Review Article

Photosynthetic green microalgal bio-electrochemical system for self-sustainable bioelectricity generation

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Abstract: Microalgal bioelectrochemical systems have received substantial interest among the developing technologies for bioenergy. It is based on the interaction of two major components, i.e., microalgae and electrochemical processes. Microalgal photosynthesis and electrochemical reactions integrate the microalgae bioelectrochemical systems for a sustainable and efficient technique of bioelectricity generation. In this work, we have deliberated on the critical biological component of microalgae, which captures solar energy and transform it into chemical energy via photosynthesis. This includes selecting optimal microalgal strains with high photosynthetic efficiency, optimal nutrition, and availability of carbon dioxide and designing electrodes and membrane materials to improve electron transmission and reduce energy losses. Also, we have presented microalgal bioelectrochemical systems as a promising technique for generating bioelectric energy. In addition, this system also provides an innovative method for wastewater treatment, carbon dioxide mitigation, and direct solar energy conversion by involving microalgae with electrochemical processes. We have explored the ability to address environmental concerns while producing bioelectricity, making microalgal bioelectrochemical an appealing alternative for a cleaner future. Therefore, continuous research and technological developments of revolutionary bioenergy generation platforms pave the way for a more sustainable and green energy landscape.

Keywords: Microalgae; Bioelectrochemical systems; Anode; Cathode; Bioelectricity generation

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1. Introduction

The increasing demand for clean and sustainable energy sources has led to a growing interest in exploring alternative methods for renewable energy generation. Microalgal bioelectrochemical systems have gained considerable attention among these emerging technologies (Elshobary et al., 2021). Microalgae, tiny photosynthetic organisms capable of converting light energy into chemical energy through photosynthesis, offer a promising avenue for harnessing renewable energy. Integrating microalgae with bioelectrochemical systems can provide a sustainable and efficient means of generating electricity, biofuels, and other value-added products (Saratale et al., 2022).

The concept of microalgal bioelectrochemical systems revolves around combining two key components, i.e., the microalgae and the electrochemical processes. Microalgae serve as the main biological component, harnessing solar energy and converting it into chemical energy through photosynthesis. The electrochemical component, formed by anode and cathode electrodes, facilitates the conversion of chemical energy produced by microalgae into electrical energy. This integration enables directly harvesting electricity from photosynthetic organisms, making microalgal bioelectrochemical systems an exciting pathway for sustainable energy generation (ElMekawy et al., 2014). One of the key advantages of microalgae bioelectrochemical systems is their ability to use wastewater or other organic waste streams as a nutrient source for microalgae cultivation (Rajput et al., 2022). This aspect presents an attractive solution to two critical challenges: wastewater treatment and sustainable energy production. Integrating microalgal bioelectrochemical systems with wastewater treatment systems allows organic contaminants to be effectively removed while simultaneously producing renewable energy. This symbiotic relationship between microalgae and electrochemical processes has the potential to transform wastewater treatment plants into self-sufficient power generation facilities. A microalgal bioelectrochemical system also holds promise for carbon dioxide mitigation (Das et al., 2019).

Microalgae are remarkably able to absorb and use environmental carbon dioxide as a carbon source for photosynthesis. Integrating microalgae with electrochemical systems can convert the captured carbon dioxide into valuable products such as biofuels or high-value chemicals (Kumar et al., 2021; Jaiswal et al., 2021). This mitigates carbon dioxide emissions and provides a pathway for producing sustainable fuels and chemicals that can replace their fossil-based counterparts (Sheldon, 2018). In addition, microalgae bioelectrochemical systems can be used to generate electricity directly from sunlight, eliminating the need for complex and expensive infrastructure typically associated with conventional solar power systems. Microalgae's ability to use solar energy efficiently makes them ideal candidates for this purpose. Microalgae transform captured solar energy into chemical energy, which can then be collected as electrical energy through electrochemical reactions at the anode and cathode electrodes (Mekuto et al., 2020).

Research and development efforts in microalgae bioelectrochemical systems have been directed at improving the efficiency, scalability, and overall performance of these systems. Advances in electrode materials, reactor design, and culture techniques have improved microalgae bioelectrochemical systems' energy production and stability. In addition, genetic engineering approaches have been explored to enhance the productivity of microalgae and adapt their metabolic pathways to optimize energy generation (Bharadwaj et al., 2020). In this work, microalgal bioelectrochemical systems represent a promising technology for sustainable energy generation. By integrating microalgae with electrochemical processes, these systems offer a novel approach to wastewater treatment, carbon dioxide mitigation, and direct solar energy conversion. Also, we have deliberated the potential to address environmental challenges and produce renewable energy simultaneously, making microalgal bioelectrochemical an attractive solution for a greener future. Ongoing research and technological advancements continue to unlock the full potential of this innovative bioelectricity generation platform, opening the doors to a more sustainable and environmentally friendly energy landscape.

2. Bioelectrochemical system

Bioelectrochemical systems have emerged as a promising technology that combines biology and electrochemistry to convert organic matter into valuable energy. By utilizing the metabolic activities of microorganisms, bioelectrochemical systems allow the direct extraction of electrical current from the degradation of organic compounds. This innovative approach has gained significant attention due to its potential applications in renewable energy generation, waste treatment, and resource recovery (Bajracharya et al., 2016). At the heart, the bioelectrochemical system is the concept of extracellular electron transfer, which involves the exchange of electrons between microorganisms and solid-state electrodes. Bacteria and archaea possess unique electron transfer mechanisms, allowing them to oxidize organic matter and transfer the released electrons to an electrode, creating an electrical current. This electrochemical connection allows the direct harnessing of microbial electricity. One of the most explored applications of bioelectrochemical systems is wastewater treatment. Traditional wastewater treatment processes consume substantial energy for aeration and other treatment steps (Pant et al., 2011). The bioelectrochemical system offers an energy-efficient alternative using microorganisms to treat wastewater and simultaneously generate bioelectricity. In microbial fuel cells, microorganisms in the anode chamber oxidize organic matter while the produced electrons are transferred to the cathode through an external circuit, generating electrical power.

This integration of wastewater treatment and energy production makes bioelectrochemical systems a sustainable solution for the water-energy nexus. In addition, the bioelectrochemical system promises in the field of resource recovery. Organic matter in wastewater or other waste streams can serve as a valuable source for producing high-value chemicals, biofuels, and other bioproducts (Ashokkumar et al., 2022). The bioelectrochemical system enables the selective production of target compounds by redirecting the flow of electrons toward desired chemical reactions. This concept, known as microbial electrosynthesis, transforms waste into valuable resources, promoting a circular economy and reducing dependence on fossil fuels. Another exciting application of bioelectrochemical systems is environmental remediation, specifically removing contaminants (Dutta et al., 2020). Certain microorganisms can degrade or immobilize various pollutants, such as heavy metals, hydrocarbons, and emerging pollutants (Fatima et al., 2020; Jaiswal et al., 2020; Jaiswal et al., 2021; Nanda et al., 2021). By combining these microbial capabilities with the electrochemical interface provided by bioelectrochemical systems, researchers have explored the use of bioelectrochemical systems for efficient and sustainable remediation strategies. Microbe-driven reactions in bioelectrochemical systems can enhance contaminants' degradation or immobilization, providing a greener approach to environmental cleanup (Mohapatra and Phale, 2022). Beyond wastewater treatment and environmental remediation, the bioelectrochemical system has also shown potential in other areas. For example, bioelectrochemical system can be used in biosensors to detect and quantify target analysts by monitoring electrical signals generated by microorganisms in response to specific stimuli.

This potential application opens up possibilities in various fields, including healthcare, environmental monitoring, and food safety. Advances in electrode materials, reactor design, and microbial engineering have driven the development and optimization of bioelectrochemical system technologies (Mier et al., 2021). The researchers are exploring novel electrode materials that improve system performance and stability, while reactor design improvements aim to maximize contact between microorganisms and electrodes for efficient electron transfer. Microbial engineering approaches, such as genetic modification or synthetic biology, allow the optimization of microbial strains to improve their electrochemical activities and increase overall system performance. Bioelectrochemical systems represent an innovative approach integrating biology and electrochemistry for sustainable energy generation, wastewater treatment, and resource recovery (Marami et al., 2022). By harnessing the bioenergy of microbial electricity, the bioelectrochemical system offers solutions to environmental challenges while providing an opportunity to produce valuable products (Jaiswal et al., 2022). The bioelectrochemical system's ongoing research and development efforts have great potential to unlock its full capabilities, driving the transition toward a cleaner and more sustainable future.

3. Microalgae in a bioelectrochemical system

Microalgal bioelectrochemical systems are a promising technology that integrates biological processes with electrochemical reactions to convert organic matter into energy or valuable chemicals. An exciting application of bioelectrochemical systems involves using microalgae, microscopic photosynthetic microorganisms capable of converting sunlight and carbon dioxide into biomass. The role of microalgae in bioelectrochemical systems, their benefits, and their potential applications have been assessed efficiently. Microalgae offer several advantages in bioelectrochemical systems (Wang et al., 2022). First, they have high photosynthetic efficiency, which allows them to capture solar energy and convert it into chemical energy through photosynthesis. This characteristic makes them an excellent candidate for the use of renewable energy. Additionally, microalgae can proliferate and produce large amounts of biomass quickly, making them highly productive organisms. Further, microalgae can be grown in various environments, including freshwater, seawater, and wastewater, providing flexibility in their application (Leu and Boussiba, 2014).

In typical bioelectrochemical systems, microalgae are integrated into the system differently. A common approach is to immobilize the microalgae on the surface of an electrode. The electrode acts as a support structure and electron acceptor. As the microalgae photosynthesize, they release electrons the electrode captures, generating an electrical current (Jaiswal et al., 2020). This phenomenon is known as microbial photosynthetic cathodic current. The induced current can be used for various applications, such as powering devices or feeding into the grid. Another approach is to couple microalgae with other electrochemically active microorganisms, such as bacteria, in what is known as a microbial fuel cell. In a microbial fuel cell, the microalgae provide the primary source of electrons through photosynthesis, while the bacteria in the system facilitate the transfer of electrons to the electrode (Mekuto et al., 2020). This synergy between microalgae and bacteria increases energy production and provides a platform for simultaneous wastewater treatment. The integration of microalgae in bioelectrochemical systems has several benefits. First, it enables the production of renewable energy from sunlight and carbon dioxide. This is crucial in fighting climate change and reducing dependence on fossil fuels. Additionally, using microalgae in bioelectrochemical systems can help mitigate carbon dioxide emissions by capturing and using this greenhouse gas (Pahunang et al., 2021).

Additionally, microalgae-based bioelectrochemical systems can be used for wastewater treatment, as the organisms can remove nutrients and contaminants from the water. This dual functionality of energy production and wastewater treatment makes microalgae attractive for sustainable applications. The potential applications of microalgae in bioelectrochemical systems are diverse. One notable area is bioenergy production. The electrical current generated can be used to power small devices or stored in batteries for later use (Kumar et al., 2019). Furthermore, the biomass produced by microalgae can be converted into biofuels such as biodiesel, bioethanol, etc., offering an alternative to traditional fossil fuels (Jaiswal and Pandey, 2014). This can contribute to a more sustainable and environment-friendly energy sector. The microalgae in bioelectrochemical systems also have implications for agriculture and aquaculture. The generated electrical current can be used to power sensors or actuators in precision agriculture, optimizing resource management and crop yields (Maraveas et al., 2022). Additionally, microalgae can be grown in wastewater or nutrient-rich streams, providing a cost-effective, renewable feed source for aquaculture.

4. Anode and cathode in a microalgal bioelectrochemical system

Bioelectrochemical systems represent a revolutionary approach to sustainable energy generation, drawing inspiration from nature's inherent ability to harness the power of microorganisms. The anode and cathode are central components to the operation of bioelectrochemical systems (Figure 1). This may play a critical role in facilitating electron transfer and achieving efficient energy conversion (Gong et al., 2020). This work explores the intricate workings of the anode and cathode in bioelectrochemical systems, exploring their significance and potential applications for a greener future. A bioelectrochemical system is an electrochemical system in which microorganisms are used as catalysts for various electrochemical reactions. These systems are designed to harness the metabolic capabilities of microbes, particularly electroactive microorganisms, to promote the conversion of organic matter into electricity or valuable chemicals. The central components of a bioelectrochemical system are the anode and cathode, where vital redox reactions occur (Ivase et al., 2020).

4.1 The anode: microbial oxidation

The anode is the electrode in a bioelectrochemical system where microbial oxidation occurs. This electrode acts as an electron donor and provides an interface for the microbial community to transfer electrons from the oxidation of organic compounds to the external circuit. Microbial oxidation at the anode generally involves decomposing complex organic matter by microorganisms, such as bacteria, using extracellular enzymes (Rabaey et al., 2009). This process releases electrons, protons, and other byproducts. Microorganisms with the capacity to transfer electrons extracellularly, known as exoelectrogens, are essential for the functioning of the anode. These exoelectrogens use specialized proteins, such as cytochromes and conductive pili, to facilitate the transfer of electrons to the anode surface. Notable exoelectrogens include Geobacter, Shewanella, and Rhodoferax species (Kumar et al., 2015). In addition, some microorganisms can perform direct electron transfer, eliminating the need for extracellular electron transfer mediators.

4.2 The cathode: microbial reduction

The cathode is the electrode in a bioelectrochemical system where microbial reduction occurs. It acts as an electron acceptor, capturing electrons from the external circuit and facilitating the removal of specific compounds. The cathode can be designed to promote the reduction of various compounds, such as oxygen, nitrates, sulfates, or even carbon dioxide, depending on the intended application of the bioelectrochemical system. Microorganisms involved in the cathodic process are known as electrotrophs. Electrotrophic microorganisms can use cathode electrons to reduce different compounds, driving essential bioremediation processes or producing valuable chemicals (Lovley, 2011; Nanda et al., 2021). For example, oxygen reduction at the cathode can be harnessed for microbial fuel cells to generate electricity. In contrast, carbon dioxide reduction can produce valuable chemicals such as methane or acetate.

4.3 Electron transfer mechanisms

Electron transfer in bioelectrochemical systems can occur via two main mechanisms, i.e., direct and mediated electron transfer. In direct electron transfer, direct electrical connections involve between the microbial cells and the electrode surface. In this process, proteins on the outer membrane of microbial cells, such as cytochromes or conductive hairs, facilitate the direct transfer of electrons to the anode or from the cathode. Direct electron transfer is considered more efficient as it eliminates the need for extracellular mediators, which can be expensive and unstable (Mohan et al., 2014). Another, in mediated electron transfer, the use of extracellular electron carriers or mediators involves facilitating the transfer of electrons between microbial cells and the electrode surface. These mediators can be soluble redox molecules or solid-state conductive materials that act as intermediates for electron transport. However, mediated electron transfer is more widespread in bioelectrochemical systems; it often represents additional complexity and cost due to reliance on mediator compounds (Schröder, 2007).

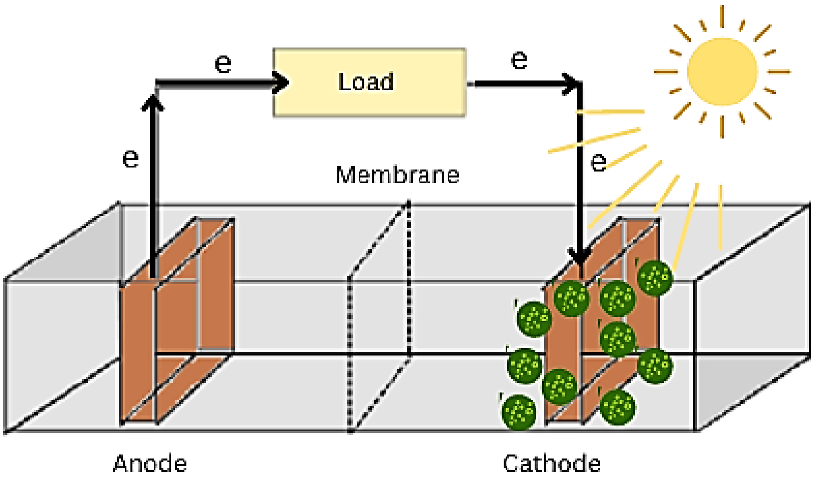

Figure 1 Schematic representation of microalgal bioelectrochemical cell

5. Energy generation in microalgal bioelectrochemical system

Microalgal bioelectrochemical systems are a promising technology that combines microalgae and electrochemical processes to generate energy. These systems take advantage of the unique abilities of microalgae to convert sunlight and carbon dioxide into biomass while also using the electrochemical reactions that occur at the anode and cathode to produce bioelectricity. Integrating photosynthesis and electrochemical reactions makes microalgae bioelectrochemical systems a sustainable and efficient approach to bioelectricity generation. Microalgae play a central role in these systems since they serve as the primary source of biomass production. They are photosynthetic microorganisms that use sunlight, carbon dioxide, and nutrients to carry out photosynthesis. During photosynthesis, microalgae convert solar energy into chemical energy by capturing light energy through pigments such as chlorophyll and using it to convert carbon dioxide and water into organic molecules, mainly carbohydrates (Sun et al., 2018). This process releases oxygen as a byproduct. The biomass produced by microalgae can be harvested and processed to extract valuable products such as biofuels, bioplastics, or high-value chemicals.

In microalgae bioelectrochemical systems, the anode and cathode compartments are separated by an ion exchange membrane, creating a two-chamber system (Figure 2). The anode compartment contains the microalgae and acts as a site for photosynthetic activity. In contrast, the cathode compartment has a suitable electron acceptor, such as oxygen or a metal catalyst, for electrochemical reactions. The anode and cathode are connected by an external circuit, allowing the flow of electrons generated during photosynthesis to be used to produce electricity (Zhou et al., 2013). At the anode, the microalgae undergo photosynthesis and release electrons. These electrons are transferred to the anode electrode, which acts as an electron acceptor. The anode electrode is usually made of a conductive material, such as carbon cloth or graphite, which provides a surface for microalgae to attach to and facilitates electron transfer. The electrons generated at the anode are then transported through the external circuit to the cathode. At the cathode, the electrons received from the anode combine with an electron acceptor, which may be oxygen or a metallic catalyst such as platinum. This reaction generates electrical current and produces water as a byproduct. The cathode electrode is designed to have a large surface area and good electrical conductivity to enhance electrochemical reactions and maximize electricity production (Zou et al., 2008). Further, the ion exchange membrane between the anode and cathode compartments allows for ion transport and prevents the mixing of microalgae and the electron acceptor. This separation is crucial to maintain the photosynthetic activity of the microalgae while facilitating electrochemical reactions at the cathode.

To optimize energy generation in microalgae bioelectrochemical systems, several factors must be considered. These include selecting suitable microalgae strains with high photosynthetic efficiency, optimizing nutrient and carbon dioxide availability, and designing electrodes and membrane materials to enhance electron transfer and minimize energy losses (Gao et al., 2014). In addition, control of environmental factors, such as light intensity, temperature, and pH, is essential to ensure optimal growth and performance of microalgae. Microalgae bioelectrochemical systems have the potential to provide a sustainable and renewable energy source by harnessing the power of microalgae and electrochemical reactions (Kusmayadi et al., 2020). They offer advantages such as carbon dioxide sequestration, wastewater treatment, and biomass production, making them versatile technology for power generation. Ongoing research and development efforts aim to improve the efficiency and scalability of microalgae bioelectrochemical systems to realize their full potential as a clean energy solution for the future.

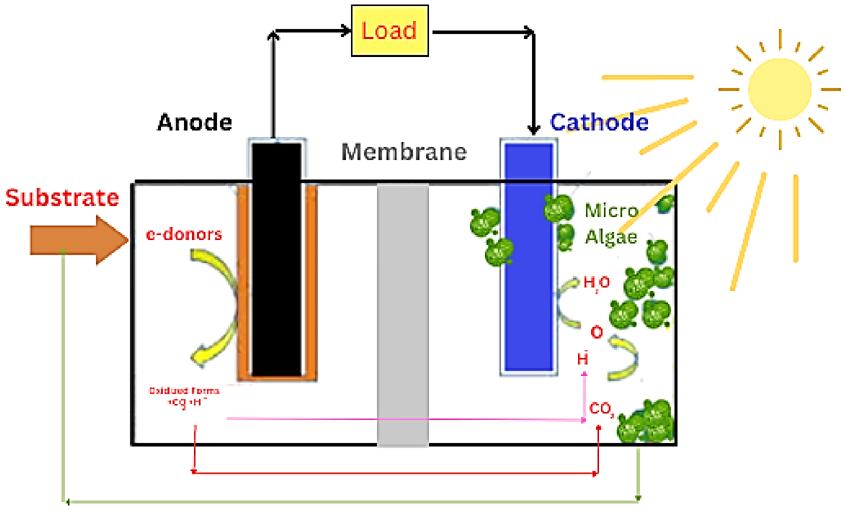

Figure 2 Bioelectricity generation using microalgal bioelectrochemical system

6. Conclusion

Microalgae have an extraordinary ability to capture and use atmospheric carbon dioxide as a carbon source for photosynthesis. The captured carbon dioxide can be transformed into valuable products such as biofuels or high-value compounds by merging microalgae with electrochemical apparatus. Research and development activities in microalgae bioelectrochemical systems have focused on enhancing the efficiency, scalability, and overall performance of bioelectrochemical systems. Advances in electrode materials, reactor design, and growth techniques have all led to the improved energy generation and stability of microalgae bioelectrochemical systems. Also, genetic engineering approaches have been investigated to boost microalgae productivity and alter their metabolic pathways to optimize energy generation. Several aspects must be considered to maximize energy generation in microalgae bioelectrochemical systems. Selection of suitable microalgae strains with high photosynthetic efficiency, optimization of nutrition and carbon dioxide availability, and design of electrodes and membrane materials to promote electron transport and minimize energy losses are all part of this. By combining the power of microalgae and electrochemical processes, microalgae bioelectrochemical systems have the potential to create a sustainable and renewable energy source. Microalgae bioelectrochemical systems provide carbon dioxide sequestration, wastewater treatment, and biomass production benefits, making them a versatile bioenergy generation technology.

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