive microorganisms, have been discussed in the existing literature [3].

Fundamentals of Bioelectrochemical Systems

Bioelectrochemical systems (BESs) bridge the gap between microbial redox reactions and electrochemical devices by exploiting the metabolism of electroactive bacteria [1]. Such biological/electrochemical conjugators enable the use of microorganisms in electrochemical devices and offer a new tool for electrochemistry. The systems comprise two electrodes, the anode and the cathode, and microorganisms that catalyze electrode reactions [2]. At the anode, microorganisms oxidize fuels, release electrons as part of respiration, and entrust them to the electrode, which acts as the extracellular electron acceptor. The electrons flow, via an external circuit, to the cathode responsible for an electrochemical reduction. The microbial anodic oxidation must necessarily be carried out by anaerobic bacteria to prevent oxygen, an even better electron acceptor, from diverting the electron flow from the electrode 3. Several classes of bacteria and archaea have been classified as electroactive microorganisms. Studies indicate that microbial fuel cells (MFCs) are one of the suitable technologies for sustainable CITW treatment due to their ability to generate electricity and degrade aromatic compounds and hydrocarbons concurrently [2]. In microbial anodic oxidation, microorganisms produce a sustained current until either the substrate or the electron acceptor (i.e., the anode) becomes unavailable, which results in their number increasing proportionally with the current produced. Microbial-assisted production of electrons is initially exploited for the generation of power from wastewaters, the removal of recalcitrant organic and inorganic compounds, and the supply of power to small-scale off-grid electronic devices. This microbial-based process can even be used in highly contaminated wastewaters characterized by low pH or high salinity. At the cathode, the electrons do not directly interact with the coupled carrier, which always requires a catalyst, either metallic or microbial. The oxidation at the anode represents the source of electrons able to sustain the reduction occurring at the cathode [1, 2].

Microbial Fuel Cells: Principles and Applications

Microbial fuel cells (MFCs) harness the catabolic activity of microbial consortia to convert the energy stored in chemical bonds into electrical current [4]. The rectangular design includes an anode, cathode, and intervening proton exchange membrane. When organic substrates degrade at the anode interface, the residual electrons enter the anode and continue to travel via the external circuit to the cathode, where the simultaneous migration of protons through the membrane combines with electrons and oxygen (or other electron acceptors) to produce water. Fuel cells therefore exploit microbes to facilitate the oxidation process and generate electrons and protons. MFCs provide a promising alternative to conventional wastewater treatment technologies, in which many energy-costly steps disable the reclamation of energy-rich components [4]. Instead, MFCs undergo the full degradation of organic pollutants and generate electricity as a by-product. In addition, MFCs produce biofuels, volatile fatty acids, and biopolymers during the electricity generation process. With their substrate and strain flexibility, MFCs can degrade an array of materials ranging from domestic and industrial organic wastewaters to lignocellulosic biomass (LCB) [5]. The abundant and underexplored LCB reservoirs contain a diverse assortment of carbon sources, and many of its components include inhibitors to microbial growth. LCB hydrolysates therefore serve as ideal carbon sources for microbes in MFC operations, enabling biological recycling of this bioresource and valorizing other forms of waste [6]. The electrogenic capacity of MFCs depends on the chosen microbial strains, substrates, electrode properties, and operating conditions, but the use of mediators further enhances this interaction and balances the electron uptake/transfer rates to improve performance. Contemporary MFC research and development has primarily focused on wastewater treatment, value-added product synthesis, biosensor applications, and future prospects [6].

Electroactive Microorganisms

Electroactive microorganisms are commonly referred to as exoelectrogens or electricigens. They are capable of transferring electrons extracellularly during their metabolic processes. Most of these microorganisms generate energy through anaerobic respiration with electron acceptors such as Fe3+, PO43−, nitrite, nitrate, or sulfate substances. Among the various electron acceptors used, these organisms could exchange electrons with electrodes in bioelectrochemical systems (BES), acting either as electron donors or electron acceptors [5].These microorganisms can either take up electrons from an electrode for reductive metabolism or transfer electrons produced during their metabolic processes to an electrode via extracellular electron transfer (EET). Based on the latter process, microbial fuel cells (MFCs) operate, enabling energy recovery from water or waste. Many of the well-studied electroactive microorganisms belong to the genera Geobacter and Shewanella, although the ability to transfer electrons to electrodes is assumed to be widespread. Electron transfer mechanisms during anode respiration in electroactive microorganisms have been studied extensively. Microorganisms may either be anode-respiring bacteria (ARB) that secrete electron shuttles, or the electrons may be transferred through nanowires or directly from cell surface cytochromes, with different microorganisms adopting different approaches [2, 5].

Types of Electroactive Microbes

Microbial electro-biotechnology refers to those technologies that integrate microbes with bioelectrochemical systems in a beneficial manner [2]. A wide spectrum of biotechnological applications of these systems has been explored, but with major emphasis on environmental applications. Bond and Winfrey (2001) were among the first to suggest the use of biofilm anodes for wastewater treatment. The concept was developed further by other microbiologists. Rabaey et al. (2004) documented the removal of organic components in wastewater and the simultaneous recovery of energy. Reimers et al. (2006) demonstrated energy generation from marine sediments, and tender et al. (2008) extended it to bioremediation. Microbial fuel cells have also been used in the detection of biological oxygen demand in wastewater (Yang et al. 2012) and in power generation as a supplement to renewable energy sources such as solar and wind energies [2]. Despite its immense commercial potential, microbial electro-biotechnology has encountered several limitations or challenges, which restrict its commercial application. Around the world, efforts continue to overcome the technical and economic disadvantages inherent in the design and construction of these bioelectrodes. The area is attracting the interest of researchers from various disciplines, who are being joined at present by representatives of the microelectronics and automobile industries [2, 3].

Mechanisms of Electron Transfer

Electrical energy can be generated by respiration and fermentation processes that occur during the metabolism of microorganisms. The first observation of electricity generated by microorganism activity dates from 1911 by Potter. Bioelectrochemical systems (BESs) can be considered as a class of biosystems that harness electron transfer from extracellular catabolic pathways to generate electricity or synthesis products of interest at the anode or cathode, respectively [1]. To maintain energy generation, BESs require electron acceptors and donors that can be solid, soluble, biological, or inorganic substances. Microorganisms capable of trapping and transferring these electrons are considered electroactive. Different microorganisms can be applied to the bioanode or the biocathode in order to reduce costs and contribute to the maximization of the reaction kinetics in BES applications. As the microbial metabolic electron transfer process is highly efficient, it has been exploited to harvest energy from organic waste with an electroactive bioanode associated with the development of microbial fuel cells (MFCs). The process involves the removal of simple electrons from inert organic matter that would otherwise carry out a respiratory metabolism by producing methane [2]. In MFCs, electrons are transferred to an anode and the energy harvested is used to reduce oxygen, producing water on the cathodic side (electricity production). However, the transfer of electrons to a cathode is not limited to oxygen reduction. When the cathodic reaction consumes additional energy, hydrogen can be generated in the microbial electrolysis cell (MEC). Oxygen and hydrogen rates obtained with BESs are extremely competitive with respect to conventional oxygen generation or hydrogen extraction via the electrolysis of water. Moreover, BESs have a wider range of applications, extending into bioremediation and the control of the greenhouse effect. An important aspect of the design of BESs for specific operations is the minimization of external energy consumption and the maximization of energy recovery [2, 3].

Bioanodes and Biocathodes

The microbe-electrode interface plays a crucial role in electron exchange. Anodes and cathodes serve as platforms for electrons to flow into or out of the system, from either inside to outside of a microorganism, or vice versa. In a microbial fuel cell, electroactive microbes attached to the anode oxidize fuel-producing electrons that travel through a circuit to the cathode [2, 3]. Redox active enzymes and cytochromes act as transecting zones that facilitate transfer of electrons from cell to electrode. Similarly, a biocathode combines biological catalysts such as enzymes or microbes with an electrode, promoting reduction half-reactions. The biocathode provides a reducible catalyst that reduces the overall overpotential at the electrode, enabling an injected electron to more easily drive a given reaction [2]. The most common anodic electrode material is carbonaceous. Carbon cloth, carbon felt, carbon brush, carbon paper, and graphite rods are favoured because of their excellent chemical stability, high conductivity, wide potential window, cost effectiveness, biocompatibility, and environmentally friendly properties. New anodes fabricated from nano-materials are currently receiving considerable attention. Carbon nanotubes, nano-engineered electrodes, nanofilms, and nanowires support the colonization of electroactive bacteria and enhance electron transfer by providing high surface-area-to-volume ratios, good catalytic properties, and favourable biocompatibility [7]. Numerous physico-chemical and biological properties define a good cathode material. Chemically, the cathode must be hydrophilic and polarizable, with comparatively low resistance, to act as a catalyst. Physically, it should feature a large surface area and high porosity to facilitate biofilm formation. Biologically, the material must be biocompatible, to ensure that surface cells remain healthy and viable [2]. Various materials are frequently drawn upon to achieve these requirements notably carbon cloth, carbon felt, and graphene oxide – alongside precious metals such as platinum and silver. Platinum stands apart as a widely favored catalyst for cathode reactions, but it is often more expedient to foster a mixed-species microbial community on the cathode that can stimulate oxygen reduction [3].

Design and Materials

Mediating the biotic/abiotic interface by chemical isolation alongside electronic connection of complementary catalysts addresses bio–inorganic incompatibilities while limiting voltage losses [2]. Together, materials and design criteria enable the evolution of microbial electro-biotechnology beyond energy into commodity chemicals and sustainable environmental solutions. Microbial electro-biotechnology integrates micro-organisms with bioelectrochemical systems, handheld devices exploiting the bi-directional transfer of electrons between microbes and electrodes to drive redox reactions for chemistry, energy and remediation [3]. Bioelectrochemical systems employ bioanodes or biocathodes to incorporate electroactive microbes that use electrodes exclusively as electron donor or acceptor, respectively, enabling targeted cell redox modulation without the inherent inefficiencies of mediators or external voltage. Interfacing microbes with electrodes colloidally or on immobilizing supports that permit metabolic interaction with the unbound biomass expands the scope of electrochemical participation to species that are naturally non-electroactive or are excluded by the physical barriers of the electroactive biofilm. Tailored electrode quantity, location and architecture, interim storage and run modes, or the use of membrane-separated cells reconciles microbiological with physical chemical design criteria and facilitates implementation of a broad array of bioelectrochemical technologies in a real-world context [8].

Performance Optimization

Several strategies have been identified to increase the performance of microbial fuel cells (MFCs) operating under widely different conditions [9]. Enhancing salinity tolerance extends application to high-salinity wastewaters, such as particular industrial effluents or seawater, while improving soil MFCs enables more-effective degradation of organic pollutants. Harvesting bioelectricity from natural environments, such as rice plants, represents a promising sustainable-energy production route [9]. Power output can be raised by selecting suitable waste inputs and by optimising operational conditions, including temperature and electrode design. Advances in the field are illustrated by tests of different food-industry by-products as sources of electricity, investigations of the microbial consortia involved, and fabrication of complex three-dimensional anode scaffolds incorporating nanomaterials. Microfluidic and flow architectures provide new opportunities to enhance fuel-cell function at electrode surfaces. Varying the anode-membrane surface-area ratio strongly influences overall operation under continuous mode, with an optimum ratio of around unity reported [9].

Microbial Electrolysis Cells

Microbial electrolysis cells (MECs) provide a complementary biotechnology to microbial fuel cells, but whereas microbial fuel cells generate electricity from waste organic material, microbial electrolysis cells generate hydrogen gas at the cathode [10, 11]. At the anode, a catalytic biofilm oxidizes organics and transfers released electrons to the anode. With 0.2–0.8 V of external power applied to counter the thermodynamic barrier to hydrogen evolution, and with protons diffusing from the anode through the separator to the cathode, electrons flow to the cathode, where the electrotrophic biofilm forms hydrogen gas through the combined activity of enzymes such as hydrogenases responding to the local electrochemical conditions. The electrodes and biofilms are immersed in electrolyte, which contains reactants and products alike [10].

Applications in Wastewater Treatment

Microbial Electro-Biotechnology: Integrating Microbes with Bioelectrochemical Systems. In the recent years, applications of Microbial Electro-Biotechnology have expanded significantly. Microbial communities bacteria, archaea, yeasts, and fungi are exploited for the development of bio-electrochemical systems (BESs) such as microbial fuel cells (MFCs) [10]. The MFCs are bio-electrochemical systems capable of converting renewable bioenergy into electrical energy by exploiting microbial catabolic activities. The treatment and reuse of wastewater is an important activity within the water industry. The depletion of fossil fuels and the high demand for energy play important roles in encouraging wastewater treatment plants to become resource recovery facilities. The implementation of BESs in wastewater treatment can indeed enable the simultaneous removal of organic pollutants and recovery of electric energy. However, this is currently limited by the high-cost of the electrodes used for the realization of bioanodes and biocathodes for energy recovery. The higher cost of the bioanodes used for the generation of electrons and protons combined with low energy recovery represent limiting factors to the exploitation of the MFCs at large scale [10, 11].

Treatment Mechanisms

Microbial electrochemical technology combines the versatility of microorganisms with electrochemical techniques to create sustainable solutions for water and wastewater treatment, contaminated sediment bioremediation, and the electrochemical conversion of waste into biofuels through microbial electrolysis. Central to these processes is the transfer of electrons that connects the microbial metabolism of pollutants to the anode (or cathode) of bioelectrochemical systems, thereby facilitating the degradation or recovery of contaminants [3]. Submerged microbial fuel cells employ microorganisms to harvest electrical energy from organic matter directly from wastewater, while microbial electrolysis cells apply external voltages less than 0.5 V to drive hydrogen production from diverse substrates. Electroactive microorganisms also accelerate reactions at cathodes, thereby expanding the range of substrates amenable to microbial electrochemical technologies. For instance, microbial fuel cells have been implemented on a 1.2-m3 scale to treat municipal wastewater, underscoring their potential for large-scale application [7]. In bioelectrochemical systems, electroactive organisms permit the operation of a bioanode at several hundred millivolts below the anodic potential measured in abiotic systems containing conventional redox mediators such as ferricyanide. In microbial fuel cells, electroactive microorganisms oxidize organic matter to carbon dioxide and subsequently transfer the deriving electrons to the anode. Their interaction with the anode can be direct or mediated; in the latter case, microbes release redox-mediating compounds that shuttle electrons between the organism and the electrode. The substrate requirement is linked to the microbial metabolism, implying that the macromolecules must be fermentable or biodegradable to smaller compounds that can be readily consumed by electroactive bacteria [7, 11].

Case Studies

Microbial electro-biotechnology harnesses electrochemically active microorganisms to generate electrical current in bioelectrochemical systems (BES). The technology can either be used for electrical power generation or to convert electrical energy into chemical energy [3]. The ability of microbes to provide or accept electrons to and from solid-state electrodes under aerobic or anaerobic conditions is well established. Electroactive microorganisms are ubiquitous in nature and belong to a wide variety of taxonomic ranks, including Geobacter species, Shewanella species, Pseudomonas aeruginosa, fermentative mixed communities, and natural consortia [12]. Because electron transfer and cellular metabolism remain coupled, the identity of electrons resembles the identity of metabolisms [8], and the electron transfer can be direct, indirect, dependent on special extracellular molecules such as redox proteins, riboflavins, or solid metal conductive nanowires. The development of microbial anodes and biocathodes has led to the advent of microbial electrolysis cells (MECs) as the complementary technology to microbial fuel cells (MFCs). Potential applications include wastewater treatment and bioremediation. Coupling BES with photovoltaic or other renewable energy sources is an additional route for exploiting the medium- and long-term sustainability of BES applications. Despite these opportunities, several challenges remain on the path to large-scale deployment. Case studies often provide validation of the previous sections and illustrate practical examples of the scientific findings and technological perspectives [3, 8, 12].

Energy Recovery from Organic Waste

Industrial activity and urban populations generate large quantities of organic wastes, often with high chemical oxygen demand (COD) [13]. Treatment of these materials generally requires relatively high levels of energy input, although the organic content of the wastewater can serve as the basis for recovering energy in the form of odour-free biogas or electricity. Bioelectrochemical systems (BESs) can treat such wastes at relatively low operational costs while using the organics as the energy source. This dual functionality makes BESs an attractive option, as sewage or effluents can be treated with the potential to produce useful energy [13]. Efficient treatment processes with energy recovery improve the economic viability of waste treatment [14]. Since the energy content of most wastewaters is significant, generating more energy than the process requires, energy-positive treatment is a realistic goal. Already the possibility of energy-neutral operation of wastewater treatment is pursued worldwide and BESs are gaining recognition for their potential to work as energy-positive methods at treatment plants [14].

Process Overview

Microbial electro-biotechnology describes technological applications in which living microbial cells are integrated with electrodes or electrode materials, thus constituting bioelectrochemical systems. Microbial electrochemical technologies exploit the ability of electroactive microorganisms to produce electrical energy from organic waste in microbial fuel cells, whereas in microbial electrolysis cells a small energy input is used for hydrogen production. In comparison with conventional waste treatment, both technologies have the advantage of combining resource recovery with the removal of organic compounds and pollutants from wastewater [13]. Treating domestic or industrial wastewater is the most common biotechnological application of microbial electrolysis cells, as waste streams can function as a bioanode fuel. The use of microbial electrolysis cells for energy recovery from organic waste or wastewater can improve the energy balance of wastewater treatment facilities. Additionally, hydrogen produced under anaerobic conditions is a chemical intermediate that can be exploited as a renewable fuel. Bioelectrochemical systems can also serve as a scaffold for assembling renewable, low-power consortia for the biodegradation of stubborn contaminants or the generation of value-added bioproducts [14].

Economic Considerations

Economic considerations of microbial electrochemical technologies are huge. Indeed, the costs associated with supporting the growth, metabolism, and electron transfer of living microorganisms are very low compared to the costs of highly refined catalysts such as platinum and ruthenium oxide, which are often used as cathode catalysts for HER and ORR, respectively. In addition, microbial electrochemical technologies offer the possibility of harassing energy from organic waste or wastewater streams. Lastly, removal of harmful organic or inorganic compounds is essential for life-cycle assessment and can offer additional benefits during resource-recovery engineering [14]. The coupling of microbial conversion with the electrochemical process can maximize the product spectrum and economic benefits. For example, the production of methane driven partially by solar and wind energies has recently attracted significant attention for the advantage of energy storage. The storage of low-quality energy, such as wind or solar energy, through the power-to-gas process is very important because it solves the problem of energy balancing and fluctuation; however, its actual operation can still be very costly. Integrating microbial conversion with electricity-assisted methane production provides a promising way of enhancing energy recovery from organic waste while minimizing operating cost [14].

Bioremediation using Bioelectrochemical Systems

Pollutants from industrial and urban activities, including organic chemicals, heavy metals and synthetic dyes, are often toxic and persistent, posing serious risks to aquatic and terrestrial ecosystems. Conventional remediation technologies, based on physicochemical treatments, are either ineffective or very expensive. Microbial electrochemical technologies offer an exciting alternative for enhancing the degradation rates and the remediation efficiency of polluted soil and groundwater [13]. Bioelectrochemical remediation systems can be implemented as combined biodegradation/electrochemical polishing units or as single cleaning technologies, in which the electrodes play the role of terminal electron acceptors/donors for microbial metabolism. Depending on the scientific literature available, the two approaches cannot be considered as truly independent technologies. Abiotic treatment stages have only been implemented as polishing units following biological processes and, conversely, what is usually called "main" biological treatment is always followed by a water discharge stage or by in situ biotic/abiotic extraction processes [14].

Integration with Renewable Energy Sources

Coupling bioelectrochemical systems to solar panels, wind turbines, or other sources of renewable energy extends the sustainable production of energy carriers and chemicals to cases of low-input-power delivery, while exploiting the microbial catalysis of oxidation and reduction reactions [15]. In the microbial electrosynthes is of fuels and chemicals, electricity from renewable sources such as solar- or wind-generated power is used to provide electrons to bio-catalysts for the reduction of CO_2 to fuels and other organic compounds. Efficient anodic oxidation of complex organic wastes to CO_2 with simultaneous production of electrons for the generation of electric power or the synthesis of H_2, while also enabling the recovery of pure metals from ionic solutions, requires both the design of stable conductive materials with high microbial affinity and the investigation of active microbial populations with capabilities for flexible substrate utilisation and extracellular electron transfer [15].

Solar Energy Integration

Bioelectrochemical systems powered by electroactive microorganisms have great prospects for a range of biotechnological applications that benefit sustainable development. Here, the basics of microbial electro-biotechnology, a discipline that integrates microorganisms with bioelectrochemical systems along with important aspects, are introduced [16]. Solar-energy inputs can be coupled to microbial electrogenesis to significantly expand the sustainability, efficiency, and range of applications. Electroactive microorganisms catalyse the oxidation of organic substrates and the formation of hydrogen using a poised electrode, and photo-electrodes have been designed to supply electrons to microorganisms at a cathode [16]. These microbial-electrode hybrid systems may be integrated for sustainable energy production and conversion.

Wind Energy Integration

Wind energy generation requires immediate operation of the turbine once wind velocity reaches the operational threshold, and during periods of extreme wind velocity, turbine brakes are applied. Therefore, energy storage for off-grid applications or to alleviate the burdens on the power grid is necessary to enhance the fitness of this energy source [17]. Microbial fuel cells in this field can provide immediate injection of stable current upon load by using bio-catalysed anodes in conjunction with semi-conducting oxides, overcoming drawbacks of physical storage methods and maintaining turbine operation through sustained electricity generation [15]. Integration of power bioreactors with wind energy systems could also be employed to harvest and store energy within chemical bonds.

Challenges and Limitations

Microbial electro-biotechnology combines microorganisms and bioelectrochemical systems to enable sustainable energy and environmental applications. Microorganisms such as bacteria, yeast, microalgae, and fungi, catalyse chemical reactions and mediate essential electron exchange between substrates and electrodes [3]. Bio-electrochemical systems exploit microorganism metabolism to generate electrical energy or useful products [1]. Examples include microbial fuel cells (MFCs) for bioelectricity production and microbial electrolysis cells (MECs) for sustainable hydrogen generation. Technical bottlenecks and economic constraints still limit large-scale application of bioelectrochemical systems [18]. Operational limitations include low microbial electron-transfer rates, limited substrate bio-availability, complex reactor design requirements, poor efficiency of scalable cathodic reactions, reduced material durability over extended use, and maintenance of a stable microbe–electrode interface. Thermodynamic challenges such as limited use of electrons for growth further limit performance at the microbial level. Scaling-up to industrial volumes is hindered by the cost and availability of membranes, electrode bulk, material durability, and construction requirements. Economic analysis finds that, at best, installation could recover approximately 1% of the chemical energy from waste in the form of electrical energy, while also reducing cleaning costs and community-level greenhouse gas emissions [3, 18].

Technical Barriers

Microbial electro-biotechnology harnesses electroactive microorganisms, electrochemical systems and abiotic components [3]. Integrated bioelectrochemical systems exceed the sum of their parts. Improved understanding can launch new research and biosolutions for sustainable electricity, fuels and chemicals [2]. Compatibility and operational reliability are central engineering challenges. Therefore, the science and engineering communities strive to resolve technical barriers that limit practical applications [8].

Economic Viability

Bioelectrochemical technologies, which integrate microbes and electrodes, offer promising future pathways for the treatment of wastewater and waste while simultaneously recovering useful energy in the form of biohydrogen or electrical power. However, the applications of these technologies at scale are not yet technically or economically viable. Substantial improvements in microbial bioelectrochemistry, as well as the development of new and/or hybrid applications, may lead to future technological and economic viability [8]. Developing an advanced understanding of bioelectrochemical processes focusing on the types of microbes involved, their electron transfer mechanisms, the materials utilized as bioanodes and biocathodes, and bioelectrode conditions may eventually allow for the integration of bioelectrochemical technologies with more conventional processes, such as solar and wind. Overcoming current limitations through novel designs and modifications could realize the potential for efficient bioremediation of wastewater waste and the harvesting of energy from organic waste [8].

Future Trends in Microbial Electro-Biotechnology

Innovative approaches to bioelectrochemical systems are focusing on diverse issues, including renewable energy and wastewater treatment, yet many aspects of these technologies remain unexplored [1]. Integrating new materials, modifying reactor setup, and selecting strategic microbial consortia can ameliorate deficiencies in key components. Recent research trends indicate that microbial electro-biotechnology continues to develop toward innovative configurations for new market opportunities [1, 19].

Innovative Research Directions

Microbial electro-biotechnology is based on the integration of microorganisms in bioelectrochemical systems, such as microbial fuel cells, where oxidation of biodegradable substrates takes place in the anodic compartment. The microorganisms involved are also referred to as electroactive organisms, or electricigens, and they might catalyze the oxidation or the reduction of the fuel, while simultaneously generating electricity or directly converting chemical into electrical energy. The recent knowledge acquired about electroactive microorganisms and the modification of electrode materials have paved the way for electro chemically-assisted processes such as energy recovery through dedicated microbial fuel cells, hydrogen production through microbial electrolysis cells, and wastewater treatment via bioanodes and biocathodes. An overview of fundamental aspects and applications provides a framework for this discussion [8].

Potential Market Applications

Microbial Electro-Biotechnology is an emerging field that integrates microorganisms into bioelectrochemical systems (BESs), which use biological catalysts at electrodes to convert chemical energy into electrical energy [3]. Microbes can stimulate or catalyse electrochemical reactions involving inorganic and organic compounds and generate electrons that reach the electrode via extracellular electron transfer mechanisms [1]. The resulting technology has a wide range of environmental and industrial applications, including sustainable energy generation, water treatment and chemical production. Microbial electrochemical systems (MESs) employ microorganisms to convert chemical energy into electrical energy. Electroactive bacteria interact with electrodes through biofilm formation and other mechanisms such as flavins, cytochromes, cell surface appendages and metabolites to facilitate electron transfer[1]. Various strategies, including proteomics and genetics, are employed to enhance electron-transfer efficiency in electroactive bacteria. Electroactive biofilms play a critical role in electron transfer in BESs. The chemical–microbial–photocatalytic-electrochemical regulations of the bioelectrochemical systems can be utilised for multi-purpose exploitation of energy and environment security. These are self-powered systems for near-time wastewater treatment, carbon-dioxide emission mitigation, and biofuel production with environmental protection [6]. Coupling of solar and wind power, the major renewable energy (RE) sources, is required to cope with continuous fluctuations in output power and frequency from RE systems owing to uncertainty and randomness of solar irradiation and wind speed. Hybrid fuel cell–photovoltaic (PV) wind and hybrid PV wind power systems are regarded as one of the most promising RE systems [1].

Regulatory and Ethical Considerations

Attention to regulations and safety considerations is important as microbial communities and their electroactive components are explored for real-world applications. Optimization of the microbial electron transfer network is necessary to guide environmental biotechnologies [19]. Efforts to enhance sustainability could benefit from electrochemical methods in the synthesis and recycling of chemicals and materials. Bioelectrochemical platforms present attractive alternatives to traditional chemical routes; they can operate rapidly and efficiently, under ambient conditions, and with decreased environmental impact. Because they degrade biological material and produce minimal waste and no methane, electrochemical devices can be characterized as renewable energy sources and as environmentally sustainable. In locations with low or no light and insufficient air movement for wind generation, bioelectrochemical systems could be designed that are environmentally useful and can operate under their own power [20].

Comparative Analysis with Other Technologies

Microbial electro-biotechnology possesses certain characteristics that differentiate it from other technologies. Traditional chemical and physical methods used for energy recovery from wastes frequently require high investment and maintenance costs and are often associated with the generation of secondary polluting streams. In contrast, microbial electrochemical technologies offer a relatively low-cost alternative to convert waste-derived substances and renewable materials [19]. The ability to stimulate specific biochemical reactions through the application of an external voltage represents an additional feature, extending the range of potential processes and compounds that can be produced. Furthermore, bioelectrochemical technologies are unique in enabling the use of waste streams as electron donors or acceptors without requiring stringent control of medium composition, thereby offering advantages over biocatalytic and enzymatic fuel cells [20].

Conventional Treatment Methods

Conventional treatment methods are broadly categorized into physical or chemical and biological approaches. Physical or chemical methods, including membrane filtration, air stripping, ion exchange and chemical oxidation, are commonly applied for pollutant removal [11]. Nevertheless, they are energy intensive and often generate hazardous by-products. Biological treatment technologies are generally more economically feasible and environmentally friendly than physicochemical processes. Biological methods are also employed as post-treatment for chemical or physical processes to polish and diminish residues. However, biological treatment methods are only applicable to biodegradable organic pollutants [11].

Emerging Technologies

Microbial electrodes offer the possibility of developing a range of novel technologies, including microscale devices for biofilm studies and sensing applications, and macroscale systems for water desalination, wastewater treatment, bioremediation, energy generation and storage, remote power and robotics, and as biosynthetic platforms to produce bulk and specialty chemicals [11]. Power-to-chemicals electro-fermentation approaches offer the possibility of lowering the energy required for biochemical manufacturing of fuels and chemicals. Together, these new research developments are transforming microbial electro-biotechnology from a fundamental, laboratory discipline to a nascent technology platform. Key domains with emerging prospects include (i) microscale microbial electrochemical systems, (ii) microbially mediated electrochemical sensor systems, (iii) integration of microbial electrochemically active technologies into water, waste/wastewater and biosolids treatment, (iv) energy storage via electromicrobiology, (v) electromicrobiology for circular economy biosynthetic systems, and (vi) the emerging relevance of extremophiles to microbial electrochemistry. The emerging relevance of these domains is discussed below in order of apparent significance. Microbial electrodes could be used in relatively small volumes of precisely defined electrolyte to develop microscale microbial electrochemical systems. These would find potential application as simple analytical devices to examine microbial interactions, processes and physiology in biofilms and sediments. Coupling microscale microbial electrochemical systems with microfluidics produces an ideal platform to generate shear and to examine the role of flow and diffusion on system function. Electrodes adapted to record current can be incorporated into microfluidic systems to generate devices that look, feel, work and flow like natural microbial consortia. Microscale systems offer low reagent consumption and are well adapted for studying biofilm formation and development, analysing interspecies electron transfer mechanisms, and as sensors to gauge the effect of pollutants or biocidal reagents [11].

Case Studies in Microbial Electro-Biotechnology

Microbial electro-biotechnology has revealed multiple real-world applications that transcend traditional microbial ecology and can be deployed in remote areas lacking electrical infrastructure [3]. Examination of different scenarios indicates that BES offers a promising platform for developing sustainable strategies to address the major challenges faced by society in the coming decades [3].

Methodologies for Research and Development

Investigation of microbial electro-biotechnology systems relies on comprehensive experimental approaches articulated as methodologies to determine and characterize these bio-electrochemical mechanisms. Biogeochemical, analytical, and biochemical strategies have been formulated to sustain the experimental requirements of research into microbial electro-biotechnology devices [21]. Such experimental procedures establish processes leading to real-world and market-technological collaborations and opportunities to evaluate and investigate biological and technological mechanisms at the micro-scale, facilitating techno-socio-economic feasibility studies [3].

Experimental Design

Bioelectrochemical systems (BESs) exploit the ability of microbes to transfer electrons to and from insoluble materials by interacting with a conductive electrode. The general design of a BES is a three-electrode setup consisting of a working, counter, and reference electrode [21]. When microbes donate electrons to the electrode and produce electricity, the system is called a microbial fuel cell (MFC). If microbes accept electrons from the electrode, it is called a microbial electrolysis cell (MEC). These systems can be set up in the lab or environment to study microbial activity. The working electrode can act as either an anode or cathode depending on the direction of electron flow, allowing microorganisms to use the electrode as a donor or acceptor. Microbial activity within BESs can be monitored in many ways. For example, current production provides a proxy for metabolic activity in MFCs where electron transfer rates are directly coupled to microbial respiration. Cyclic voltammetry, electrochemical impedance spectroscopy and an array of other electrochemical techniques are also used to characterize the chemico-physical environment during EET processes. Other techniques include gas chromatography, microscopy, and mass spectrometry to probe metabolism, electrode coverage and community composition, respectively [21].

Data Analysis Techniques

Data analysis methods are essential for determining the performance of microbial electro-biotechnology systems [22]. Cultivation of anodic electroactive microbial biofilms from waste water inocula in fed-batch reactors is demonstrated with a three-electrode set-up controlled by a potentiostat. April-from growth onwards, electrochemical activity of the biofilms is monitored and recorded using chronoamperometry. Analysis of the resulting electrochemical data includes the derivation of fundamental thermodynamic parameters of microbial extracellular electron transfer, such as peak potential, peak current density, formal potential, and peak separation. Further bioelectrocatalytic parameters characterizing performance of electrodes and biofilms are considered, including maximum current density, anodic biomass activity, and coulombic efficiency. The importance of controlled and reproducible growth of electroactive biofilms, especially for fundamental and application-oriented studies, is discussed. In addition, the need for consistent terminology in the (comparative) description of microbial bioelectrochemical systems and electroactive biofilms is emphasized [22]. Most microbial fuel cells are operated without monitoring or control of the electrode potential, as the potential results from the electrochemical reaction and the load applied. Control of the electrode potentials is therefore inherently difficult in conventional two-electrode set-ups. This drawback has been recognized early, and significant efforts have been invested to realize alternative bioreactor designs capable of controlling individual electrode potentials. Bioreactor designs utilizing potentiostats, electronic loads, or power supplies deliver a very important contribution to molecular biological, biomass, substrate or release control of microbial bioelectrochemical systems and represent a powerful engineering tool for development and optimization of microbial electro-biotechnology [22].

Collaboration Between Disciplines

Microbial electro-biotechnology is guided by multidisciplinary collaborations between electrochemists, microbiologists, material scientists, and engineers [3]. Teams from academia and industry cooperatively develop cutting-edge application platforms ranging from wastewater treatment to biofuel cells and microbial electrosynthesis modules. These joint consortia accelerate the technologies' broad deployment in sectors such as agriculture, chemical production, and energy storage [19].

Interdisciplinary Approaches

Microbes have extensive roles in biodegradation, fermentation, and the generation of bioelectricity. In microbial electro-biotechnology, microbes integrate into bioelectrochemical systems to address critical societal problems such as global warming, environmental pollution, the depletion of fossil fuels, and the dependable provision of clean water [19]. Effective solutions in these spheres could have profound social and economic impacts. To that end, bioelectrochemical systems hold considerable promise. They can generate electricity from the oxidation of waste materials, produce hydrogen at low energy costs, synthesize valuable chemicals by reducing carbon dioxide or organics, and recover energy directly from biomass [19]. They are also capable of extracting contaminants from wastewater and sediments through oxidation and reducing heavy metals and other pollutants to less toxic states while treating wastewater [3]. Diverse microbes bacterial and archaeal, catalysis-competent aerobes and anaerobes are used to facilitate these processes; some even form symbiotic partnerships with electrochemical catalysts to boost catalysis. Given the complexity of microbial processes and the sophisticated electrochemical technology involved, microbial electro-biotechnology is inherently interdisciplinary [2]. Microbiologists, electrochemists, electrochemical engineers, and policy experts working in academia, government, and industry all have critical roles to play in its advancement. Translating fundamental discoveries into practical-scale implementation, industrial applications, market viability, and ultimately market uptake depends on sustaining robust interdisciplinary collaboration and industry engagement [3, 2, 19].

Industry Partnerships

The integration of distinct scientific disciplines and industrial issue-driven requirements establishes a solid foundation for the advancement of microbial electro-biotechnology [3]. Industrial collaborations are invaluable for practical validation and maturation of innovative developments. The optimal strategy to accelerate both fundamental and application-driven progress involves the collaboration and synergy among scientific, engineering, and industrial communities [2,19].

CONCLUSION

Microbial electro-biotechnology represents a transformative approach at the interface of microbiology, electrochemistry, and environmental engineering. By harnessing the unique electron transfer abilities of electroactive microbes, BESs provide sustainable alternatives for electricity generation, hydrogen production, wastewater treatment, and pollutant degradation. The integration of bioanodes and biocathodes with advanced electrode materials and microbial consortia has expanded the scope of these systems beyond laboratory studies to pilot-scale applications. Nevertheless, scalability, cost-efficiency, and long-term stability remain critical challenges. Addressing these through innovations in reactor design, material optimization, and renewable energy integration will be essential for the translation of microbial electro-biotechnology into viable commercial technologies. With continued interdisciplinary research, this field holds the potential to contribute significantly to clean energy transitions, circular bioeconomy development, and global environmental sustainability.

REFERENCES

1. Dopson M, Ni G, HJA Sleutels T. Possibilities for extremophilic microorganisms in microbial electrochemical systems. 2015. ncbi.nlm.nih.gov
2. A. Cornejo J, Sheng H, Edri E, M. Ajo-Franklin C et al. Nanoscale membranes that chemically isolate and electronically wire up the abiotic/biotic interface. 2018. ncbi.nlm.nih.gov
3. Singha Roy A, Sharma A, Sen Thapa B, Pandit S et al. Microbiomics for enhancing electron transfer in an electrochemical system. 2022. [PDF]
4. Wang J, Ren K, Zhu Y, Huang J et al. A Review of Recent Advances in Microbial Fuel Cells: Preparation, Operation, and Application. 2022. ncbi.nlm.nih.gov
5. C. Biffinger J, R. Ringeisen B. Air-exposed microbial fuel cells and screening techniques. 2010. [PDF]
6. Rabiço F, Pedrino M, Pereira Narcizo J, Rodrigues de Andrade A et al. Synthetic Biology Toolkit for a New Species of Pseudomonas Promissory for Electricity Generation in Microbial Fuel Cells. 2023. ncbi.nlm.nih.gov
7. Wang H, Zhai P, Long X, Ma J et al. Research progress on using biological cathodes in microbial fuel cells for the treatment of wastewater containing heavy metals. 2023. ncbi.nlm.nih.gov
8. J. Zajdel T, Baruch M, Méhes G, Stavrinidou E et al. PEDOT:PSS-based Multilayer Bacterial-Composite Films for Bioelectronics. 2018. ncbi.nlm.nih.gov
9. Dominguez-Benetton X, Godon JJ, Rousseau R, Erable B et al. Exploring natural vs. synthetic minimal media to boost current generation with electrochemically-active marine bioanodes. 2016. [PDF]
10. Catarina da Costa Ralo C. Coupling organic substrate removal to methane production in a fully biological microbial electrolysis cell. 2016. [PDF]
11. Wang J, Zhao S, Kakade A, Kulshreshtha S et al. A Review on Microbial Electrocatalysis Systems Coupled with Membrane Bioreactor to Improve Wastewater Treatment. 2019. ncbi.nlm.nih.gov
12. Fapetu S, Fapetu S. Enhancing energy recovery from industrial wastewater using microbial fuel cells. 2018. [PDF]
13. Ziara R, Dvorak B, Subbiah J. Sustainable Waste-to-Energy Technologies: Bioelectrochemical Systems. 2018. [PDF]
14. Tremblay PL, Zhang T. Electrifying microbes for the production of chemicals. 2015. ncbi.nlm.nih.gov
15. Kuruvinashetti K, Kornienko N. Pushing the methodological envelope in understanding the photo/electrosynthetic materials-microorganism interface. 2021. ncbi.nlm.nih.gov

16. Matthew Leininger A. Evaluation of treatment and resource recovery potential of bioelectrochemical systems to DC Water process streams by bench and pilot system. 2018. [PDF]
17. H. Mahmoud R, M. Gomaa O, Y. A. Hassan R. Bio-electrochemical frameworks governing microbial fuel cell performance: technical bottlenecks and proposed solutions. 2022. ncbi.nlm.nih.gov
18. Zhou S, Song D, Gu JD, Yang Y et al. Perspectives on Microbial Electron Transfer Networks for Environmental Biotechnology. 2022. ncbi.nlm.nih.gov
19. H. Nealson K. Bioelectricity (electromicrobiology) and sustainability. 2017. ncbi.nlm.nih.gov
20. Jeanette Gardel E. Microbe-electrode interactions: The chemico-physical environment and electron transfer. 2013. [PDF]
21. Gimkiewicz C, Harnisch F. Waste Water Derived Electroactive Microbial Biofilms: Growth, Maintenance, and Basic Characterization. 2013. ncbi.nlm.nih.gov

CITE AS: Chukwudi Anthony Ugwuanyi (2025). Microbial Electro-Biotechnology: Integrating Microbes with Bioelectrochemical Systems. NEWPORT INTERNATIONAL JOURNAL OF SCIENTIFIC AND EXPERIMENTAL SCIENCES, 6(3):238-248. https://doi.org/10.59298/NIJSES/2025/63.238248