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Carbon Capture and Storage Via Electrochemical and Bioelectrochemical Techniques: A Review

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The urgent need to mitigate climate change has spurred innovative research in carbon capture and storage (CCS) technologies. Electrochemical approaches utilize electrocatalysis and electrochemical reduction to capture carbon dioxide (CO_2) from industrial emissions, demonstrating high selectivity and enabling the production of valuable chemicals and fuels from captured CO_2. Bioelectrochemical techniques leverage microorganisms to convert CO_2 into biomass or biofuels, enhancing carbon capture efficiency through biological and electrochemical synergy. Integrating bioelectrochemical systems with renewable energy sources provides a carbon-negative pathway, aiding industry decarbonization. This review underscores the transformative potential of these techniques in revolutionizing CCS strategies, emphasizing their role in addressing climate change while fostering a sustainable, circular economy.

Keywords: Bioelectrochemical, Capture, Carbon, Electrochemical, Storage, Techniques.

1. Introduction

The escalating threat of climate change, driven primarily by the accumulation of greenhouse gases, necessitates innovative and sustainable solutions to mitigate its adverse impacts. Among the various strategies employed, Carbon Capture and Storage (CCS) stands out as a crucial technology in the global effort to reduce carbon dioxide (CO_2) emissions. As traditional approaches face challenges, recent research has increasingly focused on advancing CCS through novel electrochemical and bioelectrochemical techniques, offering promising avenues for more efficient and economically viable carbon sequestration (Nunes 2023).

The combustion of fossil fuels for energy production, industrial processes, and transportation remains a significant source of anthropogenic CO_2emissions. To address this, the scientific community has been exploring electrochemical methods that leverage the principles of electrocatalysis and electrochemical reduction for capturing CO_2 directly from industrial flue gases. These techniques not only demonstrate high selectivity in capturing CO_2 but also present an opportunity for the transformation of the captured CO_2into valuable chemicals and fuels. The ability to convert CO_2 into useful products not only aids in mitigating climate change but also promotes a circular economy by turning a greenhouse gas into a resource (Masoumi et al., 2023).

One key aspect of electrochemical CCS involves the development of efficient and selective electrocatalysts. These catalysts facilitate the conversion of CO_2 into a range of carbon-based products, such as methane, ethylene, or formic acid. This not only contributes to the reduction of CO_2 levels but also adds value by producing chemicals that can be utilized in various industrial processes. Additionally, advancements in electrochemical storage techniques offer a means for the long-term sequestration of captured CO_2, addressing concerns related to the intermittent nature of emissions and ensuring a reliable and stable storage solution (Maniam et al., 2023).

On a parallel front, bioelectrochemical techniques have emerged as a sustainable and environmentally friendly approach to carbon capture. These methods capitalize on the catalytic capabilities of microorganisms to facilitate the conversion of CO_2 into biomass or biofuels. By integrating biological processes with electrochemical interfaces, bioelectrochemical systems enhance the overall efficiency of carbon capture while providing a pathway for the development of carbon-negative technologies. This integration with renewable energy sources further aligns these approaches with the broader goal of achieving a more sustainable and decarbonized energy landscape (Kurt et al., 2023).

The synergy between electrochemical and bioelectrochemical techniques has recently gained attention as researchers explore combined systems that harness the strengths of both approaches. Such hybrid systems aim to maximize efficiency, selectivity, and scalability, offering a holistic solution to the challenges associated with carbon capture. The integration of electrochemical and biological processes in a synergistic manner not only enhances the overall performance of CCS but also opens up new possibilities for tackling emissions from diverse industrial sectors (Alkhadra et al., 2022). This review provides an overview of the growing importance of electrochemical and bioelectrochemical techniques in the realm of CCS. As we delve deeper into these innovative approaches, subsequent sections of this discourse will explore their principles, advancements, challenges, and potential applications. The subsequent chapters aim to present a comprehensive understanding of how these cutting-edge technologies contribute to the imperative task of carbon capture and storage (**Figure 1**), ultimately paving the way for a more sustainable and resilient future (Baranwal et al., 2023).

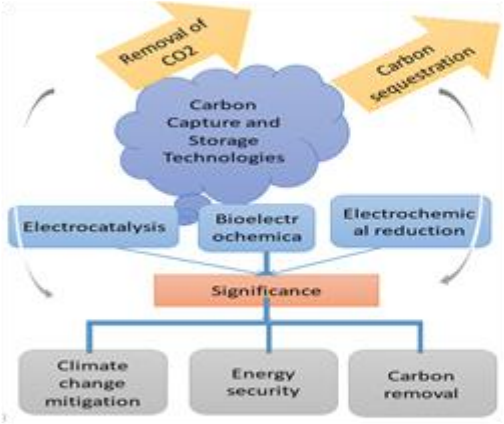

Figure 1: Schematic representation of carbon capture and storage technologies.

2. Significance of Carbon Capture and Storage (CCS)

The accelerating pace of global climate change underscores the critical need for transformative technologies capable of mitigating carbon dioxide (CO_2) emissions, the primary driver of anthropogenic climate change. In this context, Carbon Capture and Storage (CCS) has emerged as a pivotal strategy to address the challenge of reducing greenhouse gas emissions, particularly from industrial processes and power generation. The significance of CCS lies in its potential to play a decisive role in achieving climate goals, fostering sustainable development, and ensuring a transition to a low-carbon future (Nunes 2023).

Climate Change Mitigation: CCS represents a key tool in the arsenal against climate change, offering a direct means of reducing CO_2 emissions at their source. As the world strives to meet ambitious emissions reduction targets set forth in international agreements such as the Paris Agreement, CCS provides a practical solution for industries and sectors that are challenging to decarbonize entirely, such as cement, steel, and chemical manufacturing. By capturing CO_2before it is released into the atmosphere, CCS contributes significantly to mitigating the impact of human activities on the global climate.

Preservation of Fossil Fuel-Based Industries: Many industries heavily rely on fossil fuels for their operations, and a sudden transition away from these energy sources can have profound economic implications. CCS allows for the continued use of fossil fuels while effectively reducing their environmental footprint. This not only provides a bridge to a cleaner energy future but also safeguards jobs and economic stability in regions heavily dependent on fossil fuel industries (Andreoni et al., 2023).

Energy Security: CCS enables the utilization of fossil fuels in a more sustainable manner, contributing to energy security by ensuring a stable and reliable energy supply. As the world transitions to renewable energy sources, CCS acts as a complementary technology that allows for the continued use of existing infrastructure, preventing disruptions in energy supply during the transition period (Olujobi et al., 2023).

Technological Innovation and Economic Growth: The development and deployment of CCS technologies drive innovation in engineering, chemistry, and materials science. This not only enhances the capabilities of CCS systems but also fosters the growth of new industries and job opportunities. Governments and private sectors investing in CCS research and implementation can position themselves as leaders in sustainable technology, fostering economic growth while addressing environmental challenges (Yasemi et al., 2023).

Negative Emissions and Carbon Removal: Beyond emission reductions, CCS offers the potential for negative emissions by capturing CO_2directly from the atmosphere or bioenergy with carbon capture and storage (BECCS). This negative emissions capability is crucial in offsetting historical and hard-to-abate emissions, contributing to the goal of achieving a net-zero carbon balance (Cobo et al., 2022).

Public and Policy Acceptance: CCS plays a crucial role in gaining public acceptance for certain industries, especially those deemed essential but challenging to decarbonize. By demonstrating a commitment to reducing emissions through the implementation of CCS, industries can align themselves with broader climate goals and enhance their social license to operate (Panjaitan et al., 2023).

In addition, the significance of Carbon Capture and Storage extends beyond emission reductions; it encompasses economic stability, energy security, technological advancement, and the imperative pursuit of negative emissions. As the world faces the urgency of addressing climate change, CCS stands as a pragmatic and essential solution to curbing emissions from diverse sources, ensuring a sustainable path forward for industries and societies worldwide (Adam, & Ozarisoy, 2023).

3. Electrochemical Techniques for Carbon Capture

Electrochemical reduction involves the use of electrical energy to drive the conversion of CO_2into value-added products. This section explores the fundamental principles governing electrochemical reduction and its application in capturing $CO_2$from various sources (Table 1).

Table 1: **Electrochemical Techniques for Carbon Capture**

Electrochemical Techniques for Carbon Capture	**Principles of Electrochemical Reduction**	**Electrocatalysis for CO_2Capture**	**Valorization of Captured CO_2 into Chemicals and Fuels**	**Electrochemical Storage for Long-Term Sequestration**	**Reference**
Overview	Explanation of electrochemical reduction principles and its application in capturing CO_2	Examination of electrocatalysts' role in enhancing CO_2capture efficiency	Discussion on the conversion of captured CO_2 into valuable chemicals and fuels through electrochemical pathways	Exploration of electrochemical storage methods for sequestering captured $CO_2$for extended periods	Chen et al., 2023
Key Concepts	Highlighting the electrochemical processes involved in reducing $CO_2$to desired products	Introducing various electrocatalysts, their properties, and their impact on CO_2capture	Illustrating the potential chemical and fuel products derived from electrochemical conversion of CO_2	Discussing different electrochemical storage technologies, such as batteries and capacitors, for long-term CO_2sequestration	Poon et al., 2022
Benefits	Improved selectivity, allowing for targeted CO_2capture	Enhanced efficiency in capturing and converting CO_2into valuable products	Integration into a circular economy, creating a value stream from captured CO_2	Providing a reliable and scalable method for storing captured CO_2over extended periods	Almomani et al., 2023
Challenges	Understanding and optimizing reaction kinetics and selectivity	Identifying and developing efficient and durable electrocatalysts	Balancing economic feasibility and scalability of chemical and fuel production	Addressing issues related to the stability, cost, and energy density of electrochemical storage systems	Basyooni, & Kabatas, 2023
Recent Developments	Overview of recent breakthroughs in electrochemical reduction technologies	Emerging electrocatalysts and their performance advancements	Novel electrochemical pathways for producing high-value chemicals	Innovations in electrochemical storage technologies for improved sequestration efficiency	Mei, &Xu, 2023
Applications	Industrial applications of electrochemical CO_2capture	Use cases for electrocatalysts in various industrial	Industries utilizing electrochemical pathways for CO_2-based	Deployment of electrochemical storage solutions in different	Gawel et al., 2022

	technologies	settings	chemical and fuel production	industrial and environmental contexts	
Future Directions	Research pathways for refining and advancing electrochemical reduction techniques	Exploration of novel electrocatalysts and their potential applications	Integration of electrochemical pathways in a broader sustainable industrial framework	Advancements in electrochemical storage technologies for increased capacity and efficiency	Gidi et al., 2023

4. Principles of Electrochemical Reduction

The principles of electrochemical reduction form the foundation for innovative and sustainable approaches to carbon capture, offering a promising solution to mitigate the escalating impacts of climate change. Electrochemical reduction involves the use of electrical energy to drive chemical transformations, specifically targeting the conversion of CO_2 into valuable products. This section provides a comprehensive overview of the fundamental principles that underpin electrochemical reduction in the context of carbon capture (Saleh, & Hassan, 2023).

Electrochemical Reduction Basics: At its core, electrochemical reduction relies on the principles of electrolysis, where an electric current is used to induce a chemical change at an electrode. In the context of carbon capture, the target is the reduction of CO_2, a greenhouse gas with significant implications for global warming. The process involves the supply of electrons to CO_2 molecules, leading to their conversion into different chemical compounds through reduction reactions (Jaster et al., 2022; Mathew *et al*., 2024a).

Redox Reactions and CO_2 Reduction: The reduction of CO_2 during electrochemical processes involves redox (reduction-oxidation) reactions. In this context, the carbon in CO_2 undergoes a reduction reaction, gaining electrons to form carbon-based products. This transformation is crucial for diverting CO_2 away from the atmosphere, where it contributes to the greenhouse effect, and converting it into useful and potentially valuable compounds (Inobeme et al., 2023a).

Electrodes and Electrocatalysts: Electrochemical reduction requires electrodes as interfaces where the reduction reactions take place. Additionally, efficient electrocatalysts play a pivotal role in enhancing the kinetics and selectivity of CO_2 reduction. These catalysts facilitate the reaction by lowering the activation energy, making the process more energetically favorable and allowing for the production of specific carbon-based products (Serafini et al., 2023).

Selectivity and Product Formation: Achieving selectivity in electrochemical reduction is a critical challenge. The goal is not only to capture CO_2 but also to guide the reduction reactions towards the formation of desired products. The choice of electrode materials and electrocatalysts, along with the optimization of reaction conditions, influences the selectivity of the process. This selectivity is key to generating high-value chemicals or fuels from captured CO_2 (Quan et al., 2021).

Energy Efficiency and Renewable Sources: The principles of electrochemical reduction also emphasize the importance of energy efficiency, as the ultimate goal is to reduce CO_2 emissions. Integration with renewable energy sources, such as solar or wind power, enhances the sustainability of electrochemical reduction processes. Utilizing clean energy ensures that the overall carbon footprint of the process is minimized, contributing to the holistic objective of decarbonisation (He et al., 2023).

Beyond Carbon Capture: While carbon capture is the primary focus, the principles of electrochemical reduction extend beyond this application. This approach aligns with the broader goal of sustainability and resource efficiency (Cao et al., 2023).

In addition, the principles of electrochemical reduction provide a scientifically sound and technologically promising framework for addressing the urgent need for carbon capture. By leveraging these principles, researchers and engineers aim not only to capture CO_2 but also to convert it into valuable products (figure 2), contributing to the transition towards a more sustainable and low-carbon future. The ongoing advancements in electrochemical reduction technologies mark a significant step forward in the global effort to combat climate change and create a more resilient and environmentally conscious society (Rahimi et al., 2022).

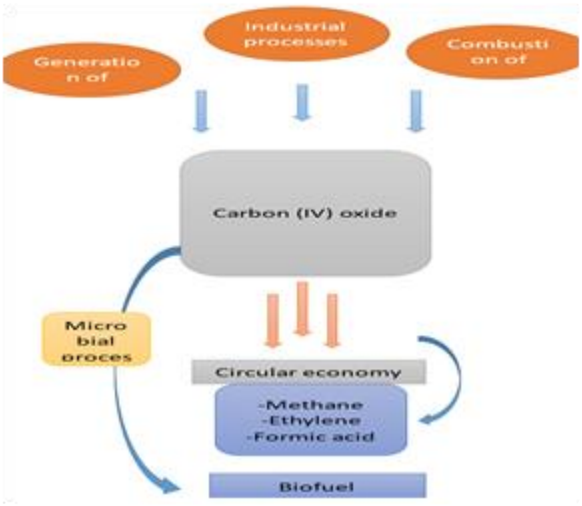

Figure 2: Valuable products obtained from carbon dioxide through circular economy

5. Electrochemical Storage for Long-Term Sequestration

As the imperative to address climate change intensifies, innovative solutions for long-term carbon capture and storage (CCS) are gaining prominence. Among these solutions, electrochemical storage technologies are emerging as a promising avenue for the sequestration of captured CO_2. This section explores the principles, benefits, challenges, and applications of electrochemical storage for long-term carbon sequestration (Nunes et al., 2023).

Principles of Electrochemical Storage: Electrochemical storage involves the conversion of electrical energy into chemical energy during charging and the reverse process during discharging. In the context of long-term carbon sequestration, this technology focuses on utilizing the electrochemical conversion of CO_2 into stable compounds that can be stored for extended periods. The storage mediums may include batteries, capacitors, or other electrochemical systems designed for reliable and prolonged retention of captured CO_2 (Chen et al., 2023)

Types of Electrochemical Storage: Various electrochemical storage technologies hold potential for long-term carbon sequestration. Battery technologies, such as lithium-ion and flow batteries, offer the ability to store large amounts of electrical energy, which can be utilized in the capture and conversion of CO_2. Supercapacitors, known for their rapid charge-discharge cycles, provide a different approach to electrochemical storage and may find applications in buffering intermittent CO_2 capture processes (Olabi et al., 2023).

Benefits of Electrochemical Storage for CCS: One of the primary advantages of electrochemical storage lies in its ability to provide reliable and continuous sequestration of captured CO_2. Unlike conventional storage methods, electrochemical systems can efficiently store and release energy, facilitating the continuous capture and conversion of CO_2, especially in situations where emissions are intermittent or variable. Additionally, these systems can be designed for scalability, enabling the storage of large quantities of captured CO_2 over extended periods (Yu et al., 2023).

Challenges in Electrochemical Storage for CCS: While electrochemical storage holds significant promise, it comes with its set of challenges. These include issues related to the stability and longevity of storage systems, the energy density of storage mediums, and the economic feasibility of large-scale deployment. Developing cost-effective and durable materials for electrochemical storage systems is a crucial aspect that researchers are actively addressing (Machín, & Márquez, 2024).

Integration with Renewable Energy: The integration of electrochemical storage for CCS with renewable energy sources enhances the sustainability of the entire process. Renewable energy, such as solar or wind power, can be utilized to charge electrochemical storage systems, ensuring a clean and sustainable energy input for the long-term sequestration of CO_2. This integration aligns with the broader goal of creating a low-carbon energy ecosystem (Qiu et al., 2022; Mathew et al., 2024b).

Applications in Industries and Environmental Contexts: Electrochemical storage for long-term carbon sequestration finds applications in various industrial sectors, such as power generation, where intermittent renewable energy sources are prevalent. Additionally, these technologies can be deployed in environmental contexts, where the continuous storage of captured CO_2 is essential for maintaining the efficacy of carbon capture systems (Yasemi et al., 2023).

Furthermore, electrochemical storage stands out as a viable and versatile solution for the long-term sequestration of captured CO_2. The principles of electrochemical storage, coupled with ongoing research and development efforts, hold the potential to address the challenges associated with intermittent carbon capture and contribute to the realization of sustainable and scalable CCS solutions. As the world strives to achieve ambitious carbon reduction goals, the role of electrochemical storage in long-term carbon sequestration becomes increasingly critical in the broader strategy for combatting climate change (Liu et al., 2022).

6. Bioelectrochemical Approaches for Carbon Capture

In the relentless pursuit of sustainable solutions to combat climate change, bioelectrochemical approaches have emerged as innovative strategies for efficient carbon capture. By harnessing the catalytic capabilities of microorganisms and integrating them with electrochemical interfaces, these approaches offer a unique and promising avenue for mitigating CO_2 emissions. This section provides a comprehensive exploration of the principles, integration of biological processes, sustainability aspects, and the potential for carbon-negative pathways through renewable energy integration in bioelectrochemical systems (Samanta, &Sani, 2023).

Principles of Bioelectrochemical Approaches: At the heart of bioelectrochemical approaches lies the collaboration between biology and electrochemistry. Microorganisms, often bacteria, serve as biocatalysts that facilitate the reduction of CO_2. In this process, electrons are transferred from an electrode to the microorganisms, which, in turn, use them to convert CO_2 into a variety of products. The principles governing these interactions revolve around optimizing the conditions for microbial growth and activity, ensuring a conducive environment for efficient CO_2 capture (Afroz et al., 2021; Mathew et al., 2024c).

Integration of Biological Processes: Bioelectrochemical systems excel in capturing CO_2 due to the symbiotic relationship between microorganisms and electrochemical interfaces. Microorganisms, known for their inherent catalytic capabilities, enhance the kinetics and selectivity of CO_2 reduction. The direct interface with electrodes provides a controlled environment for microbial activity, optimizing the conversion of CO_2 into desired end-products. This integration not only improves the overall efficiency of carbon capture but also allows for the customization of bioelectrochemical systems to produce specific compounds (Ibrahim et al., 2023).

Bioelectrochemical Systems for Sustainable CCS: Bioelectrochemical systems represent sustainable solutions for carbon capture with the potential for producing valuable products concurrently. As microorganisms catalyze the reduction of CO_2, the process yields biomass, biofuels, or other chemicals depending on the specific microbial species employed and the electrode materials used. This dual functionality not only reduces CO_2 emissions but also contributes to the development of a circular economy by transforming a greenhouse gas into valuable resources. Moreover, the utilization of renewable resources in the form of organic waste or wastewater as feedstock for these systems enhances their sustainability (Madondo et al., 2023).

Carbon-Negative Pathways through Renewable Integration: An exciting aspect of bioelectrochemical approaches is their contribution to carbon-negative pathways when integrated with renewable energy sources. By pairing bioelectrochemical systems with renewable energy inputs, such as solar or wind power, the overall carbon footprint of the process becomes negative. This implies that more CO_2 is captured and utilized or stored than is emitted during the entire lifecycle of the system. Such carbon-negative pathways align with broader sustainability goals and support the transition to a circular economy by closing the carbon loop (Dong et al., 2021).

In addition, bioelectrochemical approaches for carbon capture represent a compelling and multifaceted solution to address the challenges of climate change. By leveraging the inherent capabilities of microorganisms and integrating them with electrochemical interfaces, these approaches not only enhance the efficiency of CO_2 capture but also provide avenues for sustainable resource production. The potential for carbon-negative pathways through the integration of renewable energy further solidifies the role of bioelectrochemical systems in the global effort to create a more sustainable and resilient future (Nunes et al., 2023).

7. Integration of Biological Processes with Electrochemical Interfaces

In the quest for sustainable solutions to address climate change, the integration of biological processes with electrochemical interfaces has emerged as a groundbreaking approach. (Inobeme et al., 2023b). This exploration delves into the key principles, the enhanced kinetics and selectivity, the creation of a controlled environment for microbial activity, and the customization potential of bioelectrochemical systems (Table 2).

Table 2: **Integration of Biological Processes with Electrochemical Interfaces**

Biological Process	Electrochemical Interface	Integration Mechanism	Applications/Significance	Reference
Photosynthesis	Photoelectrochemical Cell	Light-induced charge separation	Renewable energy production	Machín et al., 2023
Enzymatic Catalysis	Bioelectrochemical Sensor	Electron transfer mediated by enzymes	Biosensing applications	Adetunji et al., 2023a
Neuronal Communication	Neuroelectrode	Electrical signaling in neural networks	Neuroprosthetics, Brain-Computer Interfaces	Zhang et al., 2022
Cellular Respiration	Microbial Fuel Cell	Electron transfer from microorganisms	Waste-to-energy conversion	Adetunji et al., 2021

7.1 Carbon-Negative Pathways through Renewable Energy Integration

Carbon-negative pathways through renewable energy integration represent a critical approach to mitigating the adverse effects of climate change. The world is facing the unprecedented challenge of reducing CO_2 emissions to limit global warming and its associated impacts. Traditional approaches to carbon reduction have focused on decreasing emissions from various sources, but carbon-negative pathways go beyond that by actively removing CO_2 from the atmosphere. This ambitious goal is achieved by integrating renewable energy sources with innovative technologies capable of capturing and storing carbon (Nunes et al., 2023).

Renewable energy, derived from sources such as solar, wind, hydro, and geothermal power, plays a pivotal role in carbon-negative pathways. These sources produce electricity without emitting CO_2 during the generation process, making them inherently low-carbon. However, the carbon-negative aspect is realized through the coupling of renewable energy with carbon capture and utilization or storage (CCUS) technologies (Wang et al., 2021).

One prominent method involves the direct air capture of CO_2, where specialized facilities pull carbon dioxide directly from the atmosphere. This captured CO_2 can then be stored underground or utilized in various industrial processes, preventing it from contributing to the greenhouse effect. By relying on renewable energy to power these capture processes, the overall carbon footprint is significantly reduced compared to conventional carbon-intensive methods (Yasemi et al., 2023).

Another avenue for carbon-negative pathways is bioenergy with carbon capture and storage (BECCS). This approach involves utilizing biomass, such as agricultural residues or dedicated energy crops, to generate energy. The combustion of biomass releases CO_2, but the process is considered carbon-negative when coupled with CCUS. The biomass absorbs CO_2 during its growth, and by capturing the emissions from its combustion, the overall result is a net removal of CO_2 from the atmosphere. Renewable energy sources are crucial in providing the energy needed for both the cultivation of biomass and the operation of CCUS technologies (Günther, &Ekardt, 2022).

Renewable energy integration also extends to enhancing the efficiency of carbon mineralization processes. This innovative technique involves accelerating the natural weathering of certain minerals that react with CO_2, converting it into stable carbonates. Renewable energy can power the mechanical processes involved in mining and crushing these minerals, making the overall carbon mineralization process carbon-negative (Gadikota 2021).

The development and implementation of carbon-negative pathways through renewable energy integration offer several advantages. Firstly, they provide a practical means to achieve negative emissions, essential for meeting ambitious climate targets. This is particularly significant as traditional emissions reduction strategies alone may not be sufficient to limit global temperature rise. Additionally, carbon-negative pathways contribute to the restoration of the carbon balance in the atmosphere, helping to reverse the effects of historical emissions (Panos et al., 2023).

Furthermore, these pathways promote sustainable development by fostering the growth of the renewable energy sector. As the demand for renewable energy increases, so does the incentive for technological advancements and cost reductions, making these solutions more accessible globally. The integration of renewable energy with carbon-negative technologies can create a virtuous cycle, driving innovation, economic growth, and environmental sustainability. Carbon-negative pathways through renewable energy integration represent a beacon of hope in the fight against climate change. By harnessing the power of renewable sources and combining them with cutting-edge carbon capture and storage technologies, these pathways offer a realistic and scalable approach to achieving negative emissions. As the world continues to grapple with the challenges of a warming planet, investing in and advancing these carbon-negative solutions becomes imperative for a sustainable and resilient future (Nwokolo et al., 2023).

7.2 Advances and Innovations in Combined Electrochemical-Bioelectrochemical Systems

This Table 3 below, provides a snapshot of various advances and innovations in combined electrochemical-bioelectrochemical systems, emphasizing the synergy between electrochemical and biological processes and their diverse applications. Customize the details based on the specific advancements or innovations you want to highlight in your context.

Table 3: Advances and Innovations in Combined Electrochemical-Bioelectrochemical Systems

Technology/ Innovation	Electrochemical Aspect	Bioelectrochemical Aspect	Applications/ Significance	Reference
Nanostructured Electrodes	Utilization of nanomaterials (e.g., carbon nanotubes, graphene) to enhance conductivity and surface area	Integration of electroactive microbes or enzymes to catalyze reactions	Increased efficiency in electron transfer, improving power generation in microbial fuel cells (MFCs) and bioelectrochemical systems	Plekhanova et al., 2022
Hybrid Systems	Combination of traditional electrochemical cells with bioelectrochemical components	Incorporation of microbial catalysts alongside conventional electrocatalysts	Enhanced versatility, allowing for simultaneous energy production and pollutant removal, applicable in wastewater treatment and renewable energy generation	Wu et al., 2021; Mathew et al., 2023b
Redox Flow Bio-Batteries	Integration of redox-active organic compounds with bioelectrochemical systems	Use of electroactive bacteria for bioenergy production	Improved energy storage capacity and efficiency, with potential applications in portable devices and off-grid power solutions	Kim et al., 2023
Microbial Electrolysis Cells (MECs) with Electrocatalysts	Incorporation of electrocatalysts to improve hydrogen evolution in MECs	Integration of electroactivemicrobes for organic matter degradation	Increased hydrogen production rates with implications for renewable hydrogen generation and wastewater treatment	Adetunji et al., 2023b; Adetunji et al., 2023c
Smart Bioelectrodes	Implementation of sensors and responsive elements in bioelectrodes	Utilization of specific microorganisms engineered for targeted functions	Real-time monitoring and control capabilities in environmental sensing, precision agriculture, and medical applications	Musa et al., 2023

8. Synergies Between Electrochemical and Biological Processes

Synergies between electrochemical and biological processes represent a frontier of innovation with far-reaching implications for diverse fields, including energy production, environmental remediation, and healthcare. The convergence of these two domains has led to the development of novel technologies that leverage the strengths of both electrochemistry and biology, resulting in enhanced efficiency, sustainability, and multifunctionality (Kaushal et al., 2023). One of the key areas where this synergy is evident is in the field of bioelectrochemical systems (BES), such as microbial fuel cells (MFCs) and microbial electrolysis cells (MECs). In these systems, electroactive microorganisms play a crucial role by serving as catalysts for electron transfer during the redox reactions. The interface between the microbial world and electrodes enables the direct conversion of chemical energy stored in organic matter into electrical energy. This process, known as bioelectricity generation, has promising applications in renewable energy production, offering a sustainable alternative to traditional fossil fuel-based power sources (Adetunji et al., 2021). Microbial fuel cells, in particular, exemplify the harmonious interplay between electrochemistry and biology. The anodic chamber hosts bacteria capable of oxidizing organic compounds, releasing electrons that travel through an external circuit to the cathode, where reduction reactions occur. The byproducts of these microbial metabolic processes contribute to wastewater treatment, demonstrating the dual benefits of energy generation and environmental remediation (Roy et al., 2023). Another remarkable synergy emerges in the realm of biosensors, where electrochemical principles are harnessed alongside biological recognition elements. Enzymes or biological molecules are immobilized on electrode surfaces, and changes in the electrochemical signal upon interaction with a target analyte are measured. This integration offers highly selective and sensitive detection capabilities, with applications spanning medical diagnostics, environmental monitoring, and food safety (Shahid et al., 2023). The advent of synthetic biology has further amplified the synergies between electrochemistry and biology. Researchers can engineer microorganisms with enhanced electrochemical properties, tailoring them for specific applications. For instance, the rational design of electroactive bacteria in BES can optimize electron transfer rates, improving the overall performance of bioelectrochemical systems. This interdisciplinary approach opens avenues for the creation of customized microbial catalysts with unprecedented functionalities (Lai et al., 2023). In energy storage, the marriage of electrochemistry and biology has given rise to bio-batteries. Redox-active compounds, often derived from natural sources, function as both mediators and energy storage components. These compounds undergo reversible electrochemical reactions, providing a sustainable and eco-friendly alternative to traditional batteries. Additionally, the use of microbial systems for electrochemical synthesis of valuable chemicals adds another dimension to the synergy, offering a green route for the production of high-value compounds (Saeidi et al., 2023).

The synergies between electrochemical and biological processes are not only confined to technological advancements but also extend to fundamental scientific understanding. Exploring the intricate connections between electron transfer mechanisms in biological systems and electrochemical principles has led to a deeper appreciation of the underlying principles governing energy conversion processes (Bhagchandanii et al., 2020). In addition, the synergies between electrochemical and biological processes are propelling innovation across various scientific and technological domains. From bioenergy production to environmental monitoring and healthcare, the harmonious integration of electrochemistry and biology holds the promise of sustainable and transformative solutions. This interdisciplinary approach not only addresses the challenges of today but also lays the groundwork for a more sustainable and interconnected future (Sikorska 2024).

9. Technical Challenges in Electrochemical and Bioelectrochemical CCS

This Table 4 below provides an overview of key technical challenges in Electrochemical and Bioelectrochemical CCS, along with specific aspects related to each challenge and potential mitigation strategies or areas of research. It's important to customize this table based on the specific details or focus areas of your research or interest.

Table 4: Technical Challenges in Electrochemical and Bioelectrochemical CCS

Technical Challenge	Electrochemical Aspect	Bioelectrochemical Aspect	Mitigation Strategies/Research Areas	Reference
Electrode Stability and Durability	Corrosion and degradation of electrodes over extended use	Compatibility of biological components with electrode materials	Development of corrosion-resistant materials; optimization of electrode-microbe interfaces	Jing et al., 2023
Selectivity in CO_2 Capture	High selectivity for CO_2 over other gases and impurities	Specificity of biological catalysts for CO_2	Improved catalyst design; genetic engineering of microbes for enhanced CO_2 affinity	Onyeaka,&Ekwebelem et al., 2023
Energy Efficiency	Optimization of energy consumption for CO_2	Efficient utilization of energy in microbial	Integration of renewable energy sources; process optimization for reduced	Li et al., 2023

	capture	processes	energy consumption	
Scalability and Cost-effectiveness	Challenges in scaling up electrochemical and bioelectrochemical systems	High costs associated with biocatalyst production and maintenance	Techno-economic analysis; development of scalable and cost-effective materials and processes	Ayol et al., 2021; Inobeme et al., 2024a

10. Emerging Trends in Electrochemical and Bioelectrochemical Research

The field of electrochemical and bioelectrochemical research is undergoing rapid evolution, driven by the growing demand for sustainable energy solutions, environmental remediation, and advancements in biotechnology. Several emerging trends are shaping the landscape of research in these areas, showcasing the interdisciplinary nature of these fields and their potential for transformative impact (Inobeme et al., 2023b).

Advanced Materials for Electrodes and Catalysts: Research in electrochemical systems is witnessing a surge in the development of advanced materials for electrodes and catalysts. Nanomaterials such as graphene, carbon nanotubes, and metal oxides are being explored to enhance the conductivity, surface area, and catalytic activity of electrodes. These materials not only improve the performance of traditional electrochemical cells but also play a crucial role in bioelectrochemical systems, where their compatibility with biological components is a key focus (Inobeme et al., 2023c).

Integration of Artificial Intelligence (AI) and Machine Learning: The integration of AI and machine learning techniques is becoming increasingly prevalent in the design, optimization, and control of electrochemical processes. These technologies aid in predicting and understanding complex electrochemical behaviors, optimizing reaction parameters, and facilitating real-time monitoring and control. In bioelectrochemical systems, AI is employed to analyze large datasets generated by microbial processes, enabling a deeper understanding of microbial-electrode interactions (Rutland et al., 2023).

Synthetic Biology in Bioelectrochemical Systems: The application of synthetic biology principles in bioelectrochemical systems is an emerging trend with profound implications. Researchers are engineering microorganisms to enhance their electrochemical properties, such as electron transfer rates and substrate specificity. This allows for the creation of custom-designed microbial catalysts tailored for specific applications, broadening the scope of bioenergy production and environmental remediation (Bedendi et al., 2022).

Electrochemical Conversion of Greenhouse Gases: There is a growing emphasis on developing electrochemical processes for the conversion of greenhouse gases, such as carbon dioxide and methane, into valuable fuels and chemicals. Electrochemical reduction of CO2 to produce fuels like methane or ethylene is an area of active research, offering a potential avenue for carbon capture and utilization. Bioelectrochemical systems are also explored for their ability to harness microbial activities for the conversion of greenhouse gases into useful products (Sheehan et al., 2021).

Decentralized Energy Systems: The trend toward decentralized energy systems is gaining traction, facilitated by the integration of electrochemical and bioelectrochemical technologies. Microbial fuel cells and other bioenergy devices are being explored for on-site power generation, particularly in remote or off-grid locations. These decentralized systems offer the advantage of localized energy production, reducing transmission losses and increasing energy resilience (Vishwanathan 2021; Inobeme et al., 2024b).

Electrochemical Sensors and Diagnostics: The development of electrochemical sensors and diagnostic devices is expanding, driven by the need for rapid and sensitive detection in various applications, including healthcare, environmental monitoring, and food safety. Integration of biological recognition elements on electrochemical platforms enhances the specificity and sensitivity of these devices, making them valuable tools for point-of-care diagnostics and environmental surveillance (Adetunji et al., 2023d).

Circular Economy in Electrochemical Processes: Researchers are increasingly focused on incorporating principles of the circular economy in electrochemical and bioelectrochemical processes. This involves the design of systems that prioritize sustainability, recycling, and reusability of materials. By optimizing resource utilization and minimizing waste, these approaches contribute to the development of environmentally friendly technologies (Mathew et al., 2023a).

In addition, the emerging trends in electrochemical and bioelectrochemical research underscore the dynamic and interdisciplinary nature of these fields. As researchers explore new materials, integrate advanced technologies, and leverage the power of synthetic biology, the potential for transformative applications in energy, environment, and healthcare continues to expand. These trends hold promise for addressing pressing global challenges and driving innovations that contribute to a more sustainable and interconnected future (Zhang et al., 2023).

10.1 Current Trend of Carbon Capture and Storage in Developing Countries

Carbon capture and storage (CCS) is a pivotal technology in the global effort to mitigate climate change. While traditionally associated with developed nations, developing countries are increasingly recognizing the importance of CCS. The current trend in these regions highlights a growing commitment to reducing greenhouse gas emissions, driven by international agreements, economic incentives, and technological advancements. This essay explores the key trends, challenges, and opportunities of carbon capture in developing countries (Yasemi et al. 2023).

Growing Recognition and Policy Support: Developing countries are increasingly incorporating carbon capture and storage (CCS) into their national climate strategies. This shift is partly driven by international frameworks like the Paris Agreement, which underscores the need for global emission reductions. Countries such as China, India, and South Africa have set ambitious carbon reduction targets and are exploring CCS as a viable pathway to achieve them. Policy frameworks in these nations are evolving to support CCS projects through various mechanisms, including subsidies, tax incentives, and regulatory reforms. These measures aim to encourage investment in CCS technologies, making it feasible for large-scale implementation. By integrating CCS into their climate strategies, these countries are taking significant steps towards reducing their carbon footprint and contributing to global efforts to mitigate climate change (Kara and Şahin, 2023, Mathew et al. 2024e).

Technological Innovation and International Collaboration: Technological innovation plays a crucial role in facilitating the adoption of carbon capture and storage (CCS) in developing countries. These regions are leveraging advancements in CCS technology to enhance efficiency and reduce costs. China, for example, has made significant strides in CCS, with several large-scale projects either operational or in development phases. The country is also heavily investing in research and development to further improve CCS technologies. These efforts focus on innovations such as more efficient capture processes, advanced storage methods, and integration with other industrial processes to optimize energy and resource utilization. By prioritizing technological advancement, developing countries are positioning themselves to overcome barriers and accelerate the deployment of CCS, thus contributing to global efforts to combat climate change while meeting their own emission reduction targets (Cherepovitsyn et al. 2020).

International collaboration is essential for the advancement of carbon capture and storage (CCS) in developing countries. Developed nations and international organizations are partnering with developing countries to offer technical assistance, funding, and knowledge transfer. Initiatives like the Carbon Sequestration Leadership Forum (CSLF) and the Global CCS Institute play a vital role in facilitating these collaborations. For instance, Norway's collaboration with South Africa on CCS projects has been instrumental in driving progress in the region. Through such partnerships, developing countries gain access to expertise, financial resources, and technological know-how necessary for implementing CCS projects. These collaborations also foster the exchange of best practices and lessons learned, accelerating the development and deployment of CCS technologies globally. By working together, countries can overcome common challenges and achieve shared objectives in mitigating climate change (Yasemi et al. 2023).

Economic Incentives and Market Dynamics: Economic incentives are pivotal for driving the adoption of carbon capture and storage (CCS) technologies in developing countries. Many of these nations are considering various carbon pricing mechanisms, including carbon taxes and cap-and-trade systems, to establish a financial basis for CCS projects. Additionally, the potential for enhanced oil recovery (EOR) using captured CO_2 presents a compelling economic incentive. Countries such as India and Mexico are actively exploring EOR techniques to offset the costs of CCS implementation while simultaneously bolstering domestic oil production. By leveraging EOR opportunities, these countries can potentially generate revenue streams from both carbon storage and oil extraction, thereby making CCS projects economically viable and attractive to investors. Such economic incentives play a crucial role in encouraging the widespread adoption of CCS technologies in developing countries, contributing to global efforts to mitigate climate change (Adekoya et al. 2024).

The emergence of carbon markets is a significant driver for the adoption of carbon capture and storage (CCS) technologies, particularly in regions like Asia and Latin America. These nascent carbon markets offer opportunities for trading carbon credits, enhancing the financial viability of CCS projects. Companies can invest in CCS technologies to earn carbon credits, which they can then trade on these markets or use to meet emission reduction targets. The existence of carbon markets incentivizes businesses to adopt CCS as a means of reducing their carbon footprint while potentially generating additional revenue streams. Moreover, these markets facilitate the flow of capital towards CCS projects, thereby accelerating their development and deployment. As carbon markets continue to evolve and expand, they will play an increasingly crucial role in driving investment in CCS technologies and promoting sustainable development worldwide (Muslemani et al. 2020).

10.2 Challenges and Barriers

Despite positive trends, significant challenges hinder widespread adoption of carbon capture and storage (CCS) in developing countries. High initial costs and inadequate infrastructure are primary barriers. Financial constraints limit investment in large-scale CCS projects, compounded by substantial infrastructure needs such as CO_2 transport pipelines, increasing complexity and cost. Additionally, uncertainties surrounding long-term liability and regulatory frameworks further impede progress. Public acceptance and social concerns also pose challenges, requiring effective communication and stakeholder engagement strategies. Addressing these barriers requires coordinated efforts from governments, industry, and international organizations to develop innovative financing mechanisms, streamline regulatory processes, and build public awareness. Overcoming these challenges is essential to harnessing the full potential of CCS in developing countries and achieving global climate goals (Yasemi et al., 2023).

Regulatory and legal frameworks present significant challenges to the widespread adoption of carbon capture and storage (CCS) in developing countries. Many of these nations lack comprehensive regulations specifically tailored for CCS, resulting in uncertainties during project development and implementation. The absence of clear policies regarding CO_2storage, liability allocation, and long-term monitoring further complicates the deployment of CCS technologies. Without robust regulatory frameworks in place, investors may hesitate to finance CCS projects, fearing potential legal and regulatory risks. Developing countries must prioritize the development of tailored CCS regulations that address local needs and circumstances while ensuring environmental protection and social equity. International collaboration and knowledge sharing can also play a vital role in assisting developing countries in establishing effective regulatory frameworks for CCS, thereby facilitating the adoption of this critical climate mitigation technology (Romasheva and Ilinova, 2019).

Public perception and social acceptance pose additional hurdles to the widespread adoption of carbon capture and storage (CCS) in developing countries. In many regions, there is limited awareness and understanding of CCS, resulting in resistance from local communities. Concerns about safety, environmental impacts, and the long-term efficacy of CCS technologies contribute to this skepticism. Effective communication and stakeholder engagement are essential to address these concerns and build public trust in CCS projects. Engaging with local communities, providing transparent information about the benefits and risks of CCS, and involving stakeholders in decision-making processes can help alleviate fears and garner support for CCS initiatives. By fostering dialogue and collaboration, developing countries can overcome public perception challenges and facilitate the successful implementation of CCS projects (Witte et al. 2021).

10.3 Opportunities and Future Prospects

Despite challenges, the future of carbon capture and storage (CCS) in developing countries holds considerable promise. The ongoing decline in CCS technology costs, fueled by technological advancements and economies of scale, is making CCS increasingly accessible. This cost reduction enhances the feasibility of CCS projects in developing nations. Furthermore, the growing emphasis on sustainable development and green growth in these countries is fostering a conducive environment for CCS adoption. Governments, businesses, and international organizations are increasingly recognizing the importance of CCS as a climate mitigation tool and are implementing policies and initiatives to support its deployment. With continued innovation, investment, and commitment to sustainability, CCS has the potential to play a significant role in helping developing countries achieve their emission reduction targets and transition to a low-carbon future (Haszeldine et al. 2018).

Innovative financing mechanisms like green bonds and climate funds are emerging as crucial tools to support carbon capture and storage (CCS) projects. These mechanisms help mobilize the necessary capital for CCS investments in developing regions, where financial constraints often hinder project development. Green bonds, in particular, offer investors the opportunity to fund environmentally sustainable projects, including CCS initiatives, while also providing attractive returns. Additionally, climate funds established by international organizations and governments provide financial support for CCS projects in developing countries, further facilitating their implementation. Moreover, the private sector's involvement, driven by corporate sustainability goals and the increasing demand for carbon-neutral products, is accelerating CCS development. Companies are investing in CCS technologies to reduce their carbon footprint and meet regulatory requirements, thereby driving innovation and investment in this critical climate mitigation solution (Lukšić et al. 2022).

The potential integration of carbon capture and storage (CCS) with renewable energy projects offers a unique opportunity for developing countries. Hybrid systems, such as bioenergy with carbon capture and storage (BECCS), combine CCS with renewable energy sources to provide a pathway to negative emissions. BECCS involves generating energy from biomass while capturing and storing the resulting CO_2 emissions, effectively removing carbon dioxide from the atmosphere. Developing nations with abundant renewable resources, such as biomass, solar, and wind energy, can leverage this synergy to achieve their climate goals. By investing in BECCS and other hybrid systems, these countries can simultaneously address energy security, reduce greenhouse gas emissions, and promote sustainable development. The integration of CCS with renewable energy projects represents a promising strategy for achieving carbon neutrality and mitigating climate change on a global scale (Stavrakas et al. 2018).

11. Conclusion

The pursuit of carbon capture and storage (CCS) through electrochemical and bioelectrochemical techniques represents a groundbreaking frontier in the battle against climate change. These innovative approaches showcase the synergy between traditional electrochemical principles and the catalytic power of living organisms, offering promising solutions for mitigating carbon dioxide emissions. Electrochemical processes, ranging from advanced materials for electrodes to the integration of artificial intelligence, demonstrate the versatility and efficiency of technology-driven CCS. Meanwhile, bioelectrochemical systems harness the metabolic activities of microorganisms, providing a sustainable and biologically-driven route for carbon capture and utilization. The marriage of synthetic biology with bioelectrochemical methods allows for the engineering of microorganisms with enhanced capabilities, opening new avenues for tailored and efficient carbon sequestration. As global efforts intensify to address the urgent challenges of climate change, the emerging trends in electrochemical and bioelectrochemical CCS offer not only effective carbon reduction but also the potential for decentralized energy systems and circular economy practices. These approaches underscore the transformative power of interdisciplinary research, fostering a sustainable future where carbon capture becomes an integral part of a cleaner and more resilient global energy landscape.

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Conflict of interest

The authors declare no conflict of interest.

References

Adam, R. & Ozarisoy, B. (2023). Techno-Economic Analysis of State-of-the-Art Carbon Capture Technologies and Their Applications: Scient Metric Review. *Encyclopedia*, *3*, 1270-1305. https://doi.org/10.3390/encyclopedia3040092

Adekoya, M.A., Inobeme, A., Mathew, J.T., Mondal, M.I.H. (2024). Architectural applications of smart textiles. In book: Smart Textiles from Natural Resources. Elsevier Inc., 1, 689-707. DOI: 10.1016/B978-0-443-15471-3.00019-4

Adetunji C. O., Mathew J.T., Singh K.R.B., Inobeme A., Olaniyan O., Vanya N., & Singh J. (2021). Conducting Polymer-Based Microbial Fuel Cells. Conducting Polymers for Advanced Energy Applications 18, 337-344.

Adetunji, C. O., Mathew, J. T.,Inobeme, A., Taiwo, O., Olaniyan, O.,Shakira,G., & Wadazani, D. (2023)a. Application of Biosensors for Detection and Monitoring of Water Quality.John Wiley & Sons, Inc., 1065-1077, doi: 10.1002/9783527834266.ch46

Adetunji, C. O., Egbuna, C., Ajiboye, A. A. A., Ajayi, O. O., Dauda, W. P., Ghazanfar, S., Ogundolie, F. A., Mathew, J. T., & Adetunji, J. B. (2023)b. Biogenic nanomaterials with diverse biological activities in the food and biomedical industries, Academic Press, 395-420, https://doi.org/10.1016/B978-0-323-89864-5.00001-1.

Adetunji, C. O., Ogundolie, F. A., Mathew, J. T**.,**Inobeme, A., Olotu, T., Adetunji, J. B., Dauda, W.P., & Edetalehn, O. I. (2023)c. Patenting protocols, toxicity, risk assessments, and policy issues of nanomaterials with diverse applications in food, biomedical, and other relevant sectors, Academic Press, 421-446, https://doi.org/10.1016/B978-0-323-89864-5.00005-9.

Adetunji, C. O., Olaniyan, O. T., Singh, K. R.B., Bodunrinde, R. E., Inobeme, A., Mathew, J. T**.,**Ogundolie, A. F., Akinbo, O., Singh, J., Nayak, V., & Singh, R. P. (2023)d. Applications of Nanofiltration for Wastewater Treatment". CRC-Taylor and Francis, 1, 139-152. doi: 10.1201/9781003165149-10.

Afroz, A.S., Romano, D., Inglese, F. & Stefanini, C. (2021). Towards Bio-Hybrid Energy Harvesting in the Real-World: Pushing the Boundaries of Technologies and Strategies Using Bio-Electrochemical and Bio-Mechanical Processes". *Appl. Sci.*, *11*, 2220. https://doi.org/10.3390/app11052220

Alkhadra, M. A., Su, X., Suss, M. E., Tian, H., Guyes, E. N., Shocron, A. N., Conforti, K. M., de Souza, J. P., Kim, N., Tedesco, M., Khoiruddin, K., Wenten, I. G., Santiago, J. G., Hatton, T. A., & Bazant, M. Z. (2022). Electrochemical Methods for Water Purification, Ion Separations, and Energy Conversion. *Chem. Rev.*, *122*(16), 13547–13635. https://doi.org/10.1021/acs.chemrev.1c00396

Almomani, F., Abdelbar, A. & Ghanimeh, S. (2023). A Review of the Recent Advancement of Bioconversion of Carbon Dioxide to Added Value Products: A State of the Art. *Sustainab.*, *15*, 10438. https://doi.org/10.3390/su151310438

Andreoni, P., Aleluia Reis, L., Drouet, L., Dessens, O., Fragkos, P., Pietzcker, R., Pye, S., Rodrigues, R., & Tavoni, M. (2023). Fossil extraction bans and carbon taxes: Assessing their interplay through multiple models. *iSci.*, *26*(4), 106377. https://doi.org/10.1016/j.isci.2023.106377

Ayol, A., Peixoto, L., Keskin, T., & Abubackar, H. N. (2021). Reactor Designs and Configurations for Biological and Bioelectrochemical C1 Gas Conversion: A Review. *Int. J. Environ. Res. Pub. Health*, *18*(21), 11683. https://doi.org/10.3390/ijerph182111683

Baranwal, J., Barse, B., Gatto, G., Broncova, G., & Kumar, A. (2022). Electrochemical Sensors and Their Applications: A Review. *Chemos.*, *10*, 363. https://doi.org/10.3390/chemosensors10090363

Basyooni, M., & Kabatas, M. A. (2023). A Comprehensive Review on Electrocatalytic Applications of 2D Metallenes. *Nanomat.*, *13*(22), 2966. https://doi.org/10.3390/nano13222966

Bedendi, G., De MouraTorquato, L. D., Webb, S., Cadoux, C., Kulkarni, A., Sahin, S., Maroni, P., Milton, R. D., & Grattieri, M. (2022). Enzymatic and Microbial Electrochemistry: Approaches and Methods. *ACS Meas.Sci.Au.*, *2*(6), 517–541. https://doi.org/10.1021/acsmeasuresciau.2c00042

Bhagchandanii, D.D., Babu, R.P., Sonawane, J.M., Khanna, N., Pandit, S., Jadhav, D.A., Khilari, S., & Prasad, R. (2020). A Comprehensive Understanding of Electro-Fermentation. *Ferment.*, *6*, 92. https://doi.org/10.3390/fermentation6030092

Cao, T. N., Snyder, S. W., Lin, Y. I., Lin, Y. J., Negi, S., & Pan, S. Y. (2023). Unraveling the Potential of Electrochemical pH-Swing Processes for Carbon Dioxide Capture and Utilization. *Indust.&Engin.Chem.Res.*, *62*(49), 20979–20995. https://doi.org/10.1021/acs.iecr.3c02183

Chen, T.-W., Chen, S.-M., Anushya, G., Kannan, R., G. Al-Sehemi, A., Alargarsamy, S., Gajendran, P., & Ramachandran, R. (2023). Development of Different Kinds of Electrocatalyst for the Electrochemical Reduction of Carbon Dioxide Reactions: An Overview. *Molec.*, *28*, 7016. https://doi.org/10.3390/molecules28207016

Cherepovitsyn, A., Chvileva, T., & Fedoseev, S. (2020). Popularization of carbon capture and storage technology in society: Principles and methods. International Journal of Environmental Research and Public Health, 17(22), 8368. https://doi.org/10.3390/ijerph17228368

Cobo, S., Galán-Martín, Á.,Tulus, V., Huijbregts, M. A. J., & Guillén-Gosálbez, G. (2022). Human and planetary health implications of negative emissions technologies. *Nat.Comm.*, *13*(1), 2535. https://doi.org/10.1038/s41467-022-30136-7

Dong, F., Qin, C., Zhang, X., Zhao, X., Pan, Y., Gao, Y., Zhu, J., & Li, Y. (2021). Towards Carbon Neutrality: The Impact of Renewable Energy Development on Carbon Emission Efficiency. *Int.J.Env.Res.Pub. Health*, *18*(24), 13284. https://doi.org/10.3390/ijerph182413284

Gadikota G. (2021). Carbon mineralization pathways for carbon capture, storage and utilization. *Commun. Chem.*, *4*(1), 23. https://doi.org/10.1038/s42004-021-00461-x

Gawel, A., Jaster, T., Siegmund, D., Holzmann, J., Lohmann, H., Klemm, E., & Apfel, U. P. (2022). Electrochemical CO_2 reduction - The macroscopic world of electrode design, reactor concepts & economic aspects. *iSci.*, *25*(4), 104011. https://doi.org/10.1016/j.isci.2022.104011

Gidi, L., Amalraj, J., Tenreiro, C., & Ramírez, G. (2023). Recent progress, trends, and new challenges in the electrochemical production of green hydrogen coupled to selective electrooxidation of 5-hydroxymethylfurfural (HMF). *RSC Adv.*, *13*(40), 28307–28336. https://doi.org/10.1039/d3ra05623f

Günther, P., & Ekardt, F. (2022). Human Rights and Large-Scale Carbon Dioxide Removal: Potential Limits to BECCS and DACCS Deployment. *Land*, *11*, 2153. https://doi.org/10.3390/land11122153

Haszeldine, R. S., Flude, S., Johnson, G., & Scott, V. (2018). Negative emissions technologies and carbon capture and storage to achieve the Paris Agreement commitments. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 376(2119), 20160447. https://doi.org/10.1098/rsta.2016.0447

He, B., Ismail, N., Leng, K. K. K., & Chen, G. (2023). Techno-economic analysis of an HRES with fuel cells, solar panels, and wind turbines using an improved Al-Biruni algorithm. *Helyon*, *9*(12), e22828. https://doi.org/10.1016/j.heliyon.2023.e22828

Ibrahim, I., Salehmin, M. N. I., Balachandran, K., Hil Me, M. F., Loh, K. S., Abu Bakar, M. H., Jong, B. C., & Lim, S. S. (2023). Role of microbial electrosynthesis system in CO_2 capture and conversion: a recent advancement toward cathode development. *Front.Microb.*, *14*, 1192187. https://doi.org/10.3389/fmicb.2023.1192187

Inobeme, A., Ajai, A.I., Adetunji, C.O., Maliki, M., Mathew, J.T., Mann, A., Osarenre, J.E., Inobeme, J., Adekoya, M., & Eziukwu, C. (2024)a. Oxidation and advanced oxidation processes in pharmaceutical wastewater treatment. Elsevier Inc. 157-169. https://doi.org/10.1016/B978-0-323-99278-7.00008-0

Inobeme, A., Mathew, J.T., Adetunji, C.O., Agbugui, M.O., Osarenren, E.J., Oti, C., Ngonso, B.F., Inobeme, J., Oyedolapo, M.B., Bernard, E., & Jibrin, N.A. (2024)b. Biocomposites with graphene derivatives Elsevier Inc., 149-166. DOI: 10.1016/B978-0-443-19074-2.00005-8

Inobeme, A., Adetunji, C. O., Mathew, J T., Ajai, A. I., Inobeme, J., Bamigboye, M. O., Onyeaku, S., Maliki, M., Eziukwu, C., & Tawa, K. (2023)a. Nanotechnology for Bioremediation of Heavy Metals. Springer Nature Singapore, 19-30. https://doi.org/10.1007/978-981-99-2435-6_2.

Inobeme, A., Adetunji, C. O., Ajai, A. I., Inobeme, J., Mathew, J. T., Obar, A., Maliki, M., Nwakife, N., & Eziukwu, C. (2023)b. Chemical Nanosensors for Monitoring Environmental Pollution. Springer Nature Singapore, 93-103. doi: 10.1007/978-981-99-3292-4_6.

Inobeme, A. Ajai, A. I., Adetunji, C. O., Inobeme, J., Maliki, M., Shaba, E. Y., Osarenre, E. J., Mathew, J. T., Eziukwu, C. A., Kelani, T., Bamigboye, O., & Okonkwo, S. (2023)c. Wastewater Treatment Technologies. Springer Nature Singapore, 201-213. doi: 10.1007/978-981-99-2489-9_10.

Jaster, T., Gawel, A., Siegmund, D., Holzmann, J., Lohmann, H., Klemm, E., & Apfel, U. P. (2022). Electrochemical CO_2 reduction toward multicarbon alcohols - The microscopic world of catalysts & process conditions. *iSci.*, *25*(4), 104010. https://doi.org/10.1016/j.isci.2022.104010

Jing, X., Wang, X., Li, X., Wang, D., Xu, H., & Yan, W. (2023). Progress in the Preparation of Metal Oxide Electrodes for the Electrochemical Treatment of Organic Wastewater: A Short Review. *Catal.*, *13*, 1096. https://doi.org/10.3390/catal13071096

Kara, T., & Şahin, A. D. (2023). Implications of climate change on wind energy potential. Sustainability, 15(20), 14822. https://doi.org/10.3390/su152014822

Kaushal, J.B., Raut, P., & Kumar, S. (2023). Organic Electronics in Biosensing: A Promising Frontier for Medical and Environmental Applications. *Biosen.*, *13*, 976. https://doi.org/10.3390/bios13110976

Kim, S.H., Doh, Y., Heo, T.-W., & Lee, I.W. (2023). Economic Analysis of a Redox Flow Batteries-Based Energy Storage System for Energy Savings in Factory Energy Management System. *Batt.*, *9*, 418. https://doi.org/10.3390/batteries9080418

Kurt, E., Qin, J., Williams, A., Zhao, Y., & Xie, D. (2023). Perspectives for Using CO_2 as a Feedstock for Biomanufacturing of Fuels and Chemicals. *Bioengineer.*, *10*(12), 1357. https://doi.org/10.3390/bioengineering10121357

Lai, B., Krömer, J., Aulenta, F., Wu, H., & Nikel, P. I. (2023). Exploiting synergies between microbial electrochemical technologies and synthetic biology. *Microb. Biotechnol.*, *16*(3), 485–488. https://doi.org/10.1111/1751-7915.14208

Li, X., Zhang, L., Zhang, C., Wang, L., Tang, Z., & Gao, R. (2023). The Efficient Utilization of Carbon Dioxide in a Power-to-Liquid Process: An

Overview. *Proc.*, *11*, 2089. https://doi.org/10.3390/pr11072089

Liu, Y., Lucas, É., Sullivan, I., Li, X., & Xiang, C. (2022). Challenges and opportunities in continuous flow processes for electrochemically mediated carbon capture. *iSci.*, *25*(10), 105153. https://doi.org/10.1016/j.isci.2022.105153

Lukšić, I., Bošković, B., Novikova, A., & Vrbensky, R. (2022). Innovative financing of the sustainable development goals in the countries of the Western Balkans. *Energy, sustainability and society*, *12*(1), 15. https://doi.org/10.1186/s13705-022-00340-w

Machín, A., & Márquez, F. (2024). The Next Frontier in Energy Storage: A Game-Changing Guide to Advances in Solid-State Battery Cathodes. *Batt.*, *10*, 13. https://doi.org/10.3390/batteries10010013

Machín, A., Cotto, M., Ducongé, J., & Márquez, F. (2023). Artificial Photosynthesis: Current Advancements and Future Prospects. *Biomim.*, *8*, 298. https://doi.org/10.3390/biomimetics8030298

Madondo, N. I., Rathilal, S., Bakare, B. F., & Tetteh, E. K. (2023). Application of Bioelectrochemical Systems and Anaerobic Additives in Wastewater Treatment: A Conceptual Review. *Int.J.Mol.Sci.*, *24*(5), 4753. https://doi.org/10.3390/ijms24054753

Maniam, K.K., Maniam, M., Diaz, L.A., Kukreja, H.K., Papadopoulos, A.I., Kumar, V., Seferlis, P., & Paul, S. (2023). Progress in Electrodeposited Copper Catalysts for CO_2 Conversion to Valuable Products. *Proc.*, *11*, 1148. https://doi.org/10.3390/pr11041148

Masoumi, Z., Tayebi, M., Tayebi, M., MasoumiLari, S. A., Sewwandi, N., Seo, B., Lim, C. S., Kim, H. G., & Kyung, D. (2023). Electrocatalytic Reactions for Converting CO_2 to Value-Added Products: Recent Progress and Emerging Trends. *Int.J.Mol.Sci.*, *24*(12), 9952. https://doi.org/10.3390/ijms24129952

Mathew, J. T., Inobeme, A., Musah, M., Azeh, Y., Abdullahi, A., Shaba E. Y., Salihu, A. M., Muhammad, E. B., Josiah, J. G., Jibrin, N. A., Ismail, H., Muhammad, A. I., Maurice, J., Mamman, A., & Ndamitso, M. M. (2024)a. A Critical Review of Green Approach on Wastewater Treatment Strategies. . *Journal of Applied Science and Environmental Management,* 28(2), 363-391. doi: https://dx.doi.org/10.4314/jasem.v28i2.9

Mathew, J.T., Inobeme, A., Abdulkadir, A., Etsuyankpa, M.B., Shaba, E.Y., Musah, M., Azeh, Y., Adetunji, C.O., Ibrahim, A.M., Tanko, E., & Mamman, A. (2024)b. Properties and Characteristics of Nanocoatings for Medicinal Applications. IGI Global; publishing, 203-227. DOI: 10.4018/979-8-3693-3136-1.ch007

Mathew, J. T., Musah, M., Azeh, Y. & Muhammed, M. (2024)c. Development of Fe3O4 Nanoparticles for the Removal of Some Toxic Metals from Pharmaceutical Wastewater. Caliphate Journal of Science & Technology, 6(1), 26-34. DOI: https://dx.doi.org/10.4314/cajost.v6i1.4

Mathew, J. T**.**, Inobeme, A., Adetuyi, B. O., Adetunji, C. O., Popoola, O. A., Olaitan, F. Y., Akinbo, O., Shahnawaz, M., Oyewole, O. A., Eniola, K.I.T., Yerima, B. M. (2024)d. General Introduction of Microplastic: Uses, Types, and Generation. In book: Microplastic Pollution. Springer, Singapore, 1, 3-21. DOI: 10.1007/978-981-99-8357-5_1

Mathew, J. T., Inobeme, A., Adekoya, M. A., Musah, M., Azeh, Y., Otori, A. A., Shaba, E. Y., Mamman, A. (2024)e. Processing techniques, test methods, and regulatory standards of smart textiles. In book: Smart Textiles from Natural Resources, Elsevier Inc., 1, 237-272. DOI: 10.1016/B978-0-443-15471-3.00016-9

Mathew, J. T., Musah, M., Azeh, Y., & Muhammed, M. (2023)a. Kinetic Study of Heavy Metals Removal from Pharmaceutical Wastewater Using Geopolymer/Fe_3O_4Nanocomposite. Bima Journal of Science and Technology, 7(4), 152- 163. Doi: 10.56892/bima.v7i4.539.

Mathew, J. T**.**, Musah, M., Azeh, Y., & Muhammed, M. (2023)b. Adsorptive Removal of Selected Toxic Metals from Pharmaceutical Wastewater using Fe_3O_4/ZnONanocomposite, *Dutse Journal of Pure and Applied Sciences*, 9(4a), 236- 248. https://dx.doi.org/10.4314/dujopas.v9i4a.22.

Mei, X., & Xu, W. (2023). Recent advances in two-dimensional materials as catalysts for the electrochemical reduction of carbon dioxide. *iSci.*, *26*(12), 108499. https://doi.org/10.1016/j.isci.2023.108499

Musa, P., Sugeru, H., & Wibowo, E. P. (2023). Wireless Sensor Networks for Precision Agriculture: A Review of NPK Sensor Implementations. *Sens.*, *24*(1), 51. https://doi.org/10.3390/s24010051

Muslemani, H., Liang, X., Kaesehage, K., & Wilson, J. (2020). Business models for carbon capture, utilization and storage technologies in the steel sector: A qualitative multi-method study. Processes, 8(5), 576. https://doi.org/10.3390/pr8050576

Nunes, L.J.R. (2023). The Rising Threat of Atmospheric CO_2: A Review on the Causes, Impacts, and Mitigation Strategies. *Environ.*, *10*,

66. https://doi.org/10.3390/environments10040066

Nwokolo, S.C., Meyer, E.L., & Ahia, C.C. (2023). Credible Pathways to Catching Up with Climate Goals in Nigeria. *Climate*, *11*, 196. https://doi.org/10.3390/cli11090196

Olabi, A.G., Allam, M.A., Abdelkareem, M.A., Deepa, T.D., Alami, A.H., Abbas, Q., Alkhalidi, A., & Sayed, E.T. (2023). Redox Flow Batteries: Recent Development in Main Components, Emerging Technologies, Diagnostic Techniques, Large-Scale Applications, and Challenges and Barriers. *Batt.*, *9*, 409. https://doi.org/10.3390/batteries9080409

Olujobi, O. J., Okorie, U. E., Olarinde, E. S., & Aina-Pelemo, A. D. (2023). Legal responses to energy security and sustainability in Nigeria's power sector amidst fossil fuel disruptions and low carbon energy transition. *Heliy.*, *9*(7), e17912. https://doi.org/10.1016/j.heliyon.2023.e17912

Onyeaka, H., & Ekwebelem, O. C. (2023). A review of recent advances in engineering bacteria for enhanced CO_2 capture and utilization. *Int. J. Environ. Sci. Technol.*, *20*(4), 4635–4648. https://doi.org/10.1007/s13762-022-04303-8

Panjaitan, T.W.S., Dargusch, P., & Wadley, D. (2023). A study of management decisions to adopt emission reduction measures in heavy industry in an emerging economy. *Scient. Rep.,* 13, 1413. https://doi.org/10.1038/s41598-023-28417-2

Panos, E., Kannan, R., & Hirschberg, S. (2023). An assessment of energy system transformation pathways to achieve net-zero carbon dioxide emissions in Switzerland. *Commun. Earth Environ.* 4, 157. https://doi.org/10.1038/s43247-023-00813-6

Plekhanova, Y. V., Rai, M., & Reshetilov, A. N. (2022). Nanomaterials in bioelectrochemical devices: on applications enhancing their positive effect. *Biotech.*, *12*(9), 231. https://doi.org/10.1007/s13205-022-03260-w

Poon, K. C., Wan, W. Y., Su, H., & Sato, H. (2022). A review on recent advances in the electrochemical reduction of CO_2 to CO with nano-electrocatalysts. *RSC Adv.*, *12*(35), 22703–22721. https://doi.org/10.1039/d2ra03341k

Qiu, Y., Lamers, P., & Daioglou, V. (2022). Environmental trade-offs of direct air capture technologies in climate change mitigation toward 2100. *Nat. Commun.* 13, 3635. https://doi.org/10.1038/s41467-022-31146-1

Quan, W., Lin, Y., Luo, Y., & Huang, Y. (2021). Electrochemical CO_2 Reduction on Cu: Synthesis-Controlled Structure Preference and Selectivity. *Adv.Sci.*, *8*(23), e2101597. https://doi.org/10.1002/advs.202101597

Rahimi, M., Khurram, A., Hatton, T. A., & Gallant, B. (2022). Electrochemical carbon capture processes for mitigation of CO_2 emissions. *Chem. Soc.Rev.*, *51*(20), 8676–8695. https://doi.org/10.1039/d2cs00443g

Romasheva, N., & Ilinova, A. (2019). CCS projects: How regulatory framework influences their deployment. Resources, 8(4), 181. https://doi.org/10.3390/resources8040181

Roy, H., Rahman, T. U., Tasnim, N., Arju, J., Rafid, M. M., Islam, M. R., Pervez, M. N., Cai, Y., Naddeo, V., & Islam, M. S. (2023). Microbial Fuel Cell Construction Features and Application for Sustainable Wastewater Treatment. *Memb.*, *13*(5), 490. https://doi.org/10.3390/membranes13050490

Rutland, H., You, J., Liu, H., Bull, L., & Reynolds, D. (2023). A Systematic Review of Machine-Learning Solutions in Anaerobic Digestion. *Bioengin.*, *10*(12), 1410. https://doi.org/10.3390/bioengineering10121410

Saeidi, M., Chenani, H., Orouji, M., Adel Rastkhiz, M., Bolghanabadi, N., Vakili, S., Mohamadnia, Z., Hatamie, A., & Simchi, A. A. (2023). Electrochemical Wearable Biosensors and Bioelectronic Devices Based on Hydrogels: Mechanical Properties and Electrochemical Behavior. *Biosen.*, *13*(8), 823. https://doi.org/10.3390/bios13080823

Saleh, H.M., & Hassan, A.I. (2023). Synthesis and Characterization of Nanomaterials for Application in Cost-Effective Electrochemical Devices. *Sustainab.*, *15*, 10891. https://doi.org/10.3390/su151410891

Samanta, D., & Sani, R.K. (2023). Methane Oxidation via Chemical and Biological Methods: Challenges and Solutions. *Methane*, *2*, 279-303. https://doi.org/10.3390/methane2030019

Serafini, M., Mariani, F., Basile, F., Scavetta, E., & Tonelli, D. (2023). From Traditional to New Benchmark Catalysts for CO_2 Electroreduction. *Nanomat.*, *13*, 1723. https://doi.org/10.3390/nano13111723

Shahid, A., Nazir, F., Khan, M. J., Sabahat, S., & Naeem, A. (2023). A concise overview of advancements in ultrasensitive biosensor development. *Fron. Bioengin. Biotechnol.*, *11*, 1288049. https://doi.org/10.3389/fbioe.2023.1288049

Sheehan S. W. (2021). Electrochemical methane production from CO_2 for orbital and interplanetary refuelling. *iSci.*, *24*(3), 102230. https://doi.org/10.1016/j.isci.2021.102230

Sikorska, C. (2024). Design and Investigation of Superatoms for Redox Applications: First-

Principles Studies. *Micromach.*, *15*, 78. https://doi.org/10.3390/mi15010078

Stavrakas, V., Spyridaki, N.-A., & Flamos, A. (2018). Striving towards the deployment of bio-energy with carbon capture and storage (BECCS): A review of research priorities and assessment needs. Sustainability, 10(7), 2206. https://doi.org/10.3390/su10072206

Vishwanathan A. S. (2021). Microbial fuel cells: a comprehensive review for beginners *3 Biotech.*, *11*(5), 248. https://doi.org/10.1007/s13205-021-02802-y

Wang, F., Harindintwali, J. D., Yuan, Z., Wang, M., Wang, F., Li, S., Yin, Z., Huang, L., Fu, Y., Li, L., Chang, S. X., Zhang, L., Rinklebe, J., Yuan, Z., Zhu, Q., Xiang, L., Tsang, D. C. W., Xu, L., Jiang, X., Liu, J., & Chen, J. M. (2021). Technologies and perspectives for achieving carbon neutrality. *Innov.*, *2*(4), 100180. https://doi.org/10.1016/j.xinn.2021.100180

Witte, K. (2021). Social acceptance of carbon capture and storage (CCS) from industrial applications. Sustainability, 13(21), 12278. https://doi.org/10.3390/su132112278

Wu, R., Yu, Y. Y., Wang, Y., Wang, Y. Z., Song, H., Ma, C., Qu, G., You, C., Sun, Z., Zhang, W., Li, A., Li, C. M., Yong, Y. C., & Zhu, Z. (2021). Wastewater-powered high-value chemical synthesis in a hybrid bioelectrochemical system. *Sci.*, *24*(12), 103401. https://doi.org/10.1016/j.isci.2021.103401

Yasemi, S., Khalili, Y., Sanati, A., & Bagheri, M. (2023). Carbon Capture and Storage: Application in the Oil and Gas Industry. *Sustainab.*, *15*, 14486. https://doi.org/10.3390/su151914486

Yu, X., Catanescu, C. O., Bird, R. E., Satagopan, S., Baum, Z. J., Lotti Diaz, L. M., & Zhou, Q. A. (2023). Trends in Research and Development for CO_2 Capture and Sequestration. *ACS Omega*, *8*(13), 11643–11664. https://doi.org/10.1021/acsomega.2c05070

Zhang, B., Shi, S., Tang, R., Qiao, C., Yang, M., You, Z., Shao, S., Wu, D., Yu, H., Zhang, J., Cao, Y., Li, F., & Song, H. (2023). Recent advances in enrichment, isolation, and bio-electrochemical activity evaluation of exoelectrogenic microorganism. *Biotechnol. Adv.*, *66*, 108175. https://doi.org/10.1016/j.biotechadv.2023.108175

Zhang, J., Wang, T., Zhang, Y., Lu, P., Shi, N., Zhu, W., Cai, C., & He, N. (2022). "Soft integration of a neural cells network and bionic interfaces". *Front. Bioengin. Biotechnol.*, *10*, 950235. https://doi.org/10.3389/fbioe.2022.950235