



Chemical and Environmental Science Archives
(ISSN: 2583-1151)
An International Research Journal

DOI: <https://doi.org/10.47587/CESA.2026.6301>

[Review Article](#)



Advances in Hydrogen, Bioelectrochemical Systems, and Advanced Biofuels for a Low-Carbon Future

Obiajulu Zion Chukwudi¹, Ibrahim Ayinla Mahmud², Atobatele Oluwatobi Idris³, Moses Adondua Abah⁴, Micheal Oladosu Abimbola⁴ and Ochuele Dominic Agida⁴

¹Department of Chemical Engineering, Federal University of Technology, Minna, Niger State, Nigeria

²School of Engineering and Built Environment, University of Greater Manchester, Bolton, United Kingdom

³Department of Petroleum Engineering, Faculty of Engineering, University of Port Harcourt, Rivers State, Nigeria

⁴ResearchHub Nexus Institute, Nigeria

(✉) Corresponding Author: Moses Adondua abah; m.abah@fuwukari.edu.ng

Received: May 1, 2026/ Revised: June 1, 2026/Accepted: June 2, 2026

Abstract

The global transition toward a low-carbon future has intensified the search for sustainable and efficient alternatives to fossil-based energy systems. Among the emerging solutions, hydrogen technologies, bioelectrochemical systems (BES), and advanced biofuels have attracted significant attention because of their potential to reduce greenhouse gas emissions, improve energy security, and support circular bioeconomy strategies. This review examines recent advances in these technologies and their contributions to sustainable energy development and decarbonization. Green hydrogen production through water electrolysis powered by renewable energy sources is highlighted as a promising pathway for clean fuel generation, particularly for transportation, industrial processes, and power applications. The review also explores the role of bioelectrochemical systems, including microbial fuel cells and microbial electrolysis cells, in simultaneous energy recovery, wastewater treatment, and carbon reduction. In addition, the development of advanced biofuels derived from non-food biomass, algae, and waste materials is discussed with emphasis on improved conversion technologies, lifecycle carbon reduction, and applications in hard-to-abate sectors such as aviation and heavy transport. Furthermore, the integration of these technologies within renewable energy frameworks and circular economy models is critically evaluated. Despite substantial progress, challenges related to production cost, infrastructure, scalability, and policy implementation continue to limit widespread adoption. The review concludes that continued technological innovation, supportive regulatory frameworks, and strategic investment are essential for accelerating the deployment of hydrogen systems, BES, and advanced biofuels toward achieving global low-carbon and net-zero energy goals.

Keywords: Hydrogen energy, Bioelectrochemical systems, Advanced biofuels, Decarbonization, Renewable energy and Low-carbon future

Introduction

The increasing demand for sustainable energy and the urgent need to mitigate climate change have accelerated the global transition toward low-carbon energy systems. Fossil fuel dependence continues to contribute significantly to greenhouse gas emissions, environmental degradation, and

energy insecurity, thereby intensifying interest in cleaner and renewable energy alternatives (Vedrtnam *et al.*, 2025). In response to these challenges, hydrogen technologies, bioelectrochemical systems (BES), and advanced biofuels have emerged as promising pathways for reducing carbon emissions while supporting sustainable industrial and economic development. These technologies provide

opportunities for renewable energy generation, efficient resource utilization, waste valorization, and carbon-neutral fuel production, making them important components of future low-carbon economies (Zhang *et al.*, 2026).

Hydrogen has gained considerable attention as a clean and versatile energy carrier because of its high energy density and environmentally friendly combustion properties. Green hydrogen, produced mainly through renewable-powered water electrolysis, is increasingly viewed as a strategic solution for decarbonizing transportation, electricity generation, and industrial sectors. Recent advances in electrolysis technologies, catalyst optimization, and system modeling have significantly improved hydrogen production efficiency and operational sustainability (Vedrtnam *et al.*, 2025). In addition, biological hydrogen production using microorganisms and organic substrates has emerged as an environmentally sustainable alternative capable of converting biomass and wastewater into valuable energy resources. Industrial-scale biological hydrogen production technologies are also receiving increasing research attention because of their potential integration into renewable energy and waste management systems (Teke *et al.*, 2023).

Bioelectrochemical systems represent another important technological innovation supporting the transition toward a low-carbon future. These systems utilize electroactive microorganisms to convert organic compounds into electricity, hydrogen, and other bioenergy products while simultaneously enabling wastewater treatment and resource recovery (Vedrtnam *et al.*, 2025). Technologies such as microbial fuel cells and microbial electrolysis cells have demonstrated substantial potential for sustainable energy generation and environmental remediation. Recent breakthroughs involving electrode materials, microbial engineering, and reactor design have improved the efficiency and stability of BES applications in waste-to-energy conversion processes (Berhouma *et al.*, 2026). Furthermore, BES technologies contribute significantly to sustainable biorefineries by facilitating the recovery of valuable products and nutrients from wastewater streams, thereby supporting circular bioeconomy principles and environmental sustainability (Dattatraya *et al.*, 2022).

Advanced biofuels have also emerged as viable alternatives to conventional fossil fuels because of their potential to reduce lifecycle greenhouse gas emissions and improve energy sustainability (Vedrtnam *et al.*, 2025). Unlike first-generation biofuels, advanced biofuels are produced from non-food biomass, algae, agricultural residues, and industrial wastes, minimizing food competition and environmental concerns. Recent progress in fermentation and electroactive fermentation technologies has improved biomass conversion efficiency and enhanced the production of renewable fuels from sustainable feedstocks (de la Puente *et al.*, 2026). Additionally, e-biofuels are increasingly recognized for their ability to support emissions reduction in hard-to-electrify sectors such as aviation, maritime transportation, and heavy

industries where conventional electrification approaches remain technically challenging (Zhang *et al.*, 2026).

This review examines recent advances in hydrogen technologies, bioelectrochemical systems, and advanced biofuels within the broader context of achieving a sustainable low-carbon future. The review focuses on the mechanisms, technological developments, and environmental significance of these emerging energy systems in reducing greenhouse gas emissions and enhancing renewable energy integration. Particular emphasis is placed on green and biological hydrogen production pathways, electroactive microbial technologies, and next-generation biofuels derived from renewable and waste-based feedstocks. Furthermore, the review critically evaluates the contribution of these technologies to circular bioeconomy strategies, sustainable industrial processes, and global decarbonization goals. Key technological innovations, operational improvements, and practical applications are discussed alongside the major challenges limiting commercialization and large-scale implementation, including economic constraints, infrastructural limitations, and process scalability. Emerging research trends involving hybrid renewable systems, advanced catalysts, and integrated biorefinery approaches are also explored as potential strategies for improving efficiency and accelerating deployment. Overall, this review aims to provide a comprehensive understanding of how hydrogen technologies, bioelectrochemical systems, and advanced biofuels can collectively support the transition toward resilient, sustainable, and low-carbon energy systems in the future.

Hydrogen Technologies for Decarbonization

Hydrogen technologies have emerged as critical components of global decarbonization strategies because of their ability to support clean energy production, reduce greenhouse gas emissions, and improve energy security (Vedrtnam *et al.*, 2025). Hydrogen is considered a versatile low-carbon energy carrier capable of integrating renewable energy into transportation, industrial, and power systems. Depending on the production pathway, hydrogen can be categorized as grey, blue, turquoise, or green hydrogen. Among these pathways, green hydrogen produced through renewable-powered electrolysis is regarded as the most environmentally sustainable option because it generates little or no direct carbon emissions during production (Reda *et al.*, 2024). Blue hydrogen, which combines natural gas reforming with carbon sequestration technologies, has also gained importance as a transitional low-carbon solution for reducing industrial emissions (Monye *et al.*, 2025). The increasing adoption of carbon capture and storage technologies further strengthens the role of low-carbon hydrogen in achieving global net-zero emission targets (Durakovic *et al.*, 2023).

Sustainable hydrogen production technologies continue to advance rapidly as researchers seek cleaner, more efficient, and economically viable methods of hydrogen generation. Water electrolysis powered by renewable energy sources such

as solar and wind remains the dominant technology for green hydrogen production. Significant progress in alkaline electrolysis, proton exchange membrane electrolysis, and solid oxide electrolysis has improved system durability, hydrogen purity, and energy efficiency (Vedrtam *et al.*, 2025). In addition to electrolysis, biological hydrogen production technologies are receiving growing attention because they enable renewable hydrogen generation from biomass and organic wastes through microbial processes (Teke *et al.*, 2023). Furthermore, bioelectrochemical hydrogen production systems utilizing agro-industrial wastewater have demonstrated considerable potential for simultaneous hydrogen production and wastewater treatment, thereby supporting circular bioeconomy principles and environmental sustainability (Berhouma *et al.*, 2026). These innovations are expected to improve the scalability and sustainability of future hydrogen production systems.

Despite substantial advancements in hydrogen production, storage and distribution remain major technical and economic challenges affecting large-scale hydrogen deployment. Hydrogen possesses low volumetric energy density, making its storage and transportation difficult compared with conventional fossil fuels. Current storage technologies include compressed gaseous hydrogen, liquefied hydrogen, underground storage, metal hydrides, and liquid organic hydrogen carriers, each associated with specific operational benefits and limitations (Xie *et al.*, 2024). High-pressure storage systems increase infrastructural costs and safety concerns, while hydrogen liquefaction requires significant energy input because of extremely low operating temperatures. Recent advances in storage materials, nanotechnology, and underground hydrogen storage systems have shown promise for improving storage efficiency and long-term safety (Farooq *et al.*, 2026). In addition, the development of reliable hydrogen transportation networks involving pipelines, shipping systems, and integrated distribution infrastructures remains essential for enabling widespread commercialization of hydrogen technologies (Rampai *et al.*, 2024).

Hydrogen technologies are increasingly being applied across transportation, power generation, and industrial sectors because of their strong potential for reducing carbon emissions and supporting sustainable energy transitions. In the transportation sector, hydrogen fuel cells are being integrated into buses, trucks, trains, ships, and heavy-duty vehicles where battery electrification remains less practical because of energy density and charging limitations (Zhao *et al.*, 2025). Hydrogen is also gaining importance in electricity systems as a long-duration energy storage medium capable of balancing intermittent renewable power generation. In industrial applications, hydrogen is increasingly utilized for low-carbon steel production, ammonia synthesis, petroleum refining, and chemical manufacturing processes aimed at reducing fossil fuel dependence and industrial carbon emissions (Durakovic *et al.*, 2023). Moreover, recent technological advances involving electrolyzer optimization, advanced catalysts, digital monitoring systems, and integrated renewable-hydrogen networks have significantly improved system efficiency and

reduced lifecycle greenhouse gas emissions (Coelho *et al.*, 2025). Collectively, these developments position hydrogen as a strategic energy vector for supporting future low-carbon economies and sustainable industrial transformation.

Bioelectrochemical Systems in Low-Carbon Energy and Waste Management

Bioelectrochemical systems (BES) have emerged as innovative technologies for sustainable energy generation, wastewater treatment, and resource recovery within low-carbon energy frameworks (Vedrtam *et al.*, 2025). These systems integrate microbiology and electrochemistry to convert organic substrates into electricity, hydrogen, and other value-added products through the metabolic activities of electroactive microorganisms. BES technologies are increasingly recognized for their ability to support circular bioeconomy strategies by simultaneously treating waste streams and recovering renewable energy resources (Jung *et al.*, 2020). In addition, their low environmental footprint and potential for greenhouse gas mitigation make them promising alternatives to conventional energy-intensive wastewater treatment systems.

Among the most widely studied BES configurations are microbial fuel cells (MFCs) and microbial electrolysis cells (MECs). Microbial fuel cells generate electricity directly from the microbial degradation of organic matter, while microbial electrolysis cells utilize external voltage input to produce hydrogen and other biofuels. These systems rely on efficient electron transfer between microorganisms and electrodes to sustain electrochemical reactions (Chakma *et al.*, 2025). Recent studies have demonstrated the growing potential of MECs for sustainable biohydrogen production using engineered microbial consortia and wastewater substrates, thereby supporting renewable fuel generation and waste valorization simultaneously (Ekadewi *et al.*, 2023). Furthermore, microbial electrosynthesis technologies are attracting increasing attention for their ability to convert carbon dioxide into renewable fuels and organic compounds, offering new opportunities for carbon-neutral biofuel production (Mirea *et al.*, 2025).

Bioelectrochemical systems also contribute significantly to carbon reduction and environmental sustainability through integrated wastewater treatment and energy recovery processes. Unlike conventional wastewater treatment systems that consume large amounts of energy, BES technologies enable simultaneous pollutant removal and renewable energy production, thereby reducing operational energy demand and associated carbon emissions (Gude, 2016). Recent advances have further expanded the application of BES in nutrient recovery processes, particularly for nitrogen and phosphorus recovery using membrane-integrated systems. These innovations improve resource efficiency while minimizing environmental pollution and supporting sustainable waste management strategies (Cerrillo *et al.*, 2023). Such multifunctional capabilities position BES as promising technologies for decentralized low-carbon wastewater treatment and renewable energy production.

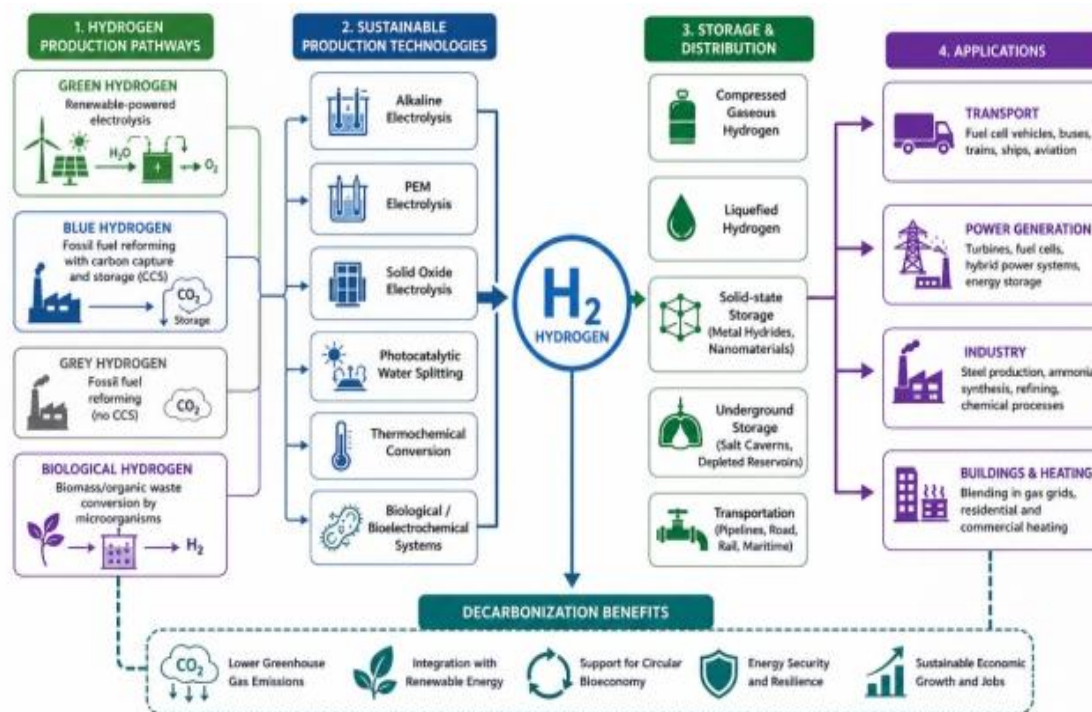


Figure 1. Overview of hydrogen technologies for decarbonization showing major hydrogen production pathways, sustainable production technologies, storage and distribution systems, and key applications in transportation, power generation, industry, and heating sectors that collectively support greenhouse gas reduction and low-carbon energy transition. Sources: Adapted from Reda *et al.* (2024); Vedrtam *et al.* (2025), and Zhao *et al.* (2025)

Significant progress has also been achieved in improving BES performance through advances in electrode materials, nanotechnology, and reactor design. Electrode materials strongly influence microbial attachment, conductivity, electron transfer efficiency, and overall system stability. Nanomaterials such as graphene, carbon nanotubes, conductive polymers, and metal-based nanocomposites have demonstrated enhanced electrochemical activity and improved microbial-electrode interactions in BES applications (Plekhanova *et al.*, 2022). In addition, recent developments in reactor configuration, membrane integration, and scale-up strategies have contributed to improved power density, operational efficiency,

and substrate utilization (Corona-Martinez *et al.*, 2025). Despite these advances, large-scale commercialization of BES technologies remains limited because of challenges including low power output, high material costs, membrane fouling, operational instability, and difficulties associated with industrial-scale implementation (Chakma *et al.*, 2025). Addressing these technical and economic limitations through interdisciplinary research and technological optimization will be essential for enabling the broader adoption of BES technologies in future low-carbon energy and waste management systems.

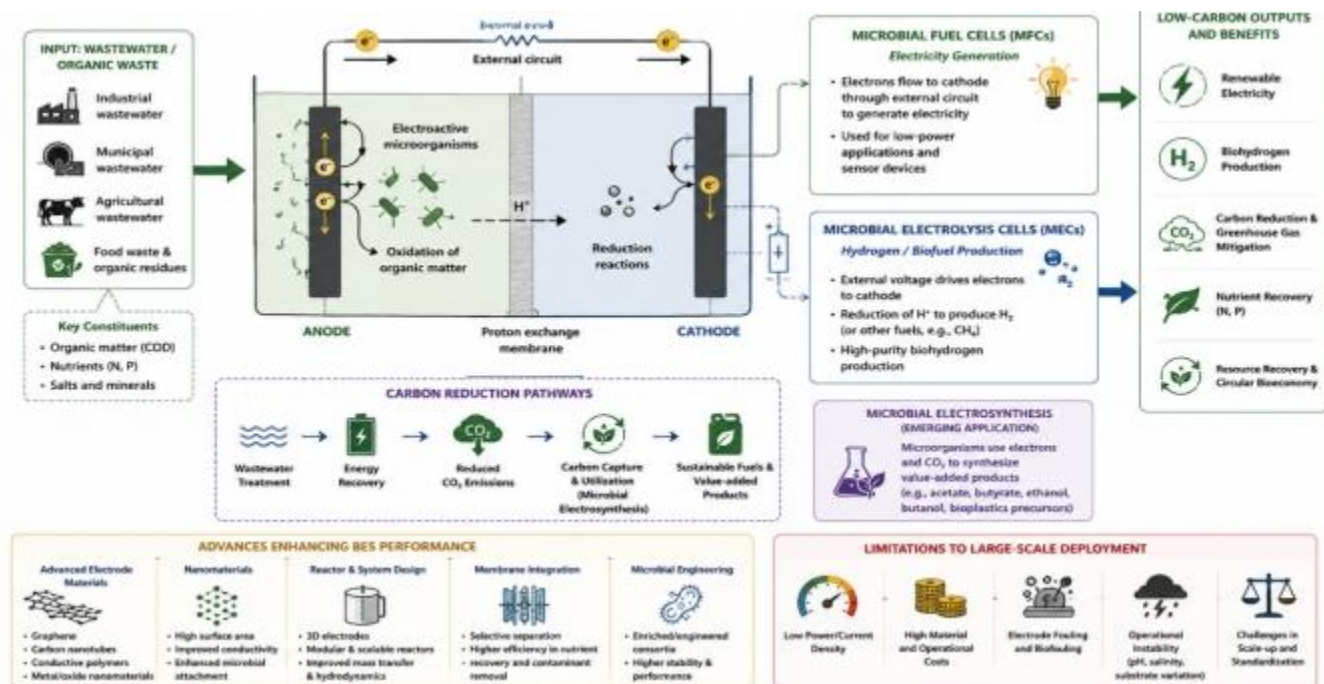


Figure 2. Bioelectrochemical systems (BES) for low-carbon energy and waste management showing the principles of microbial fuel cells and microbial electrolysis cells, wastewater-to-energy conversion pathways, carbon reduction mechanisms, advanced electrode materials, and key limitations affecting large-scale deployment. Source: Adapted from Jung *et al.* (2020), Cerrillo *et al.* (2023), Chakma *et al.* (2025), Corona-Martínez *et al.* (2025), and Mirea *et al.* (2025).

Advanced Biofuels for Sustainable Energy Transition

Advanced biofuels have become increasingly important in the global transition toward sustainable and low-carbon energy systems because of their potential to reduce greenhouse gas emissions and decrease dependence on fossil fuels. Unlike conventional first-generation biofuels derived from food crops, advanced biofuels utilize non-food biomass, lignocellulosic materials, algae, and waste-derived feedstocks, thereby minimizing competition with food production and improving environmental sustainability. These advanced biofuels are generally categorized into second-, third-, and fourth-generation biofuels according to feedstock sources and technological development pathways. Second-generation

biofuels are primarily produced from lignocellulosic biomass such as agricultural residues and forestry wastes, while third-generation biofuels are mainly derived from algal biomass because of its high productivity and carbon capture potential (Saravanan *et al.*, 2022). Fourth-generation biofuels further integrate genetic engineering and carbon capture technologies to enhance fuel productivity and support carbon-negative energy systems (Shokravi *et al.*, 2021). The continued advancement of these biofuel generations is increasingly viewed as essential for achieving long-term decarbonization goals and sustainable energy security.

Sustainable feedstock utilization and efficient biomass management remain fundamental to the environmental and economic viability of advanced biofuel systems. Biomass wastes including agricultural residues, industrial by-products, food wastes, and municipal solid wastes are increasingly being explored as renewable feedstocks because they support waste valorization and circular bioeconomy strategies while reducing environmental pollution (Francioso, 2024). The integration of waste biomass into advanced biorefineries also enhances resource efficiency by enabling the simultaneous production of fuels, chemicals, and other value-added products. In addition, bioelectrochemical systems are increasingly contributing to sustainable biomass conversion and renewable fuel production through waste-to-energy pathways and microbial processing technologies (Jung *et al.*, 2020). These integrated approaches improve carbon utilization and support the development of low-carbon industrial systems. Recent advances in thermochemical and biochemical conversion technologies have significantly improved the efficiency, sustainability, and commercial potential of advanced biofuel production. Thermochemical conversion methods including pyrolysis, gasification, and hydrothermal liquefaction are widely utilized for converting biomass into bio-oil, syngas, and renewable fuels with comparatively lower carbon emissions than conventional petroleum refining processes (Ram *et al.*, 2023). Recent innovations involving catalytic upgrading, artificial intelligence-assisted process optimization, and advanced reactor designs have further improved thermochemical conversion efficiency and product

quality (Saleh *et al.*, 2025). Biochemical conversion technologies such as fermentation, anaerobic digestion, and enzymatic hydrolysis also continue to gain importance because of their environmentally sustainable operational conditions and ability to process diverse biomass feedstocks (Saravanan *et al.*, 2022). Collectively, these technological improvements are accelerating the transition toward cleaner and more efficient renewable fuel production systems.

Advanced biofuels are increasingly being adopted in transportation, aviation, maritime operations, and other hard-to-abate sectors where direct electrification remains technically challenging. Sustainable aviation fuels (SAFs) derived from biomass and waste feedstocks have gained global attention because they can substantially reduce lifecycle greenhouse gas emissions without requiring major

modifications to existing aircraft infrastructure (Klimczyk *et al.*, 2025). Renewable diesel, bioethanol, and biojet fuels are also contributing to the decarbonization of transportation systems by lowering fossil fuel consumption and improving energy diversification. Furthermore, advanced biofuels provide important environmental benefits through lifecycle carbon reduction, waste minimization, and improved carbon recycling pathways. Their compatibility with existing fuel distribution and combustion infrastructure also enhances their feasibility for large-scale deployment within future low-carbon energy systems. Despite ongoing challenges related to feedstock availability, production costs, and commercialization, continued technological innovation and supportive policy frameworks are expected to strengthen the role of advanced biofuels in achieving sustainable global energy transitions.



Figure 3. Advanced biofuels for sustainable energy transition illustrating generations of advanced biofuels, sustainable biomass feedstocks, low-carbon conversion technologies, transportation and aviation applications, environmental benefits, and integrated pathways supporting a low-carbon future. Sources: Adapted from Saravanan *et al.* (2022), Francioso (2024), Klimczyk *et al.* (2025), Saleh *et al.* (2025), and Shokravi *et al.* (2021).

Integration with renewable energy systems

The integration of hydrogen technologies, advanced biofuels, and bioelectrochemical systems (BES) with renewable energy systems is increasingly recognized as a major pathway toward sustainable low-carbon energy transitions. Renewable energy resources such as solar, wind, hydropower, and biomass provide the clean electricity and sustainable feedstocks required for low-carbon fuel production and energy storage systems. Green hydrogen production through renewable-powered electrolysis has gained considerable attention because of its potential to decarbonize industrial and transportation sectors while improving energy flexibility and storage capacity within renewable-dominated energy grids

(Marouani *et al.*, 2023). Similarly, advanced biofuels produced from lignocellulosic biomass and waste-derived feedstocks contribute to renewable energy diversification and reduced dependence on fossil fuels (Saravanan *et al.*, 2022). The integration of BES technologies into renewable energy systems further strengthens waste-to-energy conversion, resource recovery, and decentralized energy production within sustainable energy networks (Jung *et al.*, 2020).

Circular bioeconomy principles are increasingly shaping the development of carbon-neutral energy systems through sustainable biomass utilization, waste valorization, and integrated resource recovery strategies. Biomass residues, agricultural wastes, municipal solid wastes, and industrial by-products are now being utilized as renewable feedstocks for

biofuel production and thermochemical conversion processes, thereby minimizing environmental pollution and promoting sustainable waste management (Francioso, 2024). Recent advances in biomass valorization technologies involving pyrolysis, gasification, hydrothermal processing, and artificial intelligence-assisted optimization have improved energy efficiency and carbon utilization within integrated bioenergy systems (Saleh *et al.*, 2025). In addition, thermochemical biomass conversion technologies continue to evolve through improved reactor systems and tar reduction strategies that enhance process sustainability and fuel quality (Ram *et al.*, 2023). These integrated bioeconomy approaches support the development of carbon-neutral industrial systems while improving resource efficiency and renewable energy production.

Hydrogen technologies and advanced biofuels are also expected to play major roles in achieving global net-zero emission targets, particularly within hard-to-abate sectors such as aviation, heavy transportation, and industrial manufacturing. Sustainable aviation fuels derived from renewable biomass and waste feedstocks are increasingly viewed as viable alternatives for reducing lifecycle greenhouse

gas emissions in the aviation industry without requiring significant modifications to existing infrastructure (Klimczyk *et al.*, 2025). Furthermore, fourth-generation biofuels derived from genetically modified algal biomass offer promising opportunities for carbon-negative fuel production because of their enhanced carbon capture potential and improved biomass

productivity (Shokravi *et al.*, 2021). Recent studies have also demonstrated that integrating biomass conversion systems with carbon-negative emission technologies can substantially enhance long-term climate mitigation potential and support sustainable decarbonization pathways (Yu *et al.*, 2025). These developments position renewable hydrogen and advanced biofuels as strategic components of future net-zero energy systems.

Comparative sustainability assessments indicate that integrated low-carbon energy systems combining hydrogen, advanced biofuels, biomass valorization, and carbon capture technologies possess significant carbon mitigation potential when compared with conventional fossil fuel systems. Lifecycle assessment studies have shown that hydrogen production through agricultural residue gasification and biogas reforming can substantially reduce greenhouse gas emissions while improving renewable energy utilization and waste management efficiency (Abawalo *et al.*, 2025). Additionally, the integration of carbon capture, utilization, and storage (CCUS) technologies within waste-to-energy and bioenergy systems further strengthens carbon reduction performance and supports the transition toward carbon-neutral industrial operations (Acampora *et al.*, 2025). Despite ongoing challenges related to economic feasibility, technological scalability, and policy implementation, continued innovation and integrated energy planning are expected to improve the sustainability and environmental performance of future low-carbon energy systems.

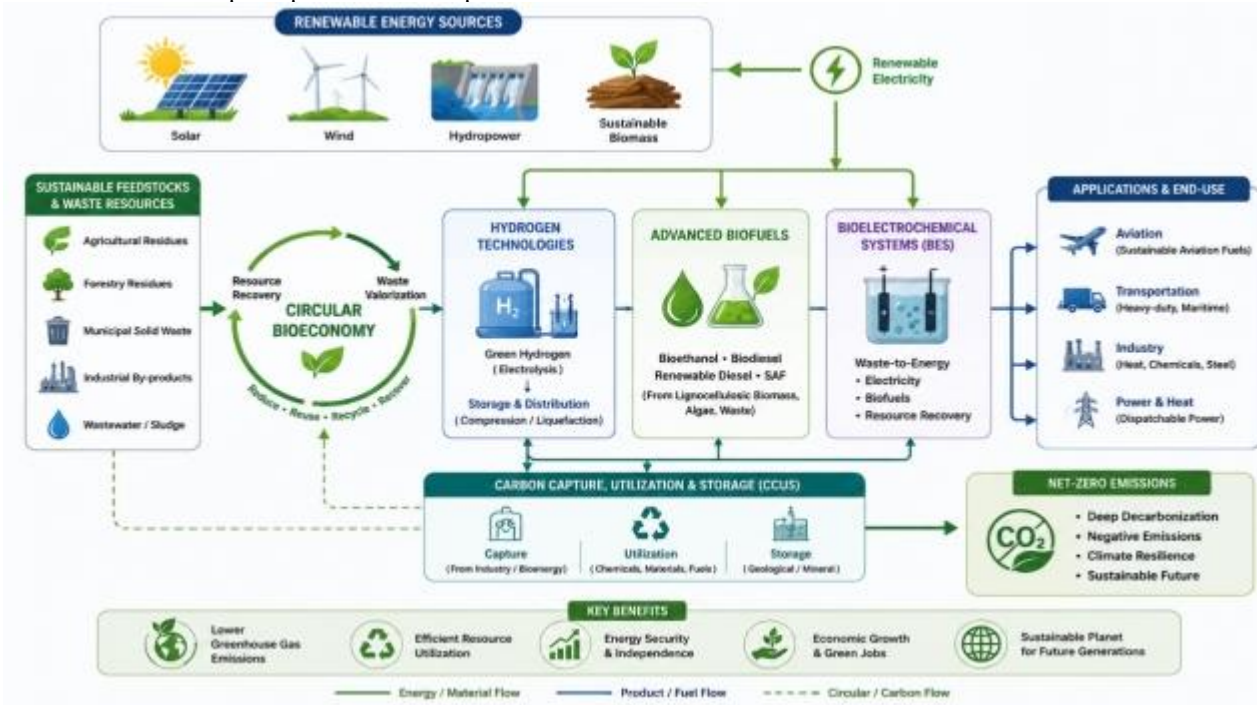


Figure 4. Integrated pathways toward a low-carbon future showing the interactions among renewable energy systems, hydrogen technologies, advanced biofuels, bioelectrochemical systems, circular bioeconomy strategies, and carbon capture technologies for achieving net-zero emissions and sustainable energy transition. Sources: Marouani *et al.* (2023); Francioso (2024); Klimczyk *et al.* (2025), and Acampora *et al.* (2025)

Table 1. Summary of key findings

Key Areas	Key Findings
Hydrogen Technologies	Green hydrogen and low-carbon hydrogen pathways show strong potential for decarbonizing transportation, industry, and power sectors through renewable-powered production and carbon reduction strategies
Bioelectrochemical Systems	BES technologies enable sustainable wastewater treatment, energy recovery, and resource valorization through microbial fuel cells and microbial electrolysis systems.
Advanced Biofuels	Advanced biofuels derived from biomass, algae, and waste feedstocks provide sustainable alternatives for transportation and aviation decarbonization with reduced lifecycle emissions
Integrated Low-Carbon Systems	Integration of renewable energy, hydrogen, biofuels, BES, and carbon capture technologies supports circular bioeconomy development and net-zero energy pathways
Challenges and Future Prospects	Economic barriers, infrastructure limitations, and commercialization challenges remain significant, although technological innovation and policy support continue to improve future deployment potential

Challenges, Policy, and Future Prospects

Despite significant advancements in hydrogen technologies, bioelectrochemical systems (BES), and advanced biofuels, several economic and infrastructural barriers continue to limit their large-scale deployment within global low-carbon energy systems. Green hydrogen production, although environmentally sustainable, remains associated with high production, storage, and transportation costs, largely due to expensive electrolyzer technologies and renewable electricity requirements (Younus *et al.*, 2025). In addition, insufficient hydrogen distribution infrastructure and limited renewable energy integration capacity continue to hinder commercialization efforts in many countries. Advanced biofuel systems also face challenges related to feedstock availability, biomass logistics, and process scalability, particularly in regions with inadequate technological infrastructure (Abawalo *et al.*, 2025). Similarly, BES technologies remain constrained by relatively low power density, operational instability, and high material costs, which collectively affect industrial-scale implementation and long-term economic feasibility (Ieropoulos *et al.*, 2024).

Strong policy frameworks and regulatory support are increasingly recognized as essential for accelerating the transition toward sustainable low-carbon energy systems. Governments and international organizations are implementing renewable energy targets, hydrogen roadmaps, carbon reduction policies, and climate mitigation strategies to support clean energy deployment and industrial decarbonization. The growing integration of renewable-energy-based green hydrogen into future energy systems demonstrates the importance of coordinated policy support, infrastructure investment, and international collaboration for achieving large-scale energy transformation (Marouani *et al.*, 2023). The International Energy Agency (IEA, 2025) further emphasizes that long-term policy consistency, financial

incentives, and global market development are necessary to improve investor confidence and accelerate low-carbon technology adoption. In addition, emerging renewable energy innovations and sustainable energy policies are expected to strengthen energy security, improve carbon mitigation strategies, and support future climate resilience (Accone and Lui, 2023).

Technological innovation and commercialization remain critical for improving the efficiency, affordability, and scalability of emerging low-carbon technologies. Recent advances involving artificial intelligence, smart grids, digital energy management systems, and integrated renewable energy optimization have demonstrated considerable potential for enhancing energy efficiency and system reliability within low-carbon infrastructures (Olagundoye *et al.*, 2026). Furthermore, innovations in biomass integration, waste valorization, and carbon-negative technologies are strengthening the environmental sustainability of advanced biofuel and renewable energy systems (Yu *et al.*, 2025). Carbon capture, utilization, and storage (CCUS) technologies are also increasingly being integrated into waste-to-energy and industrial systems to reduce greenhouse gas emissions and improve carbon management efficiency (Acampora *et al.*, 2025). In the agricultural sector, BES technologies are additionally contributing to sustainable resource recovery and renewable energy generation through environmentally friendly waste conversion pathways (Li *et al.*, 2015). These technological improvements are expected to accelerate commercialization and improve the long-term sustainability of future low-carbon energy systems.

The future outlook for global low-carbon energy systems remains highly promising as countries intensify efforts to achieve net-zero emissions and sustainable industrial transformation. Integrated systems combining renewable electricity, green hydrogen, advanced biofuels, BES technologies, artificial intelligence, and carbon capture strategies are increasingly viewed as essential pathways for deep decarbonization across transportation, industry, agriculture, and power generation sectors. Continued investments in renewable energy infrastructure, international technology transfer, and interdisciplinary research are expected to strengthen the global transition toward sustainable

energy systems. Although challenges related to economics, scalability, and infrastructure development remain significant, ongoing innovation and coordinated climate action are likely to position low-carbon technologies at the center of future global energy transitions.

Conclusion

Hydrogen technologies, bioelectrochemical systems, and advanced biofuels are emerging as key components of future low-carbon energy systems because of their ability to reduce greenhouse gas emissions, support renewable energy integration, and improve resource sustainability. These technologies contribute significantly to clean energy production, waste valorization, carbon reduction, and sustainable industrial development. Green hydrogen, advanced biofuels, and bioelectrochemical systems have shown strong potential in transportation, power generation, wastewater treatment, and hard-to-abate industrial sectors. Their integration with renewable energy systems, circular bioeconomy strategies, and carbon capture technologies further enhances their environmental and economic benefits. However, challenges related to infrastructure, production costs, scalability, and policy implementation continue to affect large-scale commercialization. Continued technological innovation, supportive regulations, strategic investments, and international collaboration will therefore be essential for accelerating the global transition toward carbon-neutral and sustainable energy systems. Overall, the combined advancement of these low-carbon technologies offers promising pathways for achieving global climate goals, strengthening energy security, and promoting a cleaner and more sustainable future.

Author Contributions

The author has significantly contributed to the study's conception, design, data collection, analysis, and interpretation. All authors were involved in writing the manuscript or critically reviewing it for its intellectual value. They have reviewed and approved the final version for submission and publication and accept full responsibility for the content and integrity of the work.

Financial Support

The authors declare that no external funding was received for this study.

Conflicts of Interest

The authors state that there are no financial, personal, or professional conflicts of interest associated with this research.

Ethical Approvals

This research did not involve the use of human participants or animal subjects and therefore did not require ethical clearance

Publisher's Note

The Journal stays neutral about jurisdictional claims in published maps and institutional affiliations

References

- Abawalo, M., Pikoń, K. and Landrat, M. (2025). Comparative Life Cycle Assessment of Hydrogen Production via Biogas Reforming and Agricultural Residue Gasification. *Applied Sciences*. 15(9):5029. <https://doi.org/10.3390/app15095029>
- Acampora, L., Grilletta, S. and Costa, G. (2025). The Integration of Carbon Capture, Utilization, and Storage (CCUS) in Waste-to-Energy Plants: A Review. *Energies*. 18(8):1883. <https://doi.org/10.3390/en18081883>
- Accone, T. and Lui, R. (2023). Renewable energy: emerging technologies and innovations. Report number: Insight Report 2Affiliation: UNICEF. DOI:10.13140/RG.2.2.21523.25123
- Berhouma, S., Saïdi, N., Sellami, G., ben Tarraf, F.Z., Elabed, S., Cherif, A. *et al.* (2026) Bioelectrochemical hydrogen production from agro-industrial wastewater: key breakthroughs and challenges. *Front. Energy Res.* 14:1767021. doi: 10.3389/fenrg.2026.1767021
- Cerrillo, M., Riau, V. and Bonmatí, A. (2023). Recent Advances in Bioelectrochemical Systems for Nitrogen and Phosphorus Recovery Using Membranes. *Membranes*. 13(2): 186. <https://doi.org/10.3390/membranes13020186>
- Chakma, R., Hossain, M. K., Paramasivam, P., Bousbih, R., Amami, M., Toki, G. F. I. *et al.* (2025). Recent Applications, Challenges, and Future Prospects of Microbial Fuel Cells: A Review. *Global challenges*. 9(5): 2500004. <https://doi.org/10.1002/gch2.202500004>
- Coelho, M. S., Gaspar, G., Surra, E., Coelho, P. J. and Ferreira, A. F. (2025). Systematic Analysis of the Hydrogen Value Chain from Production to Utilization. *Applied Sciences*. 15(15): 8242. <https://doi.org/10.3390/app15158242>
- Corona-Martínez, D. A., Martínez-Amador, S. Y., Rodríguez-De la Garza, J. A., Laredo-Alcalá, E. I. and Pérez-Rodríguez, P. (2025). Recent Advances in Scaling up Bioelectrochemical Systems: A Review. *Biotech*. 14(1): 8. <https://doi.org/10.3390/biotech14010008>
- Dattatraya Saratale, G., Rajesh Banu, J., Nastro, R. A., Kadier, A., Ashokkumar, V., Lay, C. H. *et al.* (2022). Bioelectrochemical systems in aid of sustainable biorefineries for the production of value-added products and resource recovery from wastewater: A critical review and future perspectives. *Bioresour. Technol.* 359: 127435. <https://doi.org/10.1016/j.biortech.2022.127435>
- de la Puente, R. C., Mateos, A. and Escapa, M. (2026). Current status of fermentation and electroactive fermentation technologies for biofuel production: A systematic review. *Renewable and Sustainable Energy Reviews*. 232:116818. <https://doi.org/10.1016/j.rser.2026.116818>
- Durakovic, G., Zhang, H., Knudsen, B. R., Tomsgard, A. and Crespo del Granado, P. (2023). Decarbonizing the European energy system in the absence of Russian gas: Hydrogen uptake and carbon capture developments in the power, heat and industry sectors. *arXiv*. <https://arxiv.org/abs/2308.08953>
- Ekadewi, P., Arbianti, R., Gomez, C. and Utami, T. S. (2023). Biohydrogen Production in Microbial Electrolysis Cell Operating on Designed Consortium of Denitrifying Bacteria. *Food technology and biotechnology*. 61(1): 4–13. <https://doi.org/10.17113/ftb.61.01.23.7496>
- Farooq, M.U., Saleem, M.A., Hussain, M. *et al.* A critical review of the production pathways and storage limitations and economic

- feasibility of green hydrogen fuel. *Discov. Chem.* 3:193 (2026). <https://doi.org/10.1007/s44371-026-00646-0>
- Francioso, O. (2024). Current and future perspectives for biomass waste management and utilization. *Scientific reports.* 14(1): 9635. <https://doi.org/10.1038/s41598-024-59623-1>
- Gude, G. V. (2016). Wastewater Treatment in Microbial Fuel Cells – An Overview. *Journal of Cleaner Production.* 122(8). DOI:10.1016/j.jclepro.2016.02.022
- Ieropoulos, I., Singh, A., Moreno, Z. and Greenman, J. (2024). Bioelectrochemical Systems and their readiness for commercialisation. *Current Opinion in Electrochemistry* 46:101540. DOI:10.1016/j.coelec.2024.101540
- International Energy Agency (IEA). (2025). Global hydrogen review 2025. IEA Publishing. <https://www.iea.org/reports/global-hydrogen-review-2025>
- Jung, S., Lee, J., Park, Y. K. and Kwon, E. E. (2020). Bioelectrochemical systems for a circular bioeconomy. *Bioresource technology.* 300:122748. <https://doi.org/10.1016/j.biortech.2020.122748>
- Klimczyk, W., Jasiński, R., Niklas, J., Siedlecki, M. and Ziolkowski, A. (2025). Sustainable Aviation Fuels: A Comprehensive Review of Production Pathways, Environmental Impacts, Lifecycle Assessment, and Certification Frameworks. *Energies.* 18(14):3705. <https://doi.org/10.3390/en18143705>
- Li, X., Abu-Reesh, I. M. and He, Z. (2015). Development of Bioelectrochemical Systems to Promote Sustainable Agriculture. *Agriculture.* 5(3):367-388. <https://doi.org/10.3390/agriculture5030367>
- Marouani, I., Guesmi, T., Alshammari, B. M., Alqunun, K., Alzamil, A., Alturki, M. and Hadj Abdallah, H. (2023). Integration of Renewable-Energy-Based Green Hydrogen into the Energy Future. *Processes.* 11(9): 2685. <https://doi.org/10.3390/pr11092685>
- Mirea, R., Popescu, E. and Zaharescu, T. (2025). Microbial Electrosynthesis: The Future of Next-Generation Biofuel Production—A Review. *Energies.* 18(19):5187. <https://doi.org/10.3390/en18195187>
- Monye, S. N., Monye, S. I., Adetunla, A. O., Afolalu, S. A., Okokpujie, I. P., Aderemi, K. B. *et al.* (2025). Carbon sequestration technologies from blue hydrogen production: A comparative review of efficiency, scalability, and environmental impact. *NIPES Journal of Science and Technology Research.* 7(2):3669–3673. <https://doi.org/10.37933/nipes/7.4.2025.SI451>
- Olagundoye, O., Bamisile, O., Ejiyi, J., Bamisile, O. *et al.* (2026). A Review of Artificial Intelligence Techniques for Low-Carbon Energy Integration and Optimization in Smart Grids and Smart Homes. *Processes.* 14(3):464. DOI:10.3390/pr14030464
- Plekhanova, Y. V., Rai, M. and Reshetilov, A. N. (2022). Nanomaterials in bioelectrochemical devices: on applications enhancing their positive effect. *3 Biotech.* 12(9):231. <https://doi.org/10.1007/s13205-022-03260-w>
- Ram, S., Harry, P., Yadav, A. and Chauhan, S. (2023). Recent Advancements in Thermochemical Conversion of Biomass and Technologies Used to Eliminate the Tar Formation. In book: *Advances in Fluid and Thermal Engineering.* (585-599). DOI:10.1007/978-981-99-2382-3_49
- Rampai, M. M., Mtshali, C. B., Seroka, N. S. and Khotseng, L. (2024). Hydrogen production, storage, and transportation: Recent advances. *RSC Advances.* 14:6699–6718. <https://doi.org/10.1039/D3RA08305E>
- Reda, B., Elzamar, A., Alfazzani, S. and Ezzat, M. (2024). Green hydrogen as a source of renewable energy: a step towards sustainability, an overview. *Environment Development and Sustainability.* 27(12):29213-29233. DOI:10.1007/s10668-024-04892-z
- Saleh, Y., Ali, L. and Altarawneh, M. (2025). Recent advances in biomass valorization through thermochemical processes, bio-oil production and AI strategies: a concise review. *RSC advances.* 15(54): 45943–45978. <https://doi.org/10.1039/d5ra05770a>
- Saravanan, A., Senthil Kumar, P., Jeevanantham, S., Karishma, S. and Vo, D. N. (2022). Recent advances and sustainable development of biofuels production from lignocellulosic biomass. *Bioresource technology.* 126203. <https://doi.org/10.1016/j.biortech.2021.126203>
- Shokravi, H., Shokravi, Z., Heidarrezaei, M., Ong, H. C., Rahimian Kolor, S. S., Petru, M. *et al.* (2021). Fourth generation biofuel from genetically modified algal biomass: Challenges and future directions. *Chemosphere.* 285: 131535. <https://doi.org/10.1016/j.chemosphere.2021.131535>
- Teke, G. M., Anye Cho, B., Bosman, C. E., Mapholi, Z., Zhang, D. and Pott, R. W. M. (2023). Towards industrial biological hydrogen production: a review. *World journal of microbiology & biotechnology.* 40(1): 37. <https://doi.org/10.1007/s11274-023-03845-4>
- Vedrtam, A., Kalauni, K. and Pahwa, R. (2025). A review of water electrolysis technologies with insights into optimization and numerical simulations. *International Journal of Hydrogen Energy.* 140:694-727. DOI:10.1016/j.ijhydene.2025.05.295
- Vedrtam, A., Kalauni, K. and Pahwa, R. (2025). A review of water electrolysis technologies with insights into optimization and numerical simulations. *International Journal of Hydrogen Energy.* 140:694–727. <https://doi.org/10.1016/j.ijhydene.2025.05.295>
- Xie, Z., Jin, Q., Su, G. and Lu, W. (2024). A Review of Hydrogen Storage and Transportation: Progresses and Challenges. *Energies.* 17(16): 4070. <https://doi.org/10.3390/en17164070>
- Younus, A., Al-Hajri, R., Ahmad, N. and Aljammal, N. (2025). Green hydrogen production and deployment: opportunities and challenges. *Discover Electrochemistry.* 2(1). DOI:10.1007/s44373-025-00043-9
- Yu, S., Li, Q., Zhang, Y., Yan, J. and Zhou, H. (2025). Enhancing carbon-negative emission technologies through biomass integration. *Innovation.* 6(12): 101079. <https://doi.org/10.1016/j.xinn.2025.101079>
- Zhang, Y., Millinger, M., Hedenus, F., Pettersson, K. and Brown, T. (2026). E-biofuels reduce the cost of achieving emissions targets in hard-to-electrify sectors. *arXiv.* <https://arxiv.org/abs/2604.12080>
- Zhao, P., Li, S., Xie, D., Wang, Y., Li, Z., Jen-Hwa Hu, P. *et al.* (2025). Hydrogen as the nexus of future sustainable transport and energy systems. *Nature Reviews Electrical Engineering.* 2(7). DOI:10.1038/s44287-025-00178-2

How to cite this article

Chukwudi, O. Z., Mahmud, I. A., Idris, A. O., Abah, M. A., Abimbola, M. O., & Agida, O. D. (2026). Advances in hydrogen, bioelectrochemical systems, and advanced biofuels for a low-carbon future. *Chemical and Environmental Science Archives*, 6(3), 27–36. <https://doi.org/10.47587/CESA.2026.6301>

