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Next-Generation Bioelectrochemical Systems: Bridging Synthetic Biology and Green Electronics to Harvest Renewable Energy

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Abstract

With a rise in the world's energy demand and fossil fuel dependency, there has been an urgent need for sustainable and renewable power systems. In this mini-review, recent developments in bioelectrochemical systems (BESs), i.e., microbial fuel cells (MFCs), enzymatic bio-batteries, and photobioelectrochemical platforms integrating synthetic biology and nanotechnology for power generation are discussed. These systems exploit the electrochemical potential of microbial metabolism and enzymatic redox reactions to generate electricity from organic substrates, wastewater, and sunlight. The review is focused on genetic engineering of electroactive microbes, designer enzymes for optimal electron transfer, and nanostructured electrodes for improved efficiency and scalability. It also briefly discusses real-world applications including biosensing, remote power generation, and wastewater treatment with simultaneous energy recovery. The capacity to utilize them as components of decentralized low-carbon energy systems makes them a viable solution to both energy access and environmental sustainability in the climate crisis context.

Keywords: *Bioelectrochemical systems, Microbial fuel cells, Synthetic biology, Renewable energy, Enzymatic bio-batteries, Green electronics*

Introduction

With the rising global energy demands and the associated environmental consequences of fossil fuel burning, green and sustainable renewable green technologies have evolved. While conventionally existing fossil energy sources are still major greenhouses and carbon change emitters, a push towards the setting up of alternative mechanisms technology-friendly as well as greener is the global agenda today. Among the emerging options under investigation, bioelectrochemical systems (BESs) have garnered considerable attention due to their ability to produce electricity directly from organic substrates via biological means (Bajracharya et al., 2016).

Bioelectrochemical systems are a suite of technologies including microbial fuel cells (MFCs), enzymatic bio-batteries, and photobioelectrochemical platforms. Bioelectrochemical systems take advantage of the redox properties of enzymes and microbes to generate electric power from waste-based or renewable feedstocks like wastewater and light. Efficiency and scalability of BESs have greatly enhanced with the development of nanotechnology and synthetic biology, and hence are playing a crucial role in real-life applications (Hamelers et al., 2009).

This review attempts to locate the newest developments within the field of BESs, highlighting synergy between synthetic biology and green electronics towards optimizing the efficiency of energy conversion. It also refers to practical applications and how BESs will be in a position to provide support to decentralized, low-carbon energy systems and especially solving the global climate issue. The increasing global energy demand and the environmental impacts of fossil fuels have seen the creation of green and environment-friendly renewable energy technologies. Whereas fossil energy reserves continue to represent major drivers of greenhouse gases emissions and global change, exploring alternatives that are environmentally friendly, technologically-based is now the concern of international significance. Of these new options sought, BESs have generated considerable attention in that they are capable of deriving electricity from organic substrates by biological conversions directly (Fang et al., 2020).

Recent Developments in Bioelectrochemical Systems

There has been spectacular development in bioelectrochemical systems (BESs) over the past few years, with electrochemical and biological developments of interest. Microbial fuel cells (MFCs) are one of the many configurations, which have emerged as a model system of choice. MFCs use electroactive bacteria to oxidize organic substrates, with electrons transferred to an anode and electricity as a byproduct. Enhancements in metabolic engineering and microbial strain choice have accelerated electron transfer rates to yield greater energy and system stability (Schaetzle et al., 2008).

Another area of high promise is enzymatic bio-batteries, which make use of the purified redox enzymes to catalyze directly on the surface of the electrode. These systems offer biochemical pathway control and are well suited for application for utilization in miniaturized power systems for biomedical and remote-sensing applications. Enzyme stability and efficient electron transfer remain the major challenges (Buaki-Sogó et al., 2020).

Photobioelectrochemical systems are a cross-platform system that consists of photosynthetic microorganisms or light-sensitive enzymes in combination with electrochemical interfaces for the harvesting of solar energy. The platforms are gaining popularity due to their dual function of light energy conversion and bioremediation.

In addition to these, the use of novel materials such as carbon nanostructures, metal-organic frameworks (MOFs), and conductive polymers has also improved electrode conductivity and biocompatibility. All of these individually and collectively have resulted in enhancements in better performance measures such as power density, Coulombic efficiency, and operating life, which enable wider application of BESs to practical applications (Majumdar et al., 2017).

Integration of Synthetic Biology and Nanotechnology

The combination of synthetic biology and nanotechnology has revolutionized the designing of future bioelectrochemical systems (BESs) with the potential to regulate biological and electrochemical processes more precisely. Synthetic biology offers efficient ways of re-designing microorganisms to realize better electron transfer, metabolic yields, and substrate utilization. Genetic engineering of electroactive bacteria such as Shewanella oneidensis and Geobacter sulfurreducens has provided strains overexpressing cytochrome, conductive pili, and biofilm forming ability, all of which have been helpful in enabling electron transfer to the electrodes (Chen et al., 2022).

In the meantime, optimization of BES component structure and function is within the realm of nanotechnology. Nanostructured electrodes including carbon nanotubes, graphene, and nanofibers exhibit high surface area, improved conductivity, and improved microbial adhesion. All these attributes improve efficient electron transfer as well as reduce internal resistance for further improvement in overall system performance. In addition, immobilization of redox enzymes on nanomaterials has improved enzyme stability and efficiency of catalysis in enzymatic bio-batteries (Kim et al., 2024).

The merging of these two disciplines also enables the development of hybrid bioelectronic interfaces in which the biological systems are interfaced with electronic devices. These structures should extend the limits of scaled, miniaturized, and high-performance devices that can find applications in wearable biosensors, autonomous environmental sensing networks, etc.

By leveraging novel nanotechnology and synthetic biology techniques, BESs are being designed to function more effectively, for longer, and multi-dimensionally for a variety of energy and environmental applications, a step towards decentralized and sustainable energy generation (J. Kim et al., 2018).

Applications in Renewable Energy and Environmental Sustainability

Bioelectrochemical systems (BESs) possess tremendous potential for solving the most important problems of renewable energy generation and environmental protection. With their unique feature of generating electricity from organic wastes, wastewater, and solar power, BESs become twin-function technologies with the potential of clean energy as well as environmental sustainability (Wilberforce et al., 2020).

One of the most significant applications of BESs is wastewater treatment and power generation. In microbial fuel cells (MFCs), wastewater organic pollutants are oxidized by electroactive microbes and result in simultaneous pollutant abatement and electricity production. This not only reduces the environmental cost of wastewater discharge, but it also offsets the energy need of traditional treatment plants.

BESs are further explored for application in biosensing, where growth of microbes or electrochemical response is employed as a marker to indicate the existence of toxins, pathogens, or specific chemicals. These systems find great application for remote or real-time monitoring for environmental and biomedical applications (Daniel et al., 2009).

In decentralized power supply and off-grid, photobioelectrochemical cells and enzymatic bio-batteries can power small electronic devices in remote or poor regions. Biodegradable and low impact on the environment render them to be used for low-impact or short-term applications such as disaster relief regions, wearables, and IoT (Mukha et al., 2020).

Besides other uses, BESs also offer carbon-free energy grids, compatible with renewable energy grids. BESs are capable of offering circular energy systems with biomass and solar supply, especially for rural or developing regions lacking conventional energy infrastructure. In these diversified applications, BESs demonstrate green electronics and sustainable design principles and offer a way to integrated solutions to energy shortages and ecosystem degradation (Zhang et al., 2019).

Conclusion

Bioelectrochemical systems (BESs) are a new field of investigating sustainable, decentralized energy sources. By tapping into the intrinsic redox potential of microbes and enzymes, and further enhancing their performance with the aid of synthetic biology and nanotechnology, the systems can be utilized to convert solar energy and organic wastes into edible electricity. This renders BESs not only clean energy generators but also environmental remediation and biosensing multidisciplinary platforms.

Despite recent advances, several issues need to be addressed before large-scale applications. These involve improving the long-term stability of enzyme and biological components, electron transfer efficiency, reducing system cost, and increasing production scale without losing performance. Regulation and public perception concerns may also influence commercialization rates.

Future studies will have to tackle the development of genetically designed microbial consortia, novel bio-nano interfaces, and smart control systems that allow BESs to respond dynamically to environmental changes. Integration with other renewable technology, i.e., solar or wind technology, could also facilitate hybrid platforms of peak energy yield and reliability.

In brief, as the global energy portrait transitions towards sustainability, bioelectrochemical systems are a promising, sustainable alternative. Interdisciplinary research will continue to be crucial in unlocking their complete potential and making them economically feasible components of green energy infrastructure in the future.

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