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Cultivating Microalgae with Biophotovoltaic to Produce Bioelectricity: A Bibliometric Analysis

Muhamad Maulana Azimatun Nur[1], Raden Herjun Desta K. H[2], Ryan Keane Mahardika Pratama[3], Amanda Nur Affrida[4], Aulia Rahma Putri[5], Dwi Aulia Puspitaningrum[6], Md. Hasanuzzaman[7], Resti Nurmala Dewi[8]

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***Abstract*— This review investigates the role of microalgae in bioelectricity production through biophotovoltaic (BPV) systems, focusing on their dual benefits of generating renewable energy and treating wastewater while capturing CO_2. The objective of this paper is to conduct a bibliometric analysis of publications from 2013 to 2024 to understand research trends, key contributors, and research hotspots in the field of microalgae-based BPV systems. Methods used include statistical analysis through VOSviewer to visualize the connections between articles and authors. The results show significant advancements in integrating of nanomaterials and microbial fuel cell technologies for bioelectricity generation, as well as ongoing challenges in scalability, voltage balance, and material optimization. This review provides insights into future research directions for improving BPV systems.**

Keywords— bibliometric analysis, bioelectricity, biophotovoltaic, microalgae.

I. INTRODUCTION

Microalgae are photosynthetic, single-celled, or colonial organisms that thrive in a variety of aquatic and humid environments, including rivers, lakes, oceans, and soil [1], [2], [3]. These organisms, which can range in size from a few microns to several hundred, are seen as future bio-based crops due to their rich content of carbohydrates, lipids, and proteins [4], [5]. Their photosynthetic capabilities further increase their value across multiple industries [6]. Consequently, microalgae have emerged as a promising resource for biofuels and other high-value products. Their inherent advantages include fast biomass growth, improved carbon dioxide fixation, and the capacity to store carbon as lipids and carbohydrates, up to 50%, for producing biofuels such as bioethanol, biodiesel, biohydrogen, and biomethane, as well as recovering valuable products like pigments, biopolymers, biopeptides, antioxidants, and polysaccharides [7], [8], [9]. In response to the global demand for environmentally friendly technologies, biorefineries offer a key approach to achieving sustainability [10]. With fossil fuels predicted to deplete by 2030, the urgency for alternative energy sources is growing [11]. Biorefineries focus on converting biomass into various bio-products in a single process, reducing production costs. Despite the potential of microalgae as a biomass source, complex processing is still required to produce these value-added products. Adopting a biorefinery model for microalgae cultivation and biomass production can address this challenge. By 2025, it is expected that microalgae-derived products will be produced on a larger scale and in a more environmentally sustainable manner [12], [13]. The success of such a biorefinery system hinges on selecting the right raw materials and processes to generate high-value products, with microalgae being one of the most viable options economically.

A microbial fuel cell (MFC) is a biochemical device that uses microbial activity, or digestion, to transform the chemical energy of microorganisms into electrical form [14]. Recently, MFC technology has become a viable bioelectrochemical platform that uses microorganisms to remove organic pollutants from wastewater and produce bioelectricity at the same time. [15]. Microbial fuel cells (MFCs) are a form of bioelectrochemical system that harnesses bacterial interactions to produce electricity while simultaneously treating wastewater. This system presents a promising approach to generating clean, renewable, and cost-efficient energy sources [16] While MFCs typically generate lower power densities compared to other chemical fuel cell technologies, they offer a distinct advantage in wastewater treatment by

[1]Muhamad Maulana Azimatun Nur, Department of Chemical Engineering, University of Pembangunan Nasional Veteran Yogyakarta, Sleman, Yogyakarta, 55283, Indonesia E-mail: lanaazim.st@gmail.com
[2]Raden Herjun Desta K. H, Department of Chemical Engineering, University of Pembangunan Nasional Veteran Yogyakarta, Sleman, Yogyakarta, 55283, Indonesia. E-mail: 121230116@student.upnyk.ac.id
[3]Ryan Keane Mahardika Pratama, Department of Chemical Engineering, University of Pembangunan Nasional Veteran Yogyakarta, Sleman, Yogyakarta, 55283, Indonesia. E-mail: 121230118@student.upnyk.ac.id
[4]Amanda Nur Affrida, Department of Chemical Engineering, University of Pembangunan Nasional Veteran Yogyakarta, Sleman, Yogyakarta, 55283, Indonesia. E-mail: 121230136@student.upnyk.ac.id
[5]Aulia Rahma Putri, Department of Chemical Engineering, University of Pembangunan Nasional Veteran Yogyakarta, Sleman, Yogyakarta, 55283, Indonesia. E-mail: 121230135@student.upnyk.ac.id
[6]Dwi Aulia Puspitaningrum, Department of Agribusiness, University of Pembangunan Nasional Veteran Yogyakarta, Sleman, Yogyakarta, 55283, Indonesia, E-mail: dwi.aulia@upnyk.ac.id
[7]Md. Hasanuzzaman, Higher Institution Centre of Excellence (HICoE), UM Power Energy Dedicated Advanced Centre (UMPEDAC), Level 4, Wisma R&D, University of Malaya, Jalan Pantai Baharu, 59990, Kuala Lumpur, Malaysia, E-mail: hasan@um.edu.my
[8]Resti Nurmala Dewi, Marine Product Processing Department, Polytechnics of Marine and Fisheries of Jembrana, Pengambengan, Negara, Jembrana, Bali, 82218, Indonesia, E-mail: resti.nurmala@kkp.go.id

effectively removing both inorganic and organic contaminants. This is achieved through catalytic reactions facilitated by self-sustaining electrical materials, specifically electrochemically active bacteria or anode-respiring bacteria, naturally found in wastewater [15].

While microbial fuel cells (MFCs) are aimed to generate electricity by harnessing electrons from biochemical reactions catalysed by bacteria, biophotovoltaic (BPV) systems generate electricity using sunlight and water through photosynthesis reaction [17]. These systems function as biological solar cells, producing electricity through the photosynthetic activity of microorganisms like algae or higher plants. Furthermore, unlike MFCs which rely on organic substrates to sustain living organisms, BPV devices exploit readily available and abundant sources of energy—light and water [18]. Microorganisms harness their photosynthetic apparatus, utilizing CO_2 and sunlight to break down water molecules in a process called photolysis [14]. The resulting protons and electrons are then captured by bioelectrochemical systems to produce electricity.

Despite the potential of microalgae in BPV systems to offer a sustainable energy solution, the practical application of these systems faces challenges related to efficiency, scalability, and system stability. Current research lacks comprehensive analyses of global trends and technological advancements that could improve bioelectricity production. There is a need for a detailed bibliometric review to highlight key research trends, technological advancements, and future opportunities, making this review timely and novel.

Bibliometric analysis is a valuable research strategy for efficiently and accurately analysing scientific studies. It focuses on data outcomes, highlights current trends within a specific research topic, and aids in predicting future research directions and their societal impact [19], [20]. This method is widely recognized as a tool for creating comprehensive frameworks in particular scientific areas. The goal of this review is to conduct a detailed bibliometric analysis of research on microalgae-based BPV systems for bioelectricity production. By identifying key trends, influential contributors, and research hotspots, the review aims to provide a better understanding of the current knowledge landscape. Additionally, it will examine the challenges and opportunities for improving BPV systems, with an emphasis on boosting bioelectricity production, addressing system limitations, and exploring advanced materials and designs to enhance efficiency and scalability.

II. METHOD

As seen in Figure 1, bibliometric analyses are statistical and mathematical techniques that can be applied to any subject to analyse data. The study's goal depends on researchers being able to deal with large samples of articles, which is made possible by this strategy because organizing an entire topic necessitates handling a sizable sample of articles. Furthermore, bibliometric analysis demonstrates the relationships between publications, providing researchers with information to establish their own contributions and identify new lines of inquiry for future research.

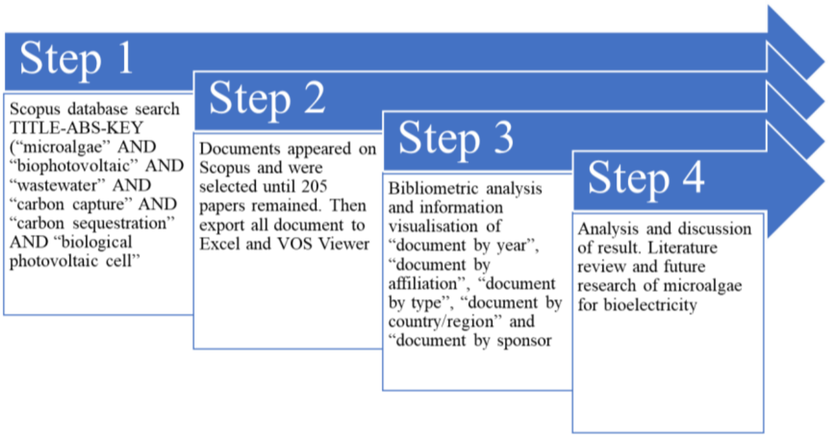


Figure 1. Bibliometric analysis of microalgae-based BPV research

To obtain all scientific publications linked to BVP and MIC, the SCOPUS core collection database keywords were ALL= ("microalgae" AND "biophotovoltaic" AND "wastewater" AND "electricity" AND "carbon capture" AND "carbon sequestration" AND "biological photovoltaic cell"). After limiting the research fields to articles published in the English language, we were able to get 205 papers for this study by searching the SCOPUS core collection database using these keywords.

For any scientific field that requires investigation, an appropriate science mapping technique should be employed [21]. Among the various programs available, VOSviewer, Gephi, Citespace, HistCite, and Sci2 are the most widely recognized. VOSviewer was the tool selected for this bibliometric analysis, as it creates two-dimensional maps using mathematical algorithms. It is highly favored in bibliometric research due to its capability to generate informative maps from network data for visual representations. This tool can display a diverse array of data types—such as authors, references, keywords, journals, organizations, and countries—as well as different types of relationships, including co-authorship, co-occurrence, citation, bibliographic coupling, and co-citation, in terms of structure and networks.

Following data cleaning, the researchers analyzed the growth of MIC and BVP during the study using Excel and VOSviewer (2013 - 2024). A tool for data analysis called Excel is used to analyze descriptive data, such as information about organizations, nations, and areas of study. It was employed in the study because of its great flexibility for changing data in databases like WOS.

Finally, the data were processed into 6 sections, which are document by year, document by affiliation, document by type, document by author, document by country/region, and document by funding sponsor.

III. RESULT AND DISCUSSION

Microalgae, due to their photosynthetic capabilities, are emerging as promising resources for producing biofuels and bioelectricity. Studies have shown that BPV systems, a subcategory of microbial fuel cells, utilize microalgae for converting sunlight and water into electricity through photolysis [18]. The ability of microalgae to simultaneously capture CO_2 and remediate wastewater makes them an ideal choice for sustainable energy production [14], [17]. Early research in this field has focused on improving the efficiency of BPV systems through enhanced material designs, including the use of nanomaterials. For example, the introduction of gold nanoparticles has been found to enhance the light-harvesting capabilities of cyanobacteria. Despite these advancements, scaling up BPV systems remains a significant challenge, especially in maintaining voltage stability across units and integrating with wastewater treatment processes. In recent years, there has been growing interest in using bibliometric analysis to identify research trends in this area. Previous studies have indicated a strong focus on regions such as India, China, and Malaysia, where government-funded projects have contributed to significant advancements in BPV research. However, further research is needed to optimize system designs and explore alternative materials for scalability and efficiency.

A. The trend of publications analysis from 2013 to 2024

Figure 2 shows the trend of publications analysis from 2013 - 2024. The highest growth occurred in 2015 - 2018 which was 14. The year with the highest number of publications occurred in 2022 with 38 documents.

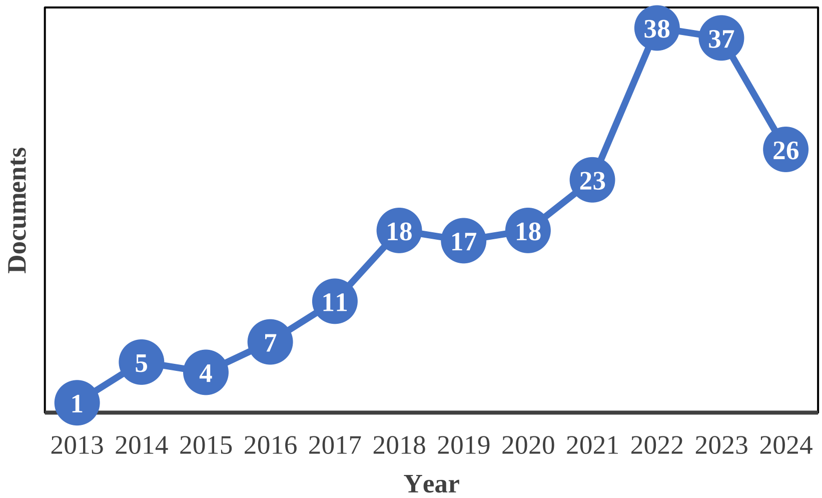


Figure 2. Total number of microalgae for bioelectricity generation publications by year (2013 to 2024)

However, the development of documents on the topic of microalgae for bioelectricity generation does not always increase. There was a notable and steady decline in the quantity of documents between 2022 and 2024. There was a drop of 1 from 38 to 37 papers in 2022–2023. From 37 to 26 documents, the number dropped by 11 in 2023–2024. Then, from 23 to 38 documents, there was the largest increase in documents between 2021 and 2022, an increase of 15.

B. Most impactful affiliation

Based on this analysis, 20 affiliations participated in scientific publications related to microalgae for bioelectricity. Figure 3 shows the number of publications owned by the top 10 institutions. The top ten Institutions are University Malaya (23 publications), University of Cambridge (18 publications), Indian Institute of Chemical Technology (16 publications), Institute of Biological Sciences (15 publications), UCSI University (12 publications), Madurai Kamaraj University (11 publications), Academy of Scientific (8 publications), Tecnologico de Monterrey (7 publications), Chinese Academy of Sciences (6 publications), and College of Sciences (5 publications).

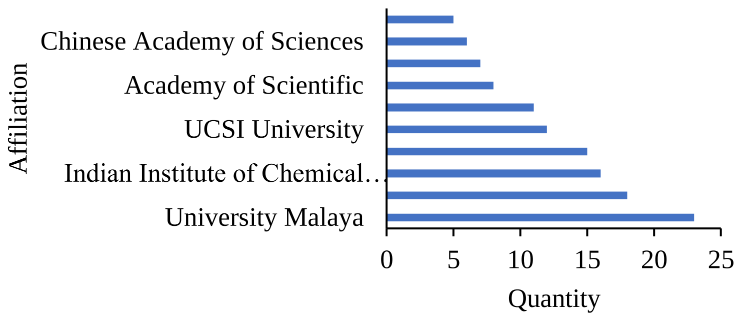


Figure 3. Top 10 the most impactful affiliation

As is well documented, University Malaya has published the greatest number of articles on the subject, according to data analysis. This evidence demonstrates that University Malaya is a leading institution in the field of microalgae for bioelectricity. The University of Cambridge is a notable second in this regard, with a strong commitment to new innovations in the field.

C. *Type of publication*

Our research found a total of 7 different types of documents published in the 11 years (2013 to 2024) in the Scopus database. From 205 publications, 108 articles were the most frequently published articles, followed by review papers (62 publications), book chapters (29 publications), conference papers (4 publications), a short survey (1 publication), and a note (1 publication).

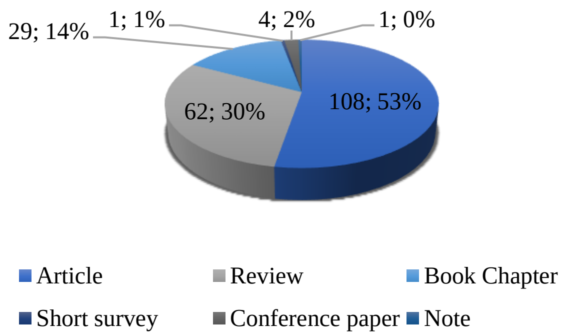


Figure 4. Type of document published about microalgae for bioelectricity generation

Figure 4 shows the distribution of microalgae for bioelectricity generation annual publication output from the first publication in 2013 to 2024, with a total of 205 publications.

D. *Most influential authors*

Research on Microalgae for Bioelectricity Generation involved 920 writers, according to an analysis of their co-authorship conducted with the VOS viewer. As seen by the various bubble colors, the writers are arranged into 11 clusters according to their co-authorship relationships. Based on the network map, Phang, S.M. appears to have the most articles on bases coating, as evidenced by the green-coloured bubble and largest label.

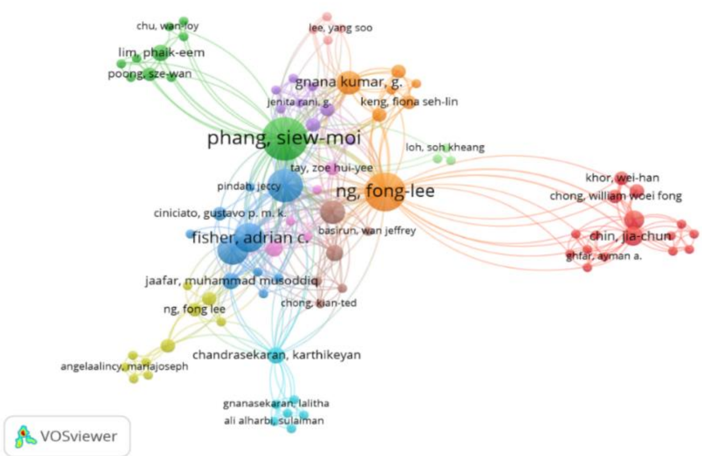


Figure 5. Co-authorship network of authors that published in microalgae for bioelectricity generation from 2013 to 2024

Figure 5 shows the details of influential authors on the topic of Microalgae for Bioelectricity Generation. The most influential author is Phang, S.M. with 23 publications followed by Ng, F.L. with 14 publications, Periasamy, V with 12 publications, Fisher, A.C., and Yunus, K. with 10 publications.

The distance of the network connection illustrates how connected the authors are through citations and collaboration in writing scientific papers. Therefore, we can conclude that Phang, S.M. often cites and collaborates with Periasamy V, Thong C.H, Al-Sehemi A.G, Pannipara N, Priyanga N, Jenita R.G, and Tay Z.H. However, Zhang Y rarely connects with Chandrasekaran K, Chu W.L, Lee Y.S, Lim P.E, Poong S.S, and Chong K.T.

E. Most influential country

Table 1 presents the number of publications in a country. Based on the total number of publications, the top ten countries are India (67 publications), Malaysia (36 publications), China (31 publications), United Kingdom (25 publications), United States (19 publications), South Korea (16 publications), Japan (10 publications), Saudi Arabia (10 publications), Taiwan (10 publications), and Mexico (8 publications).

TABLE 1.
TOP 10 NUMBER OF PUBLICATIONS AND CITATIONS BY COUNTRY

Country	Number of Citations	Number of Publication
India	1,462	67
Malaysia	501	36
China	629	31
United Kingdom	1,293	25
United States	941	19
South Korea	457	16
Saudia Arabia	65	10
Taiwan	113	10
Japan	310	10
Mexico	433	8

In recent years, India has had the most elevated volume of literature, showing that analysts put a higher priority on this field there. The difference in the number of publications between India and Malaysia is 31 publications. Two countries have the same number of publications, namely Saudi Arabia and Taiwan (10 publications). Mexico has the fewest publications among the others with a total of 8 publications.

F. Top 10 funding sponsors of microalgae for bioelectricity generation

To effectively address global challenges, researchers need to have adequate financial resources. To solve the problem, Figure 6 shows the top 10 funding sources for funding research on bioelectricity. According to data utilized by the Scopus database, 21 academic institutions have collectively funded 205 publications.

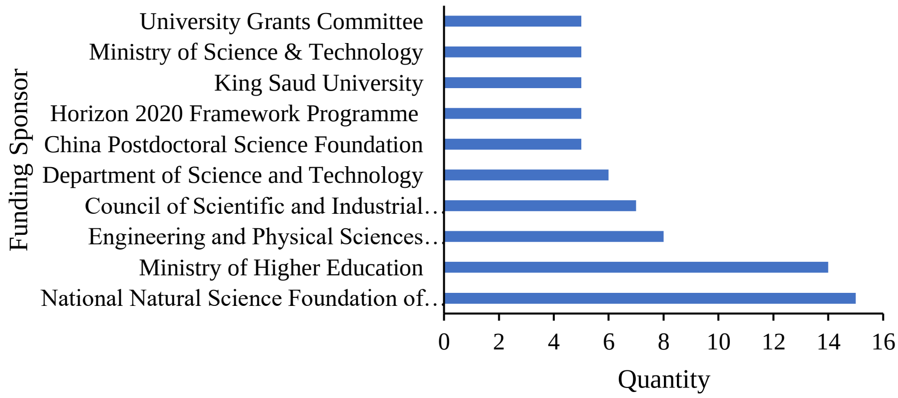


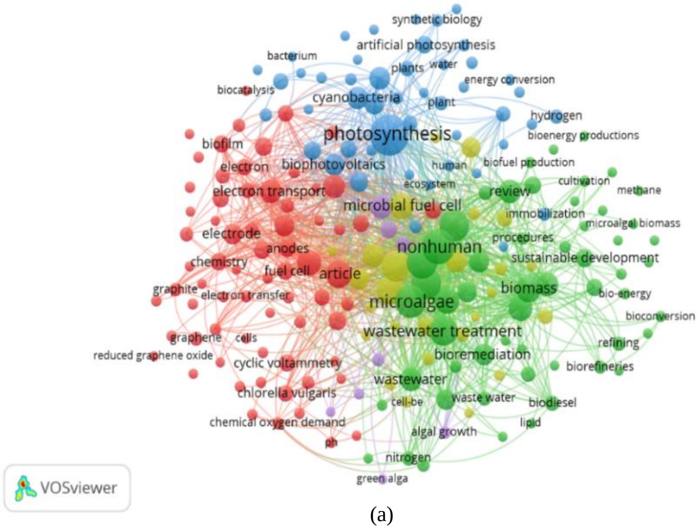
Figure 6. Top 10 funding sponsors of microalgae for bioelectricity generation

The data shown in Figure 6, indicate that the National Natural Science Foundation of China was the main body that funded the published publication on the use of microalgae for bioelectricity generation. The top ten funding bodies are National Natural Science Foundation of China (15 publications), Ministry of Higher Education (14 publications), Engineering and Physical Sciences Research Council (8 publications), Council of Scientific and Industrial Research (7 publications), Department of Science and Technology (6 publications), China Postdoctoral Science Foundation (5 publications), Horizon 2020 Framework Programme (5 publications), King Saud University (5 publications), Ministry of Science & Technology (5 publications), University

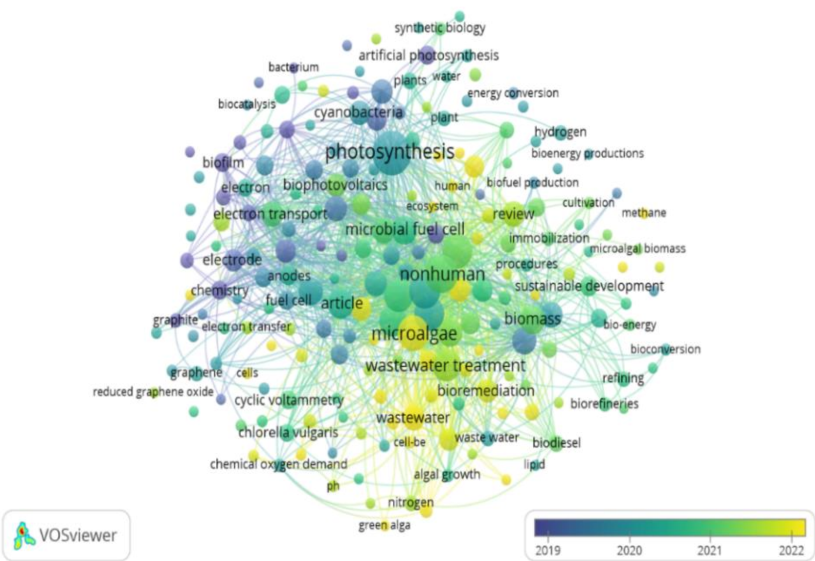
Grants Committee (5 publications). The Chinese government's interest in microalgae for bioelectricity is indicated by a significant number of funded research publications, amounting to 15 publications on the topic. In addition, some institutions have the same number of publications they fund (5 publications), namely China Postdoctoral Science Foundation, Horizon 2020 Framework Programme, King Saud University, Ministry of Science & Technology, and University Grants Committee.

G. *Keyword analysis*

One useful method for identifying research hotspots and trends is the analysis of author keywords in bibliometric studies. This study uses color-coded groups to indicate the many research fields: cluster 1 is labeled with red, cluster 2 with green, cluster 3 with blue, cluster 4 with yellow, and cluster 5 with purple. These implied the relationships between the keywords by showing the network connections between them through the lines connecting them. "Photosynthesis" ranked number one with 62 occurrences, followed by "Bioenergy" with 40 occurrences, "Microalgae" with 39 occurrences, "Microorganisms" with 38 occurrences, "Algae" with 36 occurrences, "Electrophysiology" with 31 occurrences, "Wastewater treatment" with 32 occurrences, "Article" with 29 occurrences, "Microbial Fuel Cell" with 27 occurrences, and "Biomass" with 27 occurrences. Since "photosynthesis" was the primary search term used to find the published data used in this analysis, it became clear that this keyword had the highest occurrence. The top five ranking keywords were "Photosynthesis," "Bioenergy," "Microalgae," "Microorganisms," and "Algae," with total link strengths of 716, 807, 564, 595, and 391. These implied the relationships between the keywords by showing the network connections between the keywords as evidenced by the lines between the keywords.



(a)



(b)

Figure 7. (a) Network visualization of keyword co-occurrence; (b) Overlay visualizations of microalgae for bioelectricity generation publications

From Figure 7, it can be seen that "bioenergy" as a keyword with the second largest bubble image also has a network of relationships that are also quite extensive. It can also be observed that the keyword "bioenergy" is closely related to the keyword's "algae", "microorganisms", "microalgae", "bioelectricity", "electrophysiology", "microbial fuel cell", and "wastewater treatment". This is due to the number of authors who have realized and published scientific work on the relationship between the keyword "bioenergy" and these keywords. In addition to having a close network of relationships, the keyword "bioenergy" also has a fairly distant network of relationships with the keywords "climate change", "graphite", "biofilm", "biodiesel", "*Chlorella vulgaris*", "alternative energy", "electron transport", and "alga growth". The distant network of relationships is due to the lack of authors who are aware of and publish about the relationship between the keyword "bioenergy" and these keywords. This can be used as an indication for other authors in the future to discuss the keyword "bioenergy" more with keywords that have a long distance in bibliometric co-occurrence.

TABLE 2.
PREVIOUS STUDIES OF THE INFLUENCE OF VARIOUS FACTORS ON BIOELECTRICITY PRODUCTION USING MICROALGAE

No.	Anode	Cathode	Cultivation mode	Wastewater	BPV	References
1.	Biodegradable organic matter	RVC (reticulated vitreous carbon) foam	-	Municipal wastewater treatment plant	-	[22]
2.	*Cyano-Au*	Solid-state Ag2O	Autotrophs	-	-	[23]
3.	*Chlorella vulgaris*	Myrothecium verrucaria bilirubin oxidase	Autotrophs	-	Microbial BPV	[24]
4.	Microalgae *Tetradesmus obliquus*	The microalgae *Tetradesmus reginae*	Mixotroph potentially increasing power density	Municipal wastewater	Dual-chambered BPV	[25]
5.	ITO-coated glass and ITO-coated plastic	Graphite	Aeration	-	BPV with aeration cultivation	[26]
6.	Porous ceramic anode and ITO-nanoparticle anode Porous ceramic anode and BP-ITO anode	Gas membrane	Inkjet printer	Domestic wastewater	-	[27]

Table 2 details the impact of utilizing different anode and cathode materials, cultivation methods for the microalgae, the types of wastewaters employed as a nutrient source, and the specific biophotovoltaic (BPV) configurations used in the experiments. By examining these variables, researchers can gain a deeper understanding of how to optimize the process of generating bioelectricity from microalgae.

H. Electricity Generation and CO_2 Reduction

This approach leverages the unique properties of cyanobacteria. By engineering them to produce biocompatible and highly stable gold nanoparticles intracellularly, we can create a powerful tool for enhancing their light-harvesting capabilities. These gold nanoparticles would act as efficient light absorbers, capturing more solar energy and generating a greater number of photo-excited electrons. Furthermore, the nanoparticles would function as electrical conduits, facilitating the transfer of these excited electrons across the cell membrane. This improved electron transport would ultimately lead to a significant boost in the overall efficiency of the photosynthetic process within the cyanobacteria [22].

Stacked algae microbial fuel cells (AMFC) are a powerful innovation that harnesses the combined power of light and microbes to generate usable electricity. This technology goes beyond just power generation. By directly producing oxygen at the electrodes, AMFCs create a closed-loop system that facilitates CO_2 cycling. This continuous CO_2 supply fuels the growth of algae within the system, generating valuable algal biomass. Furthermore, these AMFCs hold the potential to produce value-added biomolecules, turning wastewater treatment into a process that yields not just clean energy but also valuable products. This makes stacked AMFCs a highly sustainable and versatile technology with the potential to revolutionize bioenergy production [23].

Combining microalgae-based CO_2 capture with wastewater treatment offers a promising approach for a more economical and sustainable future. Wastewater, rich in nutrients, has become a valuable resource for microalgae growth. Microalgae, in turn, act as tiny green filters, removing nitrogen and phosphorus from the wastewater. This eliminates or reduces the need for harsh chemicals in wastewater treatment plants. The combined process tackles two environmental challenges simultaneously: capturing CO_2 through photosynthesis and cleaning up wastewater [28].

I. Challenges and Opportunities

Microbial fuel cells (MFCs) and biophotovoltaic

(BPV) systems have emerged as promising technologies for generating clean energy from renewable sources. These systems harness the power of microorganisms to convert organic matter into electricity or biofuels, offering a sustainable alternative to conventional energy sources. However, maintaining the optimal performance of MFCs and BPV systems presents several challenges that need to be addressed for their widespread adoption.

One of the primary challenges in MFC stacks is ensuring even voltage distribution across all units. Imbalanced voltages can lead to some units becoming weak (low voltage) while others become overloaded (voltage reversal), compromising the overall performance and stability of the system. This issue is particularly evident in BPV systems, where light intensity and duration significantly impact voltage. Sudden darkness can cause immediate light starvation and a voltage drop, while prolonged darkness leads to a slow starvation effect. Finding the optimal light regime is essential for stable performance in BPV systems.

A reversed voltage in an MFC or BPV unit indicates a malfunction and requires prompt attention to prevent further damage to the system. While voltage reversal blockers can be employed to protect the stack, it is crucial to identify and address the underlying cause of the reversal in the weak unit. Early detection and diagnosis of unit issues are essential for maintaining system health. In MFCs, oxygen management for optimal cathode function is critical. The experiment described in this study found that increasing oxygen supply through air bubbling improved performance slightly but could not fully compensate for a weak unit. Alternative oxygen management strategies or addressing the root cause of the weak unit are necessary.

The integration of nanomaterials into MFCs and BPV systems holds promise for enhancing their performance and efficiency. However, traditional nanoparticle synthesis methods often have limitations, including complexity, high energy requirements, and scalability issues. Moreover, incorporating nanoparticles into living organisms for BPV applications requires precise control over nanoparticle uptake, considering factors like temperature, concentration, and potential cytotoxicity to ensure the health and functionality of the biological component. Additionally, the non-uniform size and distribution of biogenic nanoparticles produced by cyanobacteria can hinder their effectiveness. Research efforts should focus on optimizing biosynthetic pathways to achieve more uniform biogenic nanoparticles.

Despite the challenges, there are numerous opportunities to enhance the performance and scalability of MFCs and BPV systems. Advanced materials research, including the development of biocompatible and efficient nanomaterials, can play a significant role in improving the efficiency and stability of these systems. Additionally, optimizing electrode designs and microbial communities can further enhance power generation and biofuel production. Furthermore, developing effective strategies for maintaining balanced voltages and addressing units.

IV. Conclusion

This review aimed to provide a bibliometric analysis of research trends in microalgae-based BPV systems for bioelectricity production. The analysis revealed that advancements in the use of nanomaterials and microbial fuel cell technologies have significantly improved bioelectricity generation. However, challenges related to voltage stability and scalability remain. Moving forward, research should focus on optimizing system designs and materials to enhance efficiency and scalability. This review highlights the importance of collaborative efforts in addressing these challenges and advancing the practical application of BPV systems.

Acknowledgments

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