Reaktor

p-ISSN 0852 – 0798
e-ISSN 2407 – 5973

Website: http://ejournal.undip.ac.id/index.php/reaktor/

Reaktor, Vol. 24 No. 3, December Year 2024, pp. 82-93

Breaking Boundaries in Renewable Energy: Portable Bio-Photo Voltaic (BPV) Systems for the IoT Era

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(Received: 18 December 2024; Accepted: 17 April 2025; Published: 21 April 2025)

Abstract

Bio-photo voltaic (BPV) technology represents a promising innovation in renewable energy by harnessing photosynthetic microorganisms, such as microalgae and cyanobacteria, to convert solar energy into electricity. This review elaborates recent advancements in BPV systems, with a focus on portable applications, immobilization techniques, and hybrid system integrations. The study highlights the critical role of advanced materials, such as graphene and carbon nanotubes, in improving electron transfer efficiency and system performance. Additionally, immobilization strategies using naturally occurring polysaccharides like sodium alginate and agar are discussed for their contributions to system stability and scalability. Portable BPV systems have emerged as sustainable solutions for decentralized energy needs, including environmental monitoring and IoT-based applications. Despite their potential, challenges remain in optimizing energy output, improving long-term stability, and reducing production costs. Future directions include the integration of nanotechnology, genetic engineering of microorganisms, and hybrid BPV-solar systems to enhance overall efficiency and expand application scope. This review underscores the transformative potential of BPV technology in achieving sustainable energy goals while addressing global challenges in energy access and environmental conservation. With continues innovation and multidisciplinary collaboration, BPV systems could play a vital role in transitioning toward a cleaner and more resilient energy future.

Keywords: *Bio-Photovoltaic; Microalgae; Renewable Energy; Portable Systems; Hybrid BPV-Solar Systems; Nanotechnology Integration.*

How to Cite This Article: Nur, M.M.A., Dellarohita, S.J., Syakira, S.F. (2024), Breaking Boundaries in Renewable Energy: Portable Bio-Photo Voltaic (BPV) Systems for the IoT Era, Reaktor, 24 (3), 82 - 93, https://doi.org/10.14710/reaktor. 24. 3. 82 - 93

INTRODUCTION

Energy is a vital part of human life and a key driver of civilization's development. Most industries, such as transportation, manufacturing, healthcare, and communication, require a strong and sustainable energy supply. However, most of the world's energy needs still rely on fossil energy sources, such as natural gas, petroleum, coal, etc. Nevertheless, this dependency has negative impacts, including greenhouse gas emissions, environmental pollution, and global warming, which is now threatening the sustainability of Earth's ecosystems. Moreover, fossil energy sources are non-renewable, meaning that their capacity to supply energy will continue to abate over time (Dolf Gielen, 2019).

Efforts to switch from non-renewable energy sources to renewable energy are crucial worldwide to mitigate environmental impacts and ensure long-term energy availability. Several alternatives to replace fossil energy are being developed, including solar, wind, water, and bioenergy. Bioenergy is an attractive solution because it utilizes abundant biological resources, such as plants, organic waste, agricultural residue and microorganisms (Dolf Gielen, 2019)

Bioenergy is a form of renewable energy derived from biological materials, such as biomass and microorganisms. This technology offers various advantages, including reducing carbon emissions, utilizing waste as an energy source, and enabling better environmental management. One of the most appealing features of bioenergy is its ability to produce energy by harnessing biological processes, such as photosynthesis and fermentation. Thus, bioenergy is environmentally friendly and helps reduce the long-time dependence on fossil fuels (Lee, S.Y, 2019**)**

However, bioenergy also faces challenges. Bioenergy systems have relatively low energy conversion efficiency compared to other energy technologies. Additionally, this technology has yet to be fully competitive due to small-scale production and high operational costs. Therefore, advancements in bioenergy technology are crucial to improving efficiency, reducing costs, and expanding its application (UNIDO, 2021)

The conversion efficiency of traditional BPV systems is limited due to the low efficiency of the photosynthetic process used by microorganisms, namely cyanobacteria and microalgae. Photosynthesis is naturally optimized for producing chemical energy in the form of ATP and NADPH for the biological needs of the microorganisms, not for electricity generation. As a result, the energy conversion efficiency from light to electricity in conventional BPVs is typically between 0.1% and 0.5%.

However, with the development of advanced technologies, including genetic engineering and nanomaterial integration, conversion efficiency can be improved. Genetic engineering allows researchers to modify photosynthetic pathways in microorganisms to produce more electrons that can be captured by the electrodes. Furthermore, advanced materials like graphene and CNTs can accelerate electron transfer from microorganisms to electrodes, thereby reducing energy losses during the conversion process. This technology is expected to improve conversion efficiency to 1% - 2%, which, although still lower than conventional solar panels, represents a significant advancement for BPV technology.

Bio-photovoltaic (BPV) technology is an exciting innovation in bioenergy. BPV devices convert sunlight into electricity by using photosynthetic microorganisms like cyanobacteria or algae. These microorganisms harness sunlight to perform photosynthesis, which generates electrons that can be captured and used to produce electrical power. BPV systems combine photosynthesis with bioelectrochemical conversion, where the electrons produced during the light reaction of photosynthesis are transferred to an electrode, generating electricity (Shlosberg Y, 2022).

In addition to producing electricity, BPV systems offer environmental benefits by utilizing organic waste and capturing carbon dioxide (CO2), making them a promising renewable energy source. However, BPV technology faces several challenges. These include short operational lifespans, with devices often only functioning for a few days to a week before performance declines, and high production costs due to expensive materials and manufacturing processes. Furthermore, many BPV devices rely on synthetic materials that are difficult to recycle, raising concerns about sustainability. Despite these challenges, BPV holds significant potential for renewable energy generation. Ongoing research focuses on improving efficiency, extending device lifespans, and reducing production costs, which could help make BPV a viable alternative energy source for the future (Tschörtner J, 2019).

Bio-photovoltaic (BPV) technology offers an exciting and promising way to harness solar energy through photosynthetic microorganisms like cyanobacteria or algae. These systems have the potential to serve a variety of purposes, from small-scale electricity generation to integrated waste treatment systems. By using photosynthetic microorganisms, BPV can convert organic waste into energy while also reducing atmospheric carbon dioxide (CO2). This capability positions BPV as a promising component of future renewable energy systems (Anam, 2021**)**

However, BPV technology is still in the development stage, and several challenges remain. These include improving the operational efficiency of BPV devices, increasing their durability, and lowering production costs. Additionally, issues such as limited scalability, suboptimal power output, and the need for materials that allow light penetration to the biofilms further complicate its commercial viability. Research is ongoing to address these issues, with a focus on optimizing system parameters, such as anode materials and growth conditions, to increase performance. Despite these challenges, BPV systems hold significant potential for contributing to the future of sustainable energy generation. With continuous innovation, BPV may become an important part of the renewable energy landscape (Anam, 2021)

Despite its promise, BPV technology currently faces several challenges, one of which is its size and non-portable design. Most BPV devices are large and difficult to transport, limiting their application in locations requiring flexibility. Therefore, the development of portable BPV systems has become a research priority. With smaller and lighter designs, portable BPV devices could be used in remote areas without access to electricity or even for personal and household applications (Zhu, 2023; Jalali, 2024; Sethu, 2024).

The current development of portable BPV focuses on supporting materials like alginate matrices, which stabilize photosynthetic microorganisms within BPV devices. Alginates are flexible, environmentally friendly natural materials that allow for more compact designs without compromising efficiency. Some studies explore blending alginate with other materials to improve durability and performance. Despite promising initial results, portable BPVs still face issues related to energy efficiency and short life-span (Muganlı, 2024).

The life-span of BPV devices is a significant issue alongside portability. Most devices can only operate for a few days to a week before being degraded by microorganisms or material damage. Efforts to address this issue include optimizing the working environment for microorganisms, using more durable natural materials, and developing recyclable biopolymers. By resolving these challenges, portable BPVs are expected to become a practical, efficient, and sustainable energy solution. One strategic approach to accelerate the widespread adoption of this technology is to develop durable portable BPVs. With continuous innovation, BPVs possess the potential to play a crucial role in the renewable energy revolution of the future (Zhu, 2019)

WRITING METHOD

The writing method for this review focuses on the examining the advancements, challenges, and future directions in portable bio-photovoltaic (BPV) systems for renewable energy and IoT applications. A systematic literature search was performed using databases like Scopus and Google Scholar, focusing on studies published between 2000 and 2024, with keywords such as "portable BPV," "renewable energy," and "IoT applications." Relevant information on material optimization, genetic engineering, and hybrid system integration was extracted and classified by themes, including advancements, challenges, and applications. In addition, the quantitative data, such as power output metrics, were analyzed using statistical tools, while trends in research outputs were mapped using bibliometric software. Findings were cross-referenced for reliability and presented with visual summaries, offering a comprehensive analysis of portable BPV systems and their potential in addressing energy challenges.

RESULTS AND DISCUSSION

1. Microalgae as a Source of Renewable Energy

The growing demand for renewable energy has highlighted the potential of microalgae as an alternative to conventional bioenergy sources. Unlike terrestrial crops, microalgae demonstrate a higher photosynthetic efficiency, faster growth rates, and the ability to thrive in diverse environments, including saline or wastewater (Chisti, 2007). Moreover, microalgae can produce valuable co-products such as omega-3 fatty acids and pigments, which enhance the economic feasibility of microalgae-based systems (Christenson & Sims, 2011; Wang et al., 2014).

In the early 2000s, studies primarily focused on the identification of high-lipid-producing microalgae strains, such as *Chlorella vulgaris* and *Botryococcus braunii* for biodiesel production. Research by Chisti (2007) highlighted the potential of microalgae to produce up to 30 times more oil per hectare compared to the terrestrial oilseed crop counterparts. However, challenges, such as low biomass productivity and high production costs limited large-scale applications.

During this period, advancements in photobioreactor (PBR) technology addressed some of the scalability challenges. For example, Xu et al. (2013) demonstrated that closed PBR systems improved light utilization and reduced contamination risks. Genetic engineering also became a focus area, with studies showing enhanced lipid accumulation in *Nannochloropsis* strains through metabolic engineering (Wang et al., 2014).

Additionally, the co-production of biofuels and valuable by-products was explored. For instance, Singh et al. (2014) highlighted the potential of coupling biofuel production with wastewater treatment, enabling cost reductions while addressing environmental issues.

Recent studies have encouraged integrating nanotechnology and artificial intelligence (AI) to optimize microalgae cultivation. Nanoparticles, such as titanium dioxide, have been used to enhance nutrient uptake, as demonstrated by Ma et al. (2023). AI-driven monitoring systems have also improved growth efficiency by maintaining optimal cultivation conditions in real time (Yadav et al., 2020).

Hybrid systems combining microalgae cultivation with carbon capture and wastewater treatment are emerging as sustainable solutions. Xu et al. (2022) showed that integrating these systems could enhance biomass productivity while simultaneously treating industrial effluents.

Microalgae are photoautotrophic microorganisms capable of performing photosynthesis and converting solar energy into chemical energy stored in the form of biomass. They are well-known for their superior carbon dioxide (CO_2) fixation efficiency over the common terrestrial plants. The advantages of microalgae include rapid growth rates, good adaptability to diverse environmental conditions, and the capability to produce valuable by-products, such as biofuels and economically valuable chemicals (Daneshvar et al., 2022). Furthermore, microalgae do not require wider and fertile land, making them as environmentally friendly choice for sustainable energy production.

Initial studies explored the concept of electricity generation using cyanobacteria and microalgae in bioelectrochemical systems. Strik et al.

(2010) demonstrated that photosynthetic organisms could transfer electrons to anodes under light conditions, producing electricity. During this time, studies on *Chlorella vulgaris* in MFCs also highlighted the feasibility of using microalgae for simultaneous electricity generation and wastewater treatment (Rosenbaum et al., 2005). However, power outputs were still limited due to its low electron transfer efficiency and suboptimal electrode designs. Bio-photovoltaics (BPV) emerged as an innovative application of microalgae for electricity. Bombelli et al. (2011) pioneered studies on photosystem II (PSII)--based electron transfer mechanisms, identifying ways to capture electrons generated during photosynthesis. Advances in electrode materials, such as indium tin oxide (ITO), improved electron transfer efficiency (Ng et al., 2017).

During this period, immobilization techniques became essential for stabilizing microalgae in BPVs and MFCs. Sodium alginate and agar-based immobilizers helped enhance biofilm stability, improving electron transfer and power output (Zhu et al., 2023). Recent studies focus on integrating nanomaterials and hybrid systems to enhance performance. For instance, Ma et al. (2023) reported that using graphene-based electrodes in BPV systems significantly increased conductivity and electron transfer rates. Genetic engineering of microalgae to overexpress electron-shuttling proteins has further improved power densities in MFC systems (Xu et al., 2022).

The growing demand for renewable energy has highlighted the potential of microalgae as an alternative to traditional bioenergy sources. Unlike terrestrial crops, microalgae exhibit higher photosynthetic efficiency, faster growth rates, and the ability to thrive in diverse environments, including saline or wastewater (Chisti, 2007). Moreover, microalgae can produce high-value co-products such as omega-3 fatty acids and pigments, which enhance the economic feasibility of microalgae-based systems (Christenson & Sims, 2011; Wang et al., 2014).

In addition to these advantages, microalgae offer several benefits over terrestrial plants when used for renewable energy applications:

1. Higher Oil Content for Biofuels
   Microalgae, such as *Nannochloropsis* and *Chlorella*, contain high lipid content, often exceeding 50% of their dry weight. This is significantly higher than palm oil (20-30%) and other biofuel crops, making them more efficient for biodiesel production (Mata et al., 2010).
2. More Efficient Water Usage
   Unlike terrestrial plants, microalgae do not require large amounts of freshwater. They can grow in brackish, saline, and even wastewater, reducing pressure on freshwater resources (Markou & Georgakakis, 2011).
3. Continuous Cultivation Cycle
   While land-based crops require seasonal planting and harvesting, microalgae can be cultivated continuously throughout the year under controlled conditions, ensuring a stable biomass supply (Richmond, 2004).
4. Higher Carbon Sequestration Potential
   Microalgae can capture CO_2 at a rate 10-50 times higher than terrestrial plants, making them an effective solution for mitigating industrial carbon emissions (Singh & Olsen, 2011).
5. No Need for Pesticides or Herbicides
   Unlike terrestrial crops that require extensive pesticide use, microalgae cultivation does not require herbicides or pesticides, reducing environmental pollution and production costs (Spolaore et al., 2006).
6. Potential for Genetic Engineering
   Advances in synthetic biology allow microalgae to be genetically modified to enhance lipid production, improve photosynthetic efficiency, or produce valuable biochemicals, which is more challenging for large-scale terrestrial plants (Radakovits et al., 2010).
7. Adaptability to Space and Urban Farming
   Due to their minimal space requirements, microalgae can be grown in bioreactors, photobioreactors, and vertical farms, making them ideal for urban farming and future space missions (Jones & Mayfield, 2012).

These advantages make microalgae an ideal candidate for bioenergy production and emerging technologies such as bio-photovoltaic (BPV) systems. By leveraging their superior photosynthetic efficiency, resource adaptability, and potential for high-value co-products, microalgae-based energy systems can contribute significantly to global renewable energy solutions.

2. Bio-photo voltaic (BPV) Technology

An innovative renewable energy technology called bio-photo voltaic (BPV) systems uses microorganisms like algae and cyanobacteria to transform solar energy into electrical power through photosynthetic processes. By utilizing natural biological processes, these systems provide a sustainable method of producing energy

Bio-photo-voltaic (BPV) technology represents an innovative and sustainable method to generate bioelectricity by harnessing solar energy through microorganisms, such as microalgae and cyanobacteria. BPVs rely on the fundamental process of photosynthesis, where light energy is used to split water molecules into electrons, protons, and oxygen, which are subsequently utilized for electricity generation (Saar et al., 2018). The electron transport that occurs in Photosystem II (PSII) facilitates the generation of electricity, with protons migrating through a proton exchange membrane (PEM), while electrons flow through an external circuit (Strik et al., 2010).

Recent Advances in Bio-photo voltaic Systems:

1. Enhanced Electrical Output: Increasing the electrical outputs of BPV systems has been the subject of recent research. Strategies include improving biofilm growth, improving electron transport processes, and optimizing the interaction between photosynthetic bacteria and electrode materials. (2)
2. Anode Material Optimization: The efficiency of BPV systems is greatly impacted by the anode material selection. Numerous materials have been investigated in studies to increase total power generation and electron transfer efficiency. (3)
3. Integration with Wastewater Treatment: By integrating BPV systems with wastewater treatment procedures, waste degradation and power production can occur at the same time. The sustainability and usefulness of BPV applications are improved by this dual functionality. (4)

2.1. Material Optimization and Nanotechnology Integration

On the other hand, proposed improvements in BPV technology involve using advanced materials such as graphene and Carbon Nanotubes (CNTs). Graphene is known for its excellent electrical conductivity, high surface area, and efficient electron transfer capabilities. When graphene and CNTs are used as electrodes, power density can be significantly increased to 0.5 mW/cm^2 (5000 mW/m^2). This enhancement is nearly 360 times greater than that of conventional BPV technology. These materials enable BPV systems to generate electricity at a much faster rate, which is essential for IoT applications and portable devices

The energy conversion efficiency of BPV systems is being steadily improved by the integration of advanced materials such as graphene and carbon nanotubes (CNTs). These materials demonstrate superior electron conductivity and have been shown to significantly enhance the efficiency of BPVs compared to traditional carbon electrodes. According to, graphene-based electrodes exhibit enhanced charge transfer rates, resulting in higher bioelectricity output and greater stability of the system over time. Similarly, CNTs' high surface area and excellent conductivity contribute to improved system efficiency, enabling more efficient electron transfer between the microorganism and the electrode (Yadav et al., 2020). Comparative Analysis: In contrast to conventional carbon electrodes (Strik et al., 2010), which struggle with slow electron transfer rates, the incorporation of graphene and CNTs has resulted in a substantial improvement in the efficiency of BPV systems. The ability of these advanced materials to facilitate faster electron transfer has enabled BPVs to achieve power densities up to 0.5 mW/cm^2, making them more viable for real-world applications, such as powering small electronic devices (Wang et al., 2021).

Improved BPV technology aims to enhance operational lifespan by using more durable materials such as graphene and CNTs, which are not only more conductive but also more resistant to harsh environmental conditions. Additionally, optimizing the microorganism environment and employing better immobilization techniques are expected to improve device stability over the long term. As a result, improved BPV devices are expected to last longer and provide more consistent electrical output over extended period

2.2. Genetic Engineering of Microorganisms

One of the most promising strategies for enhancing BPV performance is the genetic modification of microorganisms to improve their ability to produce electrons during photosynthesis. Synechocystis, a widely studied cyanobacterium, has been genetically engineered to enhance electron separation efficiency in PSII, a key step in the generation of bioelectricity (Pisciotta et al., 2011). These genetic modifications aim to increase the rate of electron flow and improve overall energy yield, making BPVs more competitive with traditional solar technologies. Comparative Analysis: While conventional BPV systems rely on wild-type microorganisms, genetically engineered strains such as Synechocystis offer a significant advantage by enhancing the rate of electron production (Pisciotta et al., 2011). This targeted approach allows for a more efficient conversion of solar energy into electricity, marking a considerable improvement over standard BPV systems.

2.3. Hybrid BPV-Solar Systems

Hybrid systems that integrate BPV technology with traditional solar power systems represent another innovative direction in BPV research. These hybrid systems combine the energy-generating capabilities of both solar panels and BPVs to increase the overall energy output. During the day, solar panels generate electricity, while BPVs continue to produce power during the night through microbial metabolism, ensuring a continuous power supply (Xu et al., 2019). Comparative Analysis: Traditional solar systems only generate electricity during daylight hours, while hybrid BPV-solar systems, as demonstrated by Xu et al. (2019), extend power generation into the night, making them more reliable and efficient. This integration of solar and microbial power offers a solution to the intermittent nature of renewable energy sources, thus increasing the overall utility of BPVs.

3. Immobilization Techniques for Microalgae

Immobilization is a technique used to restrict the movement of microalgae cells in liquid media by entrapping them in a solid matrix. This approach aims to enhance electron transfer efficiency in BPV systems, thereby increasing electrical output.

Table 1. Power output performance of immobilized cells in BPV or MFC devices

Microorganism	Matrix Material	System	Power Output	Key Findings	Reference
Chlorella vulgaris	Sodium Alginate	MFC	2572.8 mW/m³	Stable power generation.	He et al., 2014
Saccharomyces cerevisiae	Sodium Alginate	BPV	13.94 mW/m²	Enhanced electron transfer.	Hadiyanto et al., 2022
Anabaena variabilis	Alginate beads	BPV	0.6 mA	Effective in discharge cycles.	Yagishita et al., 1998
C. vulgaris	Agar	BPV	124.5 μW/cm²	Improved photosynthetic stability.	Bombelli et al., 2011
C. vulgaris	Graphine-alginate beads	MFC	3410.2 mW/m³	Superior conductivity and durability.	Ma et al., 2023

Natural polysaccharides such as alginate, agar, and carrageenan are commonly used as immobilization materials due to their low toxicity and transparency (Zhu et al., 2023). This method enables more effective integration of microalgae into BPV devices.

Previous studies have demonstrated the application of diverse immobilization techniques and materials. Sodium alginate is among the most popular immobilization materials due to its low cost, ease of use, and biocompatibility. He et al. (2014) demonstrated the immobilization of *Chlorella vulgaris* in sodium alginate for MFCs, achieving a power density of 2572.8 mW/m³. These findings emphasize sodium alginate's role in enhancing electron transfer efficiency and maintaining high photosynthetic activity.

The other option is natural polysaccharides such as agar and carrageenan offer transparency and structural integrity, facilitating photosynthesis and electron transfer. Zhu et al. (2023) highlighted the application of these materials for immobilizing *Chlorella vulgaris* in BPV systems, achieving stable energy output. Compared to sodium alginate, agar provides superior transparency, making it more suitable for light-dependent systems like BPVs.

On the other hand, Yagishita et al. (2000) explored poly-ion complexes for immobilizing *Synechocystis sp.* in BPV systems. These complexes demonstrated excellent electron transfer properties when combined with glassy carbon electrodes. However, challenges such as mass transfer limitations were identified, indicating the need for optimization. Recent advancements involve hybrid materials, such as graphene-embedded alginate beads, which significantly improve conductivity and electron transfer efficiency. Ma et al. (2023) reported that these advanced materials enhanced power density to 3410.2 mW/m³ in MFCs. These innovations address the limitations of traditional materials, such as durability and conductivity, while maintaining biocompatibility. Table 1 shows numerous studies have investigated the application of various microorganisms, matrices, and immobilization techniques in microbial fuel cells (MFCs) to improve power generation efficiency. Microorganisms such as *Chlorella sp.*, *Saccharomyces cerevisiae*, *Anabaena variabilis*, *Enterobacter aerogenes,* and *Chlorella vulgaris* have been immobilized using materials like sodium alginate, poly-ion complexes, and alginate beads. These immobilization materials play a vital role in stabilizing microorganisms within MFC systems, allowing them to efficiently produce energy under diverse environmental conditions.

4. Modeling and Kinetics of Electron Transfer

One of the main challenges of current BPV technology is its short operational lifespan. Conventional BPV devices typically function for only a few days to a week before degradation occurs. This degradation is usually caused by unstable microorganism growth and damage to electrode materials due to biochemical processes occurring during photosynthesis.

Conventional BPV systems often have large and non-portable designs, limiting their application to laboratory settings or small-scale installations. The primary factors contributing to their large size include the use of traditional hardware, inefficient immobilization methods, and suboptimal electrode designs. Additionally, materials like ITO used as electrodes often require rigidecon substrates, further increasing the size and weight of the devices.

In contrast, newer BPV technology focuses on creating portable and compact designs. The use of flexible membranes, lightweight electrodes, and natural immobilizing materials like sodium alginate and agar allows BPV devices to be smaller and easier to integrate with Internet of Things (IoT) applications and used in remote areas without access to electricity. This approach is crucial for making BPV a widely applicable technology that can compete with other renewable energy technologies

Electron transfer kinetics in BPV systems are crucial for determining bioelectricity production efficiency. Electrons generated during photosynthesis in Photosystem II must be transferred to electrodes via electron mediators. Research indicates that efficient electrode materials, such as indium tin oxide (ITO) or graphene, can significantly enhance electron transfer, thereby boosting electricity production (Ng et al., 2014). Additionally, immobilization techniques improve the contact between microalgae and electrodes, further increasing system efficiency.

In BPV systems, microalgae such as *Chlorella vulgaris* and cyanobacteria (*Synechocystis sp.*) act as biological catalysts for electron generation. During photosynthesis, PSII splits water molecules, releasing oxygen, protons, and electrons. These electrons are captured by natural or synthetic mediators, which transport them to the electrode surface for electricity generation (Bombelli et al., 2011). Mediators such as ferricyanide and quinones are frequently used to enhance the electron transfer process by reducing resistance and facilitating a smooth transfer path (Pisciotta et al., 2011).

Electron transfer efficiency is influenced by the following factors:

1. Electrode Material: The choice of electrode material determines the ease with which electrons are transferred. Materials such as indium tin oxide (ITO) and graphene exhibit excellent conductivity and surface area, making them ideal for enhancing transfer kinetics (Ng et al., 2014).
2. Electrode Surface Modifications: Coating electrodes with conductive polymers or nanoparticles increases the surface area and improves electron absorption rates (Yadav et al., 2020).
3. Immobilization Techniques: Immobilizing microalgae close to the electrode reduces the distance electrons must travel, thereby increasing transfer efficiency (Ma et al., 2023).

In recent study, the usage of advanced electrode materials becoming more popular. Graphene, with its high conductivity and large surface area, has revolutionized BPV systems. Ma et al. (2023) demonstrated that graphene-coated electrodes significantly improved electron transfer rates and enhanced power output compared to traditional carbon electrodes. The two-dimensional structure of graphene allows for a high density of electron flow, reducing losses during transfer.

Indium Tin Oxide (ITO) electrodes are widely used in BPV systems due to their transparency and conductivity. Transparency is particularly advantageous in BPVs as it allows light to penetrate the microalgae layers effectively, sustaining photosynthetic activity (Ng et al., 2014). Additionally, ITO electrodes support stable long-term electron transfer, making them a reliable choice for extended operations.

The combination of materials such as graphene and metal oxides has led to hybrid electrodes that merge the benefits of both materials. For example, Yagishita et al. (2000) reported that glassy carbon electrodes enhanced with poly-ion complexes improved electron transfer kinetics by providing a stable and efficient platform for electron conduction.

5. **Portable Bio-Photo Voltaic**

Portable Bio-Photo Voltaic (BPV) systems represent an innovative step forward in renewable energy technology, designed to meet the growing need for small-scale, decentralized, and sustainable energy sources. These systems have shown significant promise in powering portable devices and environmental sensors, particularly in off-grid and remote locations, thereby addressing the global demand for reliable and compact energy solutions (Wang et al., 2021; Kumar et al., 2020).mode

5.1. Technical Advancements in Portable BPV Systems

The development of portable BPV systems has been fueled by significant advancements in materials and design. Most systems utilize miniaturized reactors equipped with flexible membranes and lightweight electrodes, ensuring portability and ease of use. Wang et al. (2021) demonstrated a portable BPV device capable of generating 0.5 mW/cm^2, suitable for IoT-based sensor applications, while Tanaka et al. (2020) highlighted the role of durable, flexible materials in enhancing system scalability and resilience.

Incorporating advanced materials like nanostructured electrodes and biofilm-enhancing substrates has further improved efficiency and stability. Graphene-based electrodes, noted for their high conductivity and biocompatibility, have significantly enhanced electron transfer processes, a critical factor for improving energy output (Liu et al., 2022; Zhang et al., 2023). These developments make portable BPVs a viable alternative to traditional portable power solutions such as batteries or fuel cells, particularly in resource-constrained environments.

5.2. Comparative Advantages and Applications

Compared to solar panels and conventional batteries, portable BPVs demonstrate superior adaptability, particularly in low-light and resource-limited settings. BPV systems harness microbial or photosynthetic activity, enabling energy generation across a wide range of environmental conditions (Nguyen et al., 2021). Additionally, BPVs integrate seamlessly with IoT systems, enabling real-time data collection, control, and monitoring, which is particularly valuable for disaster response and environmental management (Tanneru et al., 2019; Gupta et al., 2021).

Environmental Monitoring: Portable BPV systems have been successfully deployed for applications such as monitoring water quality and air pollution in remote areas, where conventional energy infrastructure is inaccessible (Kumar et al., 2020). Remote Healthcare: BPVs provide sustainable power for medical diagnostics in isolated regions, facilitating advancements in telemedicine and portable health monitoring devices (Singh et al., 2022). Agricultural Applications: BPV-powered sensors are being utilized for soil health and crop monitoring, offering precision agriculture solutions that rely on renewable energy sources (Nguyen et al., 2021).

5.3. Challenges and Future Directions

Despite their advantages, BPV systems face challenges related to energy density and long-term operational stability. Key areas for improvement include optimizing microbial biofilms and electrode designs to enhance efficiency under varying environmental conditions (Zhang et al., 2023). Additionally, reducing production costs through scalable manufacturing techniques is critical to ensuring commercial viability (Lee et al., 2020).

Future research could explore the integration of BPV systems with other renewable energy technologies, such as solar cells and thermoelectric devices. Hybrid systems hold the potential to enhance energy reliability and broaden application scopes, making them suitable for multifunctional roles in agriculture, environmental conservation, and disaster response (Nguyen et al., 2021; Liu et al., 2022). Hybrid Innovations: By combining BPVs with solar cells, systems could leverage both microbial activity and solar energy, offering dual-generation capabilities even in challenging environments (Zhang et al., 2023).

Cost Reduction Strategies: Advances in manufacturing processes, particularly in electrode and biofilm materials, are essential for reducing costs while maintaining performance (Lee et al., 2020). Scalability: Developing modular designs that allow for customization based on specific application needs could facilitate wider adoption in both developed and developing regions.

Portable BPV systems, designed for small-scale applications, are an exciting development in the field of BPVs. These systems are intended for use in remote areas or for powering portable environmental sensors. Wang et al. (2021) developed a portable BPV system capable of generating power up to 0.5 mW/cm², sufficient for operating Internet of Things (IoT)-based sensors. These portable BPVs typically use mini reactors with flexible membranes and lightweight electrode systems, making them easy to transport and deploy.

Portable BPV systems have the distinct advantage of being adaptable to off-grid environments, unlike traditional solar or fuel-powered devices. As shown in studies by Wang et al. (2021), portable BPVs can be easily integrated into IoT-based applications, offering a sustainable and efficient energy source in remote areas where conventional energy infrastructure is lacking.

6. Research Needs and Future Directions of Bio-photo voltaic Technology

Bio-photo voltaic (BPV) technology offers significant potential in the development of sustainable energy systems and environmental applications. However, this technology faces various substantial challenges that hinder its implementation on an industrial scale. One of the main challenges is the low electron transfer efficiency. In BPV systems, the electron transfer from microorganisms to the electrode is often suboptimal, directly impacting system efficiency (Wang et al., 2021). Additionally, system stability is a concern, especially under long-term operating conditions, necessitating improvements in electrode materials and cell configurations to enhance durability (Kumar et al., 2020).

The stability of BPV systems is also heavily influenced by environmental factors, including light intensity, temperature, and the type of electrode used. For instance, research by Tanneru et al. (2019) demonstrated that extreme temperatures, either too high or too low, could reduce the photosynthetic activity of microorganisms, thereby affecting electricity production efficiency. These factors highlight the need for optimizing operating conditions to maintain BPV performance across various application environments.

Stability under real-world conditions is a key challenge for portable BPVs. Bombelli et al. (2011) reported that BPVs using *Synechocystis sp.* showed consistent performance over extended periods but were sensitive to environmental variations such as temperature and light intensity. Meanwhile, Yadav et al. (2020) proposed the use of anti-fouling coatings on electrodes to address these challenges, resulting in improved durability under variable outdoor conditions. Comparatively, Wang et al. (2021) emphasized the importance of optimizing immobilization techniques to ensure cell viability, which directly impacts long-term performance.

The versatility of portable BPVs has been demonstrated in various applications. For instance, Wang et al. (2021) showcased BPVs for powering IoT sensors in remote locations, while Xu et al. (2019) combined BPVs with wastewater treatment systems for dual-purpose functionality. Comparatively, Ma et al. (2023) and Zhu et al. (2023) focused on enhancing system design for standalone applications, such as wearable devices and environmental monitoring tools. These studies highlight the diverse potential of BPVs but also underscore the need for tailored designs based on specific use cases.

Economically, electricity production using conventional BPV technology remains costly. This is mainly due to the use of expensive electrode materials like ITO and inefficient manufacturing processes. The estimated electricity production cost for conventional

BPV systems is around $0.20 - $0.40 per kWh, which is significantly higher compared to other renewable energy technologies like conventional silicon solar panels, which typically cost less than $0.10 per kWh.

However, by developing scalable graphene production methods and improving efficiency through genetic engineering and the use of CNTs, electricity production costs can be significantly reduced. It is estimated that the cost of electricity produced by improved BPV systems could be reduced to $0.10 - $0.20 per kWh. This cost reduction is essential to making BPV a competitive renewable energy technology in the market

Cost remains a critical factor in the commercialization of portable BPVs. Ng et al. (2014) noted that the use of ITO electrodes significantly increased system costs, limiting scalability. In contrast, Yadav et al. (2020) suggested that graphene-based materials, although initially expensive, could become cost-effective with advances in large-scale manufacturing techniques. The comparative analysis reveals a trade-off between performance and affordability, necessitating further research into low-cost, high-efficiency materials.

In addition to technical challenges, BPV systems must meet the requirements of specific applications such as environmental sensors, wastewater treatment, and sustainable energy systems in remote areas. These applications demand devices that are efficient, cost-effective, and easy to operate. Recent studies suggest that biofilm modification and the integration of nanomaterial technologies can improve BPV performance, enabling its deployment on a larger scale (Liu et al., 2022; Zhang et al., 2023).

To address these challenges, future research should focus on the development of new materials, such as nanocarbon-based electrodes, which exhibit high conductivity and excellent chemical stability, optimizing designs for specific applications, and reducing production costs to accelerate the adoption of portable BPVs in real-world scenarios. Moreover, bioengineering approaches to enhance the electron transfer capabilities of microorganisms need to be further advanced (Gupta et al., 2021). With these advancements, BPV has the potential to become a sustainable solution for global energy and environmental needs.

CONCLUSION

Portable Bio-Photovoltaic (BPV) technology holds significant potential as an innovative and sustainable energy solution. Over the years, advancements in materials, system design, and biological engineering have enhanced the efficiency and versatility of portable BPV systems. The following conclusions summarize the key findings from the review:

1. Advancements in Electrode Materials: Studies have demonstrated that using advanced materials like graphene and carbon nanotubes significantly enhances electron transfer efficiency, durability, and overall power output. These materials outperform traditional electrodes like indium tin oxide (ITO) in both portability and scalability, making them ideal for real-world applications (Ma et al., 2023; Ng et al., 2014).
2. Immobilization Techniques for Stability: Immobilization methods using materials such as sodium alginate, agar, and hybrid matrices effectively stabilize microalgae in portable BPVs. This approach not only improves electron transfer efficiency but also enhances the durability of BPV systems under diverse environmental conditions (Zhu et al., 2023; He et al., 2014).
3. Application Potential: Portable BPVs have been successfully utilized in remote sensing, IoT applications, and environmental monitoring. Their ability to operate in off-grid and low-light conditions, combined with easy integration into IoT systems, highlights their adaptability for niche applications (Wang et al., 2021; Xu et al., 2019).
4. Challenges in Cost and Longevity: Despite the progress, the commercialization of portable BPV systems remains hindered by high production costs and limited operational lifespan. Addressing these issues requires the development of scalable manufacturing processes and durable materials (Yadav et al., 2020; Zhu et al., 2019).
5. Future Directions: In spite of these developments, BPV systems still have problems with scalability and low power densities. By investigating new materials, improving microbial-electrode interactions, and creating more effective system designs, ongoing research seeks to overcome these constraints. There is hope for sustainable and environmentally friendly solar energy solutions using BPV technology. Future research should focus on optimizing system designs for specific applications, advancing genetic engineering of microalgae to improve bioelectricity yield, and exploring hybrid energy systems to enhance reliability and scalability (Pisciotta et al., 2011; Zhang et al., 2023).

In conclusion, portable BPV systems represent a transformative step forward in renewable energy technology. With continued innovation in materials, biological optimization, and hybrid system integration, BPVs have the potential to provide a practical, efficient, and sustainable energy solution for diverse applications.

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