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Review Article

Algal Microbial Fuel Cells: Integrating Wastewater Treatment with Sustainable Bioenergy Production

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ABSTRACT

Algal Microbial Fuel Cells (AMFCs) are an emerging bioelectrochemical technology that combines microbial electrogenesis and algal photosynthesis in a synergistic manner to produce electricity and treat wastewater containing organic matter. In an AMFC system, electroactive bacteria in the anodic compartment oxidize organic matter and release electrons to flow through an external circuit to the cathodic compartment, where oxygenic phototrophic microalgae consume oxygen and produce biomass. This two-chamber system not only produces clean and renewable energy but also addresses critical issues related to wastewater treatment and carbon sequestration on a global scale to mitigate the effects of climate change and fossil fuel depletion. AMFCs have been found to valorize various organic waste feedstocks effectively, converting waste into a valuable resource. The feedstocks used are varied, ranging from domestic sewage, which is rich in carbohydrates and proteins, to agricultural waste such as rice straw, sugarcane bagasse, and manure, which are rich in lignocellulose. Other feedstocks used are industrial effluent waste, which includes food processing waste such as dairy waste, brewery waste, and distillery waste, rich in chemical oxygen demand (COD). The waste is also rich in leachates from municipal waste. The waste is hydrolyzed or subjected to anaerobic digestion to support anodic spp such as Geobacter, which remove COD by 70-90%, generating 1-5 W/m^2. For the construction of an AMFC at the laboratory scale, cost-effective designs with transparent materials like polycarbonate or glass are used to build dual-chamber H-type or flat-plate reactors with effective volumes ranging between 100 and 500 mL. The anodes of the AMFC consist of carbon material like carbon cloth or graphite felt, with an inoculum of anaerobic sludge. The inoculum is 5-10 cm^2. The cathodes of the AMFC consist of algal biofilm with Chlorella vulgaris or Spirulina platensis on similar material, illuminated with LED arrays of 100-500 μmol photons $m^{-2}\,s^{-1}$.

1. Introduction

1.1 Wastewater as a Resource: From Waste to Energy

To address the pressing challenges posed by escalating resource consumption, climate change, and environmental pollution factors that threaten both resource management and security, energy recovery from wastewater emerges as a promising strategy within the framework of a circular economy (CE). This innovative approach to wastewater management not only harnesses energy but also offers a wide array of environmental, political, economic, and social advantages (Zarei, 2020).

Increasingly, wastewater is being recognized as a valuable asset rather than mere refuse. It has the potential to be converted into renewable energy sources, such as biogas and electricity, as well as nutrient-rich fertilizers and clean water suitable for various uses (Silva, 2023). Leveraging state-of-the-art technologies such as anaerobic digestion, microbial fuel cells, and thermal hydrolysis, modern treatment plants can convert sludge into electricity and heat. Remarkably, these processes can generate more energy than the facilities consume, highlighting the dual benefit of waste management and energy production in our pursuit of sustainability (Qadir et al., 2020).

1.2 Microbial Fuel Cell Technology: Principles and Evolution

Organic waste, which includes food scraps, municipal trash, agricultural byproducts, and industrial effluents, poses disposal challenges due to traditional energy-intensive methods that produce significant amounts of sludge (Naha et al., 2023). Given current financial and environmental considerations, there is an urgent need for sustainable and energy-efficient solutions that can generate value from organic waste streams. In this context, innovative technologies like Microbial Fuel Cells (MFC), a type of bioelectrochemical system (BES), offer opportunities for electricity generation from wastewater, providing notable economic and environmental benefits (Kothari et al., 2024). The BES is a cutting-edge technology that uses exoelectrogenic and/or electrotrophic microorganisms as biocatalysts within an electrochemical circuit. This system transforms organic substances into electrical energy, or alternatively, it can convert electrical energy into valuable organic chemicals using other organic materials as inputs, including the conversion of CO2 into useful products like hydrogen and butanol (Serrano-Ruiz, 2020; Kuraganti and Edla, 2025).

Exoelectrogenic microorganisms transfer electrons to an anode during the anaerobic breakdown of organic substrates, while electrotrophic organisms can utilize electrons from a cathode. This can occur through processes like electrofermentation of organic material and bioelectrosynthesis via CO2 reduction. Additionally, photosynthetic microorganisms can be incorporated into bioelectrochemical systems (BESs) (Boto et al., 2025). In these systems, they can serve as electron donors in the microbial fuel cell (MFC) bio-anodes for electricity generation. They also provide oxygen at the cathode of an MFC, which can replace the need for external aeration, or function as electron acceptors in a biocathode, allowing the formation of biofilms for various biosynthesis processes. In MFCs, exoelectrogenic microorganisms act as anodic biocatalysts at the anode. They donate electrons to the electrode while anaerobically oxidizing organic substrates. At the cathode, electrotrophic microorganisms utilize free electrons to reduce CO2/HCO3, resulting in the production of valuable products (Raheem et al., 2018; Sharma et al., 2020).

1.1 Integration of Algae in MFC Systems

The use of photosynthetic microorganisms or microalgae as biocatalysts in MFCs, usually called Microalgae Microbial Fuel Cells (mMFCs) (Montoya-Vallejo et al., 2023). In such a system wherein algae act as biocatalysts in a microbial fuel cell, the system is called an Algal Fuel Cell (AFC) (Gajda et al., 2015). The reason the use of algae in a fuel cell is more beneficial is that it will produce not only energy but also biomass. Integrating algae into Microbial Fuel Cell (MFC) systems creates symbiotic, sustainable bioenergy platforms that simultaneously treat wastewater, capture CO2, and produce electricity. Algae in the cathode produce oxygen via photosynthesis, eliminating the need for energy-intensive mechanical aeration, while absorbing CO2 and nutrients (N and P) to produce valuable biomass (Liu et al., 2020). The latest development in AFC technology, highlighting its significance in application-oriented research work, relates to the development of a cost-effective outdoor AFC. This particular system produced a net energy yield of 11.5318 kWh/m3, which helps reduce the costs associated with AFC technology development (Khandelwal et al., 2020).

2. Fundamental Principles of Algal Microbial Fuel Cells

2.1. Basic Operating Mechanisms

Algal microbial fuel cells (AMFCs) are innovative bioelectrochemical systems that harness the metabolic activities of both photosynthetic algae and electrochemically active bacteria to simultaneously treat wastewater and generate electrical energy. Unlike conventional microbial fuel cells (MFCs) that rely solely on heterotrophic bacteria for substrate oxidation, AMFCs integrate oxygenic photosynthesis at the cathode, creating a self-sustaining system that addresses two critical limitations of traditional MFCs: the need for chemical catholytes and the challenge of cathodic overpotentials (Gajda et al., 2015; Nguyen and Min, 2020)

The fundamental appeal of AMFCs lies in their dual functionality: they utilize organic pollutants as electron donors while leveraging algal photosynthesis to regenerate electron acceptors, creating a synergistic cycle that enhances both treatment efficiency and power output. Recent studies have demonstrated power densities reaching 0.8-1.2 W/m^3 while achieving chemical oxygen demand (COD) removal exceeding 85% and nutrient removal rates of 70-90% for nitrogen and phosphorus compounds (Montoya-Vallejo et al., 2025).

A typical Algal Fuel Cell (AFC), as shown in Fig. 1, consists of several key components: an anode, a cathode, an electric wire that facilitates the flow of electrons, and occasionally, a proton exchange membrane (PEM). The fundamental operating principle of the algal fuel cell is based on the oxidation of a substrate at the anode. This oxidation process generates electrons, which are then transported through the wire to the cathode, where a reduction reaction occurs. This flow of electrons ultimately converts biochemical energy into electrical energy, generating electricity in the process (Rathinavel et al., 2018).

2.2 Anode and Cathode Reactions

The electrochemical performance of Algal Microbial Fuel Cells (MFCs) is fundamentally influenced by redox reactions that take place at both the anode and cathode (Fig-1).

Anode Reactions: At the anode, a fascinating interplay occurs where electrochemically active bacteria engage in the oxidation of organic substrates, which are typically derived from wastewater. In this process, these microorganisms facilitate the breakdown of organic matter, resulting in the release of electrons and protons. This transformation can be represented by a generalized reaction (Li et al., 2019)

$$\text{Organic matter} + H_2O \rightarrow CO_2 + H^+ + e^- + \text{Biomass}$$

The specific types of electron donors utilized can vary significantly, depending on the composition of the wastewater being treated. Two common organic substrates and their corresponding anode reactions are as follows:
Acetate: The oxidation of acetate can be represented by the equation:

$$CH_3COO^- + 2H_2O \rightarrow 2CO_2 + 7H^+ + 8e^-$$

This reaction highlights the energy production that occurs as acetate is converted into carbon dioxide, releasing protons and electrons in the process (Zhang et al., 2023).

Glucose: Similarly, when glucose is involved as an electron donor, the reaction is more complex: $C_6H_{12}O_6+6H_2O \rightarrow 6CO_2+24H^++24e^-$

Here, glucose undergoes breakdown, yielding carbon dioxide, a substantial release of protons, and a significant number of electrons, illustrating the high energy potential of this common organic substrate. Through these reactions, the anode plays a vital role in harnessing energy from organic components in wastewater, thereby contributing to the overall efficiency and effectiveness of algal MFCs (Zhang et al., 2023).

Cathode Reactions: In the cathode compartment of the system, photosynthetic algae play a crucial role by engaging in oxygenic photosynthesis. This process utilizes light energy to convert water into oxygen, protons, and electrons, generating oxygen that serves as the terminal electron acceptor: $2H_2O+4h\nu \rightarrow O_2+4H^++4e^-$

The oxygen generated serves as the terminal electron acceptor, enabling further chemical reactions (Bazdar et al., 2018). The overall cathodic oxygen reduction reaction (ORR), facilitated by electrons flowing from an external circuit, can be expressed as: $O_2+4H^++4e^- \rightarrow 2H_2O$

In the majority of studies focusing on Algal Fuel Cells (AFCs), the algae are introduced exclusively into the cathodic chamber. Within this chamber, electrons that have traveled from the anode encounter hydrogen ions (H+) that have permeated through the Proton Exchange Membrane (PEM). This interaction leads to the formation of water, facilitated by the presence of oxygen. Notably, this oxygen is a direct byproduct of the photosynthetic activity carried out by the algae, which harness sunlight to produce energy and release oxygen into their environment (Kakarla et al., 2015).

Recent research conducted by Ramesh et al. (2025) has revealed that the presence of algal photosynthesis can sustain dissolved oxygen levels ranging from 6 to 8 mg/L at the cathode. This notable achievement leads to a significant reduction in activation overpotentials when compared to traditional abiotic cathodes, ultimately enhancing the efficiency of the electrochemical process.

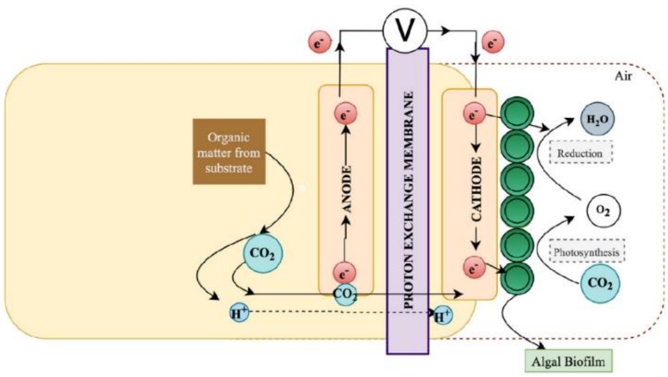

Fig.1. A diagram of a single-chamber microbial fuel cell based on (Logroño et al., 2017) shows an air cathode where oxygen is reduced to water. The algal biofilm uses atmospheric carbon dioxide for photosynthesis and biomass growth.

3. Reactor components and designs

Algae-assisted Microbial Fuel Cells (AFCs) are innovative systems that harness the synergistic interactions between microbes and algae to effectively generate electricity while simultaneously treating wastewater. These systems employ three key reactor types, each designed to optimize performance and efficiency for specific applications.

3.1 Single Chambered Microbial Fuel Cells (SCMFCs):

This type of reactor is known for its compact design and air-cathode configuration, making it well-suited for environments where space is limited. SCMFCs facilitate the direct conversion of biochemical energy into electrical energy in a single chamber, streamlining the process and reducing operational complexities. With the use of an air-cathode, oxygen from the atmosphere is utilized, enhancing the efficiency of the microbial community in oxidizing organic substrates, thus maximizing electricity output.

Single-chamber microbial fuel cells are typically designed in a cubic shape, though they can occasionally take on a cylindrical form. The decomposition of organic compounds results in the production of electrons that move from the anode to the cathode via the circuit connected to the external load, hence generating electrical power (Hou et al., 2016; Saba et al., 2017). At the cathode, the role of terminal electron acceptor is played by the algae, while to optimize the process of reduction of oxygen produced during the photosynthetic reaction, the cathodes can be subjected to open air as shown in Fig. 2. This method has several advantages since, compared to the conventional microbial fuel cell, one of the most significant aspects affecting its effectiveness is the level of dissolved oxygen in the medium (Logroño et al., 2017; Sivakumar et al., 2018).

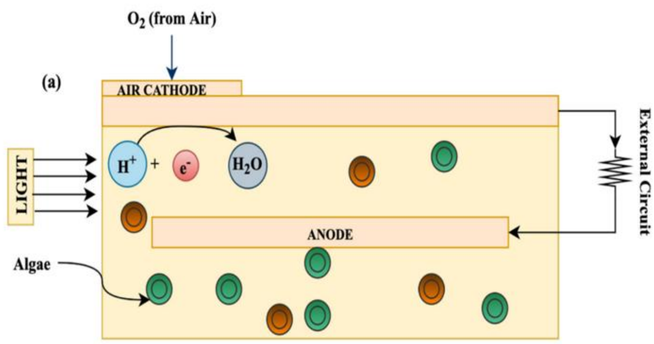

Fig.2. A typical single cell Algal microbial fuel cell

3.2 Double Chambered Microbial Fuel Cells (DCMFCs)

DCMFCs are designed with two separate chambers, separated by a proton exchange membrane. This configuration allows for more efficient separation of the anodic and cathodic reactions. Through this design, DCMFCs improve overall process efficiency, particularly for the oxidation of organic matter and the reduction of oxygen. The proton exchange membrane allows protons to pass from the anode to the cathode without permitting substrate mixing, which leads to increased energy efficiency and improved wastewater treatment performance.

The double-chamber MFCs involve a fuel cell with two separate chambers divided by the PEM. Such a configuration is most popularly applied when working with algae-based MFC research due to its highly efficient functioning in many operations. DCMFCs can be configured in two ways: either with the anode, PEM, and cathode all housed within a single tank, or arranged in an H-shaped design with the PEM integrated into one of the chambers (Fig.3) (Beenish Saba et al., 2017; Kannan and Donnellan, 2021).

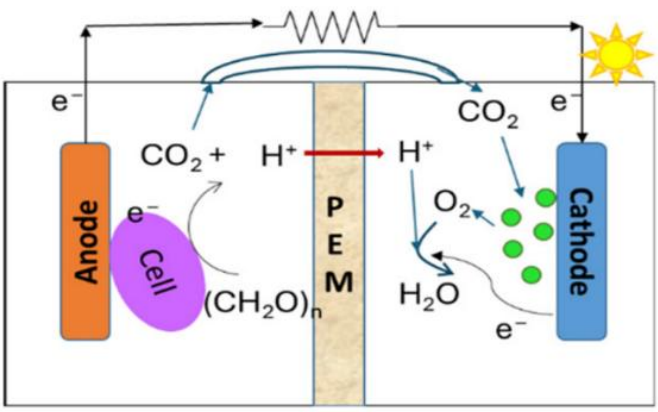

Fig.3. A double-chamber microbial fuel cell is separated by a large proton exchange membrane

3.3 Photosynthetic Algal Microbial Fuel Cells (PAMFCs):

PAMFCs leverage the natural process of photosynthesis performed by algae to enhance sustainability. In these systems, algae grow in conjunction with electroactive microbes, contributing oxygen to the cathode during daylight hours. This not only boosts the overall oxygen levels in the system, promoting aerobic microbial activity, but also aids in the removal of nutrients such as nitrogen and phosphorus from wastewater. The integration of algal photosynthesis into the energy generation process adds a layer of ecological efficiency and contributes to carbon dioxide mitigation. PAMFCs can either couple an algal photobioreactor to a DCMFC (Fig. 4), or have a bubble column inside the cathode chamber of an existing DCMFC. The method of coupling anaerobic digestion with MFCs is also a type of PAMFC (Duan and Shi, 2014; Schievano et al., 2018).

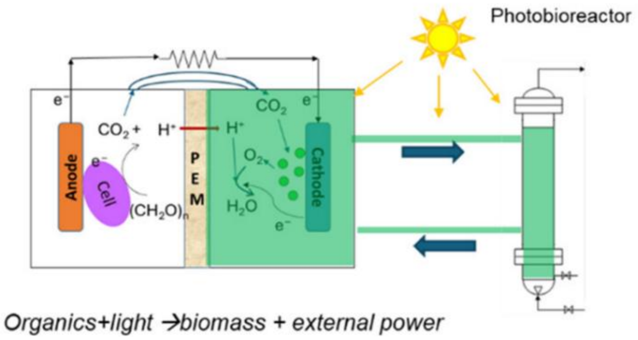

Fig.4. A microbial fuel cell utilizing photosynthetic algae, which is combined with a DCMFC and a photobioreactor

Together, these types of algae-assisted microbial fuel cells represent a promising approach to sustainable energy generation and wastewater treatment, combining principles of bioenergy with environmental benefits.

4. Algal Species and Their Specific Mechanisms

Various algae species display unique electrochemical characteristics. Chlorella vulgaris is the most frequently referenced species because of its impressive resilience to various wastewater contaminants, quick growth rate, and significant lipid production, which is advantageous for subsequent biodiesel generation. Scenedesmus obliquus is recognized for its superior nutrient uptake (specifically nitrogen and phosphorus), making it suitable for the treatment of municipal wastewater. Synechocystis sp, a well-studied cyanobacterium, is often utilized in research related to direct electron transfer from photosynthetic organisms due to its well-documented genetic potential for electrogenesis, list of some algal species is given in Table 1 (Krishnamoorthy et al., 2021; Montoya-Vallejo et al., 2025).

5. Influence of Environmental Parameters on the Functionality of Algal Microbial Fuel Cells (AMFCs)

5.1 pH Levels:

The pH of the operational environment is a critical factor for the performance of exoelectrogens, as most of these microorganisms thrive in a neutral pH range of approximately 6.5 to 7.5. Maintaining an optimal pH is essential, as it directly influences the metabolic processes of the organisms involved. When using algal cathodes, one must consider that these systems can naturally elevate the pH levels due to the uptake of dissolved carbon dioxide (CO2) during photosynthesis, potentially pushing the pH to levels between 8.5 and 9.5. This increase in pH can lead to the precipitation of heavy metals found in wastewater, which may initially appear beneficial by removing such contaminants. However, elevated pH levels can also exert stress on the algal species, which can compromise their overall health and efficiency in energy generation (Elshobary et al., 2021; Rusanowska et al., 2025).

5.2 Temperature:

The temperature at which AMFCs operate significantly affects their performance, with optimal ranges typically falling between 25°C and 35°C. At lower temperatures, microbial metabolism can slow down, leading to decreased electron transfer rates and a reduction in the overall electrochemical kinetics of the system. This sluggish microbial activity can hinder the efficiency of energy production. Conversely, operating temperatures exceeding 40°C pose risks as well; high temperatures can denature essential enzymes critical for metabolic processes and can disrupt the stability of the algal biofilm. A stable biofilm is crucial for an effective electrochemical environment, highlighting the importance of maintaining moderate temperatures for optimal performance (Zhang et al., 2014; Elshobary et al., 2021).

5.3 Light Intensity:

Light intensity plays a pivotal role in the power generation capabilities of AMFCs, exhibiting a positive correlation with energy output up to a certain saturation threshold. Generally, light conditions ranging from 3000 to 5000 lux are considered optimal for maximal algal activity and, consequently, enhanced electricity production. However, exceeding this photonic saturation level can lead to photoinhibition, a process were excessive light damages algal chloroplasts. This damage can impede the photosynthetic capability of the algae, diminishing their ability to produce oxygen and, thus, negatively affecting the overall efficiency of the AMFC system. Careful management of light conditions is therefore essential to sustain the health of the algal biomass and ensure continuous energy generation (Bazdar et al., 2018; Mahmoud et al., 2024).

Researchers are developing a cost-effective Air-Mediated Fuel Cell (AMFC) using transparent materials like polycarbonate or glass in laboratory-scale designs. The AMFC features dual-chamber H-type or flat-plate reactors with working volumes of 100 to 500 milliliters (Ying et al., 2024). The anodes consist of carbon-based materials that support microbial growth, while the cathodes cultivate microalgae, illuminated by LED arrays to enhance photosynthesis. Proton exchange membranes separate the anode and cathode, and Ag/AgCl reference electrodes measure electrochemical potential (Chaurasiya et al., 2025). The construction is airtight for optimal anaerobic conditions at the anode and allows gas exchange at the cathode, with peristaltic pumps ensuring electrolyte circulation.

6. Future Perspectives

6.1 Advanced Materials Development

The future of advanced materials in the field of electrochemistry is evolving rapidly. Innovations such as self-cleaning electrodes utilize nanotechnology to create surfaces that can repel dirt and contaminants, thereby maintain their efficiency and reduce maintenance needs. Alongside this, researchers are focusing on biodegradable membranes that not only enhance performance in various applications but also minimize environmental impact by breaking down naturally after use. Furthermore, the advent of 3D printing technology allows for the creation of customizable components tailored to specific needs, improving efficiency and functionality in various devices (Tong et al., 2023; Ramesh et al., 2025).

6.2 Synthetic Biology Approaches

The integration of synthetic biology into energy systems is paving the way for engineered microbial consortia. These consortia are designed with programmed metabolic pathways that enable precise control of biochemical reactions, enhancing the production of biofuels and other valuable chemicals. Additionally, the development of communication networks among these microbes allows for coordinated actions, improving the overall efficiency and stability of bioprocesses, thereby revolutionizing the biotechnology landscape (Jaramillo et al., 2025).

6.3 Digital Twin Technology

The implementation of digital twin technology offers significant advancements in the management and optimization of systems such as microbial fuel cells (MFCs). By creating virtual models of these systems, researchers can carry out extensive simulations that help in optimizing operational parameters, predicting potential failures, and enabling real-time monitoring. This not only enhances performance but also contributes to preventative maintenance and reduces downtime, ultimately leading to more sustainable operational outcomes (Nneoma et al., 2025).

6.4 Circular Economy Integration

A critical focus on circular economy principles is facilitating the integration of various environmental technologies, such as nutrient recovery systems and bioplastics production, alongside advanced MFC technologies (Table-1). This approach encourages the recycling of waste materials, converting them into valuable resources while also working in conjunction with carbon capture systems. This synergy not only maximizes resource efficiency but also aims to reduce overall carbon footprints across industries (Adeloju, 2024).

Table 1. Algal Species that are mostly used in the AMFC's

Algal Species	Primary Mechanism	Power Density (W/m³)	Key Characteristics
Chlorella vulgaris	Indirect via exudates	0.8-1.0	High growth rate, robust, versatile
Scenedesmus obliquus	Direct and indirect	0.9-1.1	High lipid content, good biofilm formation
Anabaena spp. (Cyanobacteria)	Direct electron transfer	0.7-0.9	Nitrogen fixation, hydrogen production
Chlamydomonas reinhardtii	Direct via cytochromes	1.0-1.2	Genetic manipulability, well-studied
Spirulina platensis	Indirect via metabolites	0.6-0.8	High protein content, commercial availability

7. Conclusion

Algal microbial fuel cells (AMFCs) represent a sophisticated integration of biological and electrochemical systems that harness natural processes for sustainable wastewater treatment and energy generation. The performance and viability of AMFCs hinge on key mechanisms involving electrochemical principles, the contributions of algae, microbial interactions, and system optimization. Recent advancements have significantly enhanced our understanding of electron transfer pathways, community interactions, and design specifications. Progress in advanced materials, genetic technologies, and monitoring tools has not only pushed power densities closer to practical limits but has also improved treatment efficacy. However, challenges related to scalability, cost, and long-term reliability remain, necessitating interdisciplinary research that merges microbiology, materials science, engineering, and data analysis. As these obstacles are addressed, AMFCs hold great promise for not only wastewater treatment but also as pathways for sustainable bioenergy production, nutrient recovery, and environmental monitoring. The next decade is poised to transition from laboratory-scale prototypes to pilot-scale demonstrations and ultimately to integrated systems within circular economy models, benefiting both environmental sustainability and energy security.

Competing interests:

The authors declare that they have no competing interests

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