Ali Akbar[1], *Abhilekha Sharma*[2], *Abhirup Mitra*[3,4], *Richa Saxena*[5]*, *Dipti Bharti*[6], *Richa Sharma*[7]

[1]Departmentof Applied Science & Humanities,Government Engineering College, Jehanabad, Bihar,India, [2] Departmentof Applied Science & Humanities, JIMS Engineering Management Technical Campus, Greater Noida, India, [3]Department of Agriculture, Invertis University, Bareilly, U.P.,India, [4]Department of Food Process Engineering, NIT Rourkela, Odisha, India, [5]Department of Biotechnology, Invertis University, Bareilly, U.P.,India, [6]Departmentof Applied Science & Humanities, Darbhanga College of Engineering, Darbhanga, Bihar, India, [7]Department of Microbiology, Mahatma Gandhi University of Medical Sciences and Technology, India.

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Novel strategies in carbon capture and utilization: A chemical perspective

ABSTRACT

The escalating threat of climate change demands innovative approaches to mitigate carbon emissions, and Carbon Capture and Utilization (CCU) has emerged as a promising paradigm. The article begins with an overview of the current carbon emission landscape, underscoring the critical role of CCU in climate change mitigation. Catalysts play a pivotal role in CCU, and the review discusses cutting-edge developments in catalytic materials and design, offering mechanistic insights into catalyzed reactions. Biological strategies, such as bioenergy with carbon capture and storage (BECCS) and microbial carbon capture, are explored alongside genetic engineering for enhanced carbon assimilation. Life cycle assessment and techno-economic analysis are scrutinized to evaluate the environmental and economic aspects of CCU. It concludes with a forward-looking perspective, outlining future prospects and research directions in CCU. This review aims to provide a valuable resource for researchers, policymakers, and industry professionals working towards a sustainable and low-carbon future.

Keywords: *Sustainable chemistry; electrochemical reduction; industrial carbon utilization; nanotechnology in CCU*

1. INTRODUCTION

The contemporary era, the escalating specter of climate change, driven by the unremitting surge in global carbon dioxide (CO_2) emissions, has propelled environmental sustainability to the forefront of global discourse [1].

Amidst this exigency, Carbon Capture and Utilization (CCU) emerges as a beacon of promise, providing a multifaceted strategy to not only mitigate the impacts of climate change but also ingeniously repurpose CO_2 as a valuable resource. This review embarks on an exhaustive exploration of the chemical intricacies and innovative strategies that underscore the evolving landscape of CCU. The urgency of addressing climate change necessitates a comprehensive understanding of the intricate mechanisms involved in the capture and subsequent utilization of carbon.

*Corresponding author: Richa Saxena
E-mail: saxena.richa50@gmail.com
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At the chemical forefront of CCU, absorption and adsorption techniques play a pivotal role [2,3]. These methods, leveraging solvents, solid absorbents, as well as porous materials and molecular sieves, form the bedrock for capturing CO_2 emissions from a spectrum of sources, including industrial processes and power generation [4,5]. The review meticulously dissects these techniques, providing insights into their mechanisms and applications. Moreover, it delves into the realm of chemical reactions driving CO_2 capture, extending the discourse beyond traditional amine-based processes to explore advanced and nuanced methodologies.

Catalysis emerges as a cornerstone in the chemical transformation of captured carbon, steering the conversion of CO_2 towards valuable end products [6]. The review embarks on an in-depth exploration of catalytic research, shedding light on cutting-edge materials, innovative designs, and mechanistic insights that fuel the efficiency of carbon utilization processes. This section illuminates the dynamic interplay between catalyst development and the expanding landscape of applications, ranging from sustainable fuels to high-value chemicals. Simultaneously, electrochemical approaches represent a vanguard in CCU, offering a sustainable pathway for CO_2 conversion. The intricate exploration of electrochemical reduction mechanisms and advances in electrocatalysis underscores the transformative potential of renewable energy integration in CCU strategies.

The chemical perspective extends its embrace into the realm of biology, where living organisms become instrumental in carbon capture and utilization. Bioenergy with carbon capture and storage (BECCS) and microbial carbon capture present bio-inspired solutions, showcasing the marriage of biological processes with chemical ingenuity.

Biological processes for carbon assimilation play a pivotal role in the carbon capture and utilization (CCU) landscape. Photosynthetic organisms, such as microalgae and cyanobacteria, are among the most efficient natural systems for carbon fixation, converting atmospheric CO_2_22 into organic compounds through the Calvin-Benson-Bassham cycle. These microorganisms can be engineered to enhance their carbon capture efficiency, optimize growth rates, and produce valuable bio-based products, such as biofuels, bioplastics, and other high-value chemicals.

Additionally, non-photosynthetic microbial systems, such as chemoautotrophic bacteria, utilize CO_2_22 as a carbon source through pathways like the reductive acetyl-CoA pathway and the 3-hydroxypropionate bicycle. Advances in synthetic biology have enabled the reprogramming of these organisms to integrate novel pathways and improve carbon assimilation capabilities. These biological processes complement chemical and electrochemical approaches, offering sustainable, scalable, and economically viable solutions for mitigating carbon emissions and addressing global climate challenges.

As CCU technologies continue to advance, the review navigates through emerging trends that hold the promise of enhancing efficiency and expanding the scope of carbon utilization [7,8]. Membrane-based separation processes and nanotechnology applications represent frontiers that have the potential to revolutionize the efficiency and selectivity of CCU processes. Among technologies for carbon assimilation, **artificial photosynthesis systems** mimic natural photosynthesis to convert CO_2_22 into energy-rich compounds using light as an energy source. Similarly, **bioelectrochemical systems**, such as microbial electrosynthesis, utilize electrogenic microorganisms to fix CO_2_22 into organic molecules, leveraging renewable electricity to drive the process.

Moreover, **enzyme-based catalysis** employs highly specific enzymes, such as carbonic anhydrase, to facilitate CO_2_22 conversion with exceptional selectivity and lower energy demands. Hydrogenotrophic microbial systems, which utilize hydrogen gas as an energy source, are also emerging as efficient methods to convert CO_2_22 into value-added chemicals.

Concurrently, life cycle assessment and techno-economic analysis provide critical lenses through which the environmental and economic viability of these CCU strategies are scrutinized, adding depth to our understanding of the broader impact of these technologies. These diverse approaches showcase the versatility of carbon assimilation technologies and their potential to transform CCU into a cornerstone of sustainable industrial practices [9].

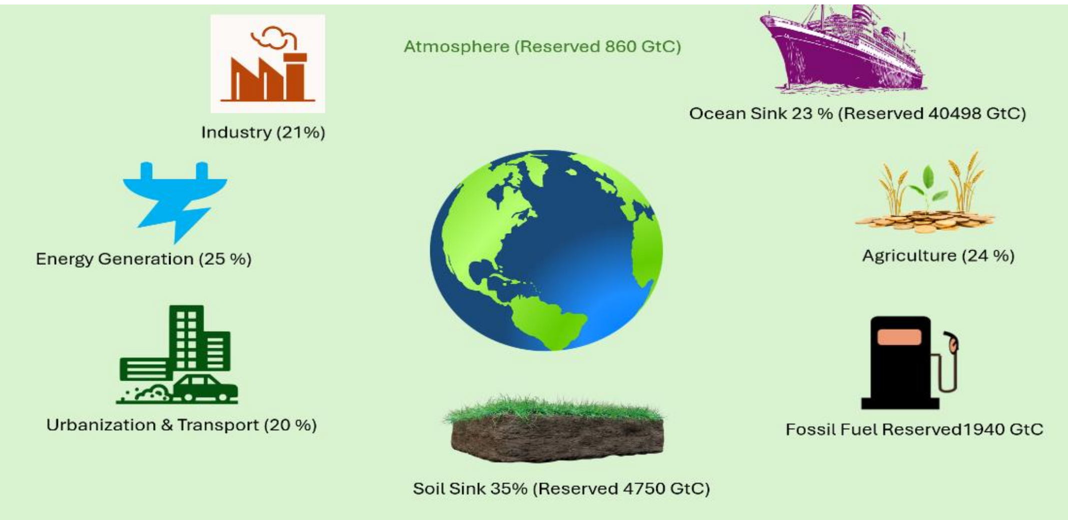

Figure 1. Schematic diagram of carbon cycle, Gigatonnes of carbon (GtC) represents the reserved carbons [80]

Yet, navigating the landscape of CCU is not solely a scientific endeavor; it is entwined with intricate policy and regulatory frameworks that shape its implementation. This review illuminates global initiatives, governmental incentives, and regulatory challenges, highlighting the complex interplay between technological innovation and the socio-political landscape. Real-world case studies drawn from industrial applications offer tangible insights into the successes, challenges, and potential scalability of CCU technologies, underscoring the need for a harmonious integration of technology and policy.

2. INTRODUCTION TO CARBON CAPTURE AND UTILIZATION (CCU):

In the contemporary epoch, the burgeoning challenge of climate change stands as an urgent and omnipresent global concern. The main culprit behind this predicament is the unabated release of carbon dioxide (CO_2) into the atmosphere, primarily from anthropogenic activities such as industrial processes and the burning of fossil fuels [10,11] As atmospheric CO_2 concentrations reach unprecedented levels, the repercussions for global climate patterns, sea levels, and biodiversity become increasingly profound.

Overview of the Current State of Carbon Emissions:

To appreciate the imperative of Carbon Capture and Utilization (CCU), it is essential to understand the current state of carbon emissions. As of the latest assessments, global CO_2 emissions continue to surge, with an ever-expanding industrial landscape and escalating energy demands contributing to this upward trajectory [12]. The repercussions of this unabated release of CO_2 extend beyond mere environmental concerns; they pose a direct threat to the delicate equilibrium of Earth's climate systems. The rise in average global temperatures, changes in precipitation patterns, and the intensification of extreme weather events serve as tangible manifestations of the burgeoning climate crisis.

Industrial activities, including energy production, manufacturing, and transportation, remain major contributors to the escalating carbon emissions. Fossil fuel combustion, a mainstay in the global energy mix, releases vast amounts of CO_2, amplifying the greenhouse effect and propelling climate change [13]. This stark reality necessitates a paradigm shift in our approach to carbon management — one that extends beyond emissions reduction to include innovative strategies for actively removing and repurposing CO_2 from the atmosphere.

Importance of CCU in Mitigating Climate Change:

In this context, Carbon Capture and Utilization (CCU) emerges as a compelling and multifaceted strategy to address the dual challenge of reducing emissions and actively mitigating the impact of existing atmospheric CO_2. Unlike traditional carbon capture and storage (CCS) methods that focus solely on sequestering CO_2 underground, CCU introduces a transformative approach by converting captured CO_2 into valuable products, thus turning a greenhouse gas into a resource [14,15].

The significance of CCU in the broader climate change mitigation landscape lies in its potential to break the linear link between economic growth and carbon emissions. By capturing CO_2 emissions at their source and converting them into usable products, CCU provides a pathway for industries to decouple their growth from environmental degradation. This not only aligns with sustainability goals but also fosters a circular carbon economy where carbon is treated as a valuable commodity rather than a waste product [16].

Furthermore, CCU offers a pragmatic solution to the intermittency challenge of renewable energy sources. As the world transitions to a low-carbon energy system, the intermittent nature of renewable energy generation poses challenges for meeting constant energy demands. CCU can act as a complementary strategy by providing a means to store excess renewable energy in the form of converted carbon-based products, creating a more resilient and adaptable energy infrastructure.

3. CHEMICAL MECHANISMS OF CARBON CAPTURE:

The pursuit of effective carbon capture strategies is at the forefront of efforts to mitigate anthropogenic carbon dioxide (CO_2) emissions [17]. Understanding the chemical mechanisms underlying carbon capture is pivotal for developing efficient and scalable technologies. This section explores the diverse chemical pathways employed in carbon capture, encompassing absorption techniques, adsorption methods, and a spectrum of chemical reactions designed for CO_2 capture [18]. The Carbon Capture and Utilization (Figure 1) represents a comprehensive overview of the stages involved in capturing and utilizing carbon dioxide (CO_2) to mitigate anthropogenic emissions. The diagram outlines key steps and chemical pathways crucial for developing efficient and scalable carbon capture technologies.

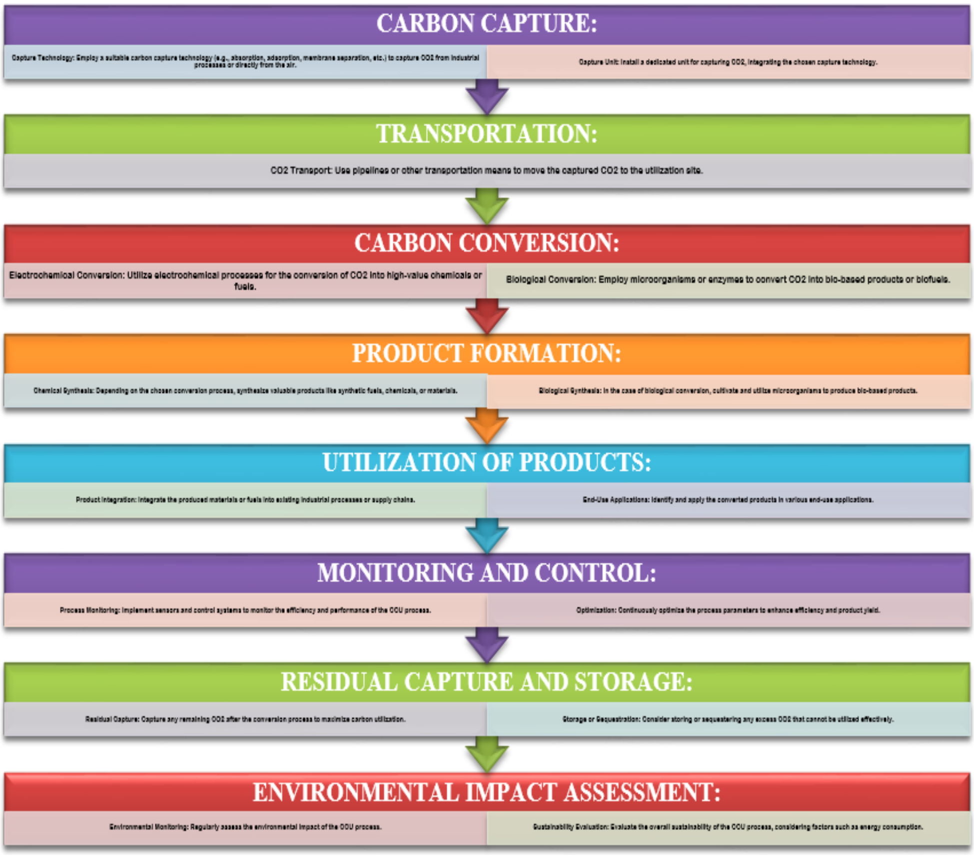

Figure 2. Pathways to sustainability: carbon capture and utilization process flow

Absorption Techniques:

Solvent-Based Absorption: Solvent-based absorption is a cornerstone of traditional carbon capture methods. In this approach, flue gases rich in CO_2 are brought into contact with a liquid solvent that selectively captures and binds with CO_2 [19]. Commonly used solvents include amines, which form stable compounds with CO_2. The resultant solution can then be processed to release the captured CO_2 for storage or utilization [20]. While effective, challenges such as solvent degradation and energy-intensive regeneration processes have prompted ongoing research into innovative solvent systems.

Solid Absorbents: Advancements in absorption techniques have led to the exploration of solid absorbents as alternatives to liquid solvents. Porous materials, such as metal-organic frameworks (MOFs) and zeolites, exhibit high surface areas and tunable chemical properties, making them effective candidates for CO_2 capture [21]. These materials adsorb CO_2 through physical and chemical interactions, and their regenerability makes them promising for repeated use. The development of novel solid absorbents with enhanced selectivity and capacity is a focal point for researchers seeking to improve the efficiency of absorption-based carbon cap.

Adsorption Methods:

Porous Materials: Adsorption methods rely on porous materials with a high affinity for CO_2 molecules. Porous materials, including activated carbons and zeolites, provide a structured environment where CO_2 molecules can adhere to the surface [22]. The porous nature of these materials facilitates high adsorption capacities, and their selectivity for CO_2 over other gases is finely tuned through material design. Advances in nanoporous materials and the synthesis of designer adsorbents contribute to the evolution of adsorption-based carbon capture technologies.

Molecular Sieves: Molecular sieves are crystalline materials with well-defined pores that selectively adsorb molecules based on size and shape. Tailoring molecular sieves for CO_2 adsorption involves precise control over pore size and functionalization. This adsorption method offers advantages in terms of scalability, stability, and regenerability [23, 24]. The exploration of novel molecular sieve architectures and the incorporation of sustainable materials enhance the efficacy of molecular sieve-based carbon capture.

Chemical Reactions for CO_2 Capture:

Amine-Based Processes: Chemical reactions provide an avenue for capturing CO_2 by forming stable chemical compounds. Amine-based processes involve the reaction of CO_2 with amines to produce stable carbamate compounds [25]. These reactions typically occur in liquid solvents and can be reversible through controlled changes in temperature or pressure. While widely employed, challenges such as energy-intensive regeneration and solvent degradation have spurred research into improving the efficiency and sustainability of amine-based carbon capture.

Beyond Amine-Based Processes: Innovations in chemical reactions for CO_2 capture extend beyond traditional amine-based processes [26, 27]. Researchers are exploring alternative reaction pathways, including the use of switchable solvents, metal-based catalysts, and hybrid approaches that combine chemical reactions with physical adsorption. These endeavors aim to overcome the limitations of conventional processes, such as high energy requirements and material degradation, opening avenues for more sustainable and economically viable carbon capture solutions [28].

In summary, the chemical mechanisms of carbon capture encompass a rich array of techniques ranging from traditional solvent-based methods to emerging adsorption strategies and innovative chemical reactions. Ongoing research in this realm seeks to enhance the efficiency, sustainability, and scalability of carbon capture technologies, addressing the imperative of reducing CO_2 emissions in the face of global climate challenges.

Innovative Catalysts for CO_2 Conversion:

The quest for sustainable solutions to mitigate carbon dioxide (CO_2) emissions has spurred intensive research into innovative catalysts for CO_2 conversion [29]. This section delves into cutting-edge developments in catalytic materials, novel catalyst design, and synthesis methods, along with the mechanistic insights thatunderpincatalyzed reactions aimed at transforming CO_2 into valuable products. (Figure 2) provides a detailed exploration of cutting-edge developments in catalytic materials, novel catalyst design, synthesis methods, and the mechanistic insights that form the foundation of catalyzed reactions aiming to transform CO_2 into valuable products.

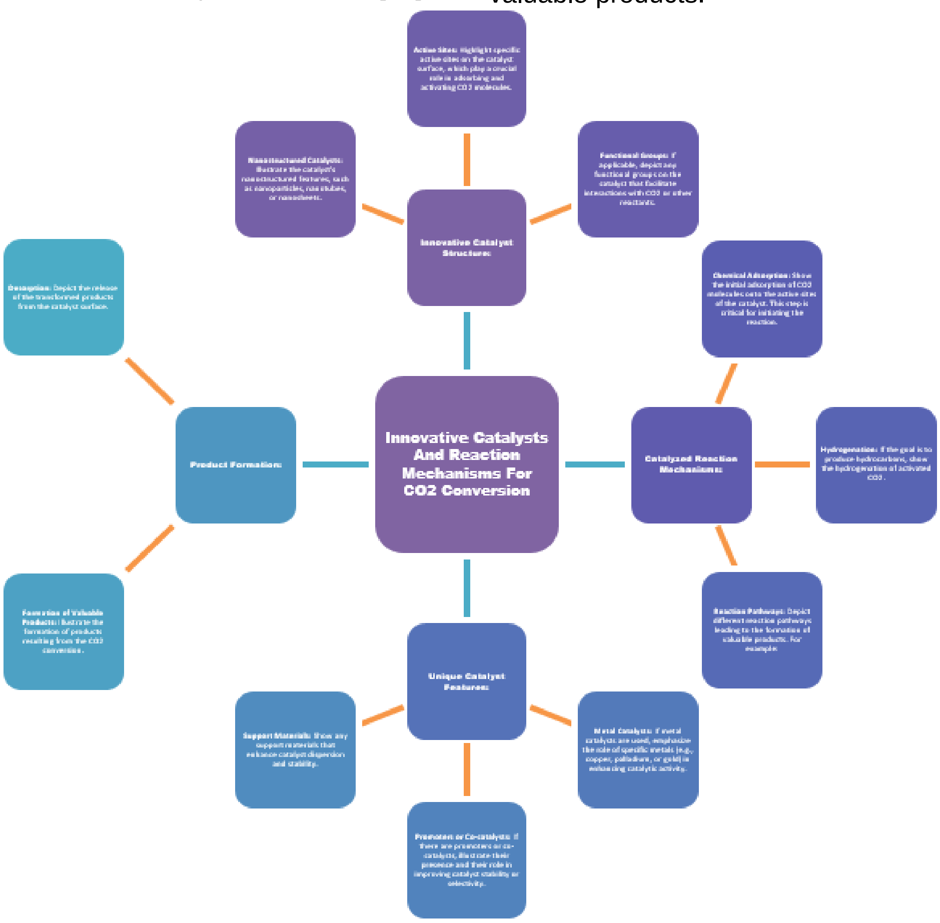

Figure 3. Advancements in Catalytic CO_2 Conversion: A Visual Exploration of Innovative Catalysts and Reaction Mechanisms

Catalytic Materials for CO_2 Reduction:

Catalysts in CO_2 Reduction: The catalytic reduction of CO_2 involves the transformation of carbon dioxide into compounds with higher value, such as fuels or chemicals, through chemical reactions. Catalysts play a central role in facilitating these reactions by lowering the activation energy and providing reaction pathways that lead to desired products [30]. Traditional catalysts include metals like copper, silver, and gold, but recent advancements extend to a diverse range of materials, including metal oxides, nanoparticles, and complex nanostructured materials. These innovative catalysts exhibit enhanced activity, selectivity, and stability in CO_2 conversion processes.

Integration of Nanomaterials: Nanomaterials, characterized by their unique properties at the nanoscale, have gained prominence in CO_2 reduction catalysis. Nanocatalysts offer high surface areas, tunable reactivity, and unique electronic structures, all of which contribute to their exceptional catalytic performance. Materials such as metal nanoparticles, metal-organic frameworks (MOFs), and carbon-based nanomaterials have demonstrated remarkable efficacy in driving CO_2 reduction reactions [31]. The tailored design of nanocatalysts allows for precise control over catalytic activity, enabling the optimization of product selectivity.

Novel Catalyst Design and Synthesis:

Tailoring Catalysts for Specific Reactions:

The design of catalysts for CO_2 conversion is evolving towards tailoring materials for specific reactions, aiming to maximize the production of desired products. Rational catalyst design involves a deep understanding of the reaction mechanisms and the identification of active sites on the catalyst surface. Computational methods, such as density functional theory (DFT), aid in predicting catalytic performance and guiding the design of catalysts with enhanced reactivity [32]. The integration of machine learning algorithms further accelerates the discovery of novel catalysts by analyzing vast datasets of material properties and catalytic performance.

Synthesis Methods and Scalability:

Innovative catalyst design is coupled with advanced synthesis methods that enable the fabrication of catalytic materials with controlled structures and compositions. Techniques such as sol-gel, co-precipitation, and chemical vapor deposition facilitate the synthesis of nanoscale catalysts with tailored properties. Scalability is a crucial consideration, and efforts are underway to develop synthesis approaches that are not only efficient in the laboratory but also amenable to large-scale production for industrial applications [33]. Continuous-flow synthesis and template-assisted methods exemplify strides toward scalable catalyst fabrication.

Mechanistic Insights into Catalyzed Reactions:

Probing Reaction Mechanisms: A profound understanding of the mechanistic intricacies of catalyzed reactions is essential for optimizing catalyst performance. Mechanistic studies involve characterizing intermediate species, reaction pathways, and the role of various catalyst components during CO_2 conversion [34]. Advanced spectroscopic and imaging techniques, such as in-situ X-ray absorption spectroscopy and operando microscopy, provide real-time insights into catalyst behavior under reaction conditions. These studies deepen our comprehension of the complex interplay of factors influencing catalytic activity and guide the refinement of catalyst design.

Dynamic Reaction Kinetics: Mechanistic insights extend to dynamic reaction kinetics, unraveling the temporal evolution of catalyzed reactions. Kinetic studies elucidate the rate-determining steps, reaction intermediates, and the influence of reaction conditions on overall performance [35]. This knowledge enables the optimization of reaction parameters to enhance reaction rates and selectivity, crucial for the practical implementation of catalytic processes.

4. ELECTROCHEMICAL APPROACHES IN CARBON CAPTURE AND UTILIZATION (CCU):

The realm of electrochemical approaches in Carbon Capture and Utilization (CCU) represents a frontier where innovative technologies converge to address the dual challenges of reducing carbon dioxide (CO_2) emissions and harnessing renewable energy sources [36]. This section explores the electrochemical reduction of CO_2, recent advances in electrocatalysis for CO_2 conversion, and the pivotal integration of renewable energy sources in electrochemical CCU.

Electrochemical Reduction of CO_2:

Fundamentals of Electrochemical Reduction:

Electrochemical reduction involves the use of an external electrical potential to drive the conversion of CO_2 into value-added products. This approach offers a versatile and selective means to transform CO_2 into various chemical compounds, including hydrocarbons, alcohols, and formic acid. At the heart of the electrochemical reduction process are electrodes, typically composed of metals or other conductive materials, thatcatalyze the reduction reactions. The ability to tailor reaction conditions, electrode materials, and catalysts contributes to the flexibility and efficiency of electrochemical CO_2 conversion.

Selectivity and Product Diversity: One of the distinguishing features of electrochemical CO_2 reduction is the ability to control the selectivity of the reaction [37]. Through careful design of electrode materials and catalytic surfaces, researchers can steer the electrochemical process towards the production of specific products. Fine-tuning the reaction conditions allows for the generation of a diverse range of chemical compounds, providing opportunities for the synthesis of fuels, chemicals, and intermediates with high economic value.

Advances in Electrocatalysis for CO_2 Conversion:

Catalytic Enhancements for Improved Efficiency:

Electrocatalysis plays a pivotal role in dictating the efficiency and selectivity of CO_2 conversion. Advances in electrocatalysis aim to overcome the inherent challenges associated with sluggish kinetics and competing side reactions [38]. Catalyst design involves the development of materials with tailored properties, such as high surface area, active sites, and enhanced stability. Noble metals, metal oxides, and complex nanostructured materials are among the evolving repertoire of electrocatalysts that demonstrate improved performance in driving CO_2 conversion reactions.

Single-Atom and Nanoparticle Catalysts: Recent breakthroughs in electrocatalysis include the exploration of single-atom catalysts and nanocatalysts. Single-atom catalysts exhibit exceptional catalytic activity due to their precisely defined active sites, while nanocatalysts leverage the unique properties of nanoparticles to enhance reactivity [39]. These advancements contribute to the quest for catalysts that are not only highly efficient but also economically viable and sustainable for large-scale implementation.

Integration of Renewable Energy Sources in Electrochemical CCU:

Symbiosis with Renewable Energy:

An integral aspect of sustainable electrochemical CCU is the integration of renewable energy sources to power the electrochemical reduction of CO_2. By leveraging electricity generated from renewable sources such as solar or wind, electrochemical processes can operate with a significantly reduced carbon footprint [40]. The intermittent nature of renewable energy sources is addressed through smart system design and energy storage solutions, ensuring a continuous and reliable power supply for electrochemical CO_2 reduction.

Electrolyzer Technologies: Renewable energy integration is closely tied to the development of efficient and scalable electrolyzer technologies. Electrolyzers facilitate the electrochemical splitting of water into hydrogen and oxygen, with the generated hydrogen serving as a valuable reducing agent in CO_2 conversion. Proton-exchange membrane (PEM) electrolyzers and solid oxide electrolyzers are key technologies that continue to evolve, enhancing the overall efficiency and feasibility of renewable energy-integrated electrochemical CCU [41].

5. BIOLOGICAL STRATEGIES FOR CARBON CAPTURE AND UTILIZATION

Harnessing biological processes for Carbon Capture and Utilization (CCU) introduces an innovative and sustainable approach to mitigate carbon dioxide (CO_2) emissions[42]. This section explores three key biological strategies: Bioenergy with Carbon Capture and Storage (BECCS), Microbial Carbon Capture and Utilization, and Genetic Engineering for Enhanced Carbon Assimilation.

Table 1. Electrochemical Approaches in Carbon Capture and Utilization (CCU): Examples

Electrochemical Approach	Description
Electrochemical Reduction of CO_2	Utilizing electrical energy to convert CO_2 into value-added chemicals or fuels such as methane, ethylene, ethanol, etc.
Carbon Capture via Electrochemical Processes	Electrochemically capturing CO_2 from industrial flue gases or ambient air using specialized electrodes or membranes.
Electrochemical Conversion of CO_2 to Carbonates	Converting CO_2 into stable carbonates through electrochemical reactions, which can be used in various industrial processes or as raw materials.
Direct Air Capture (DAC)	Utilizing electrochemical methods to directly capture CO_2 from the atmosphere, offering potential solutions for combating climate change.
Electrochemical Reduction of Carbonates	Reversing the process of carbonate formation through electrochemical means, potentially releasing CO_2 for further utilization or sequestration.
Electrochemical Conversion of CO_2 into Value-added Chemicals	Generating high-value chemicals like formic acid, carbon monoxide, or syngas from electrochemical reduction of CO2, offering sustainable alternatives to conventional synthesis routes.
Electrocatalytic Conversion of CO_2	Using electrocatalysts to enhance the efficiency and selectivity of CO_2 conversion reactions, enabling more sustainable production processes.

Bioenergy with Carbon Capture and Storage (BECCS):

Overview of BECCS: Bioenergy with Carbon Capture and Storage (BECCS) is a comprehensive strategy that integrates bioenergy production with carbon capture and storage technologies [43]. It involves the cultivation of biomass, such as energy crops or forestry residues, which absorb CO_2 during their growth. The biomass is then used for bioenergy production through processes like combustion or gasification. The resulting CO_2 emissions are captured and stored, preventing their release into the atmosphere. BECCS thus achieves negative emissions by actively removing CO2 from the air.

Sustainable Energy Generation: BECCS not only contributes to carbon capture but also addresses energy needs in a sustainable manner. By relying on renewable biomass resources, BECCS mitigates the use of fossil fuels, reducing overall greenhouse gas emissions [44]. The captured CO_2 can be stored underground or utilized in various industrial processes, contributing to the circular carbon economy.

Microbial Carbon Capture and Utilization:

Harnessing Microorganisms for Carbon Capture: Microbial carbon capture and utilization leverage the metabolic activities of microorganisms, such as bacteria and algae, to capture and convert CO_2 into valuable products. Algae, for instance, are adept at photosynthesis, where they absorb CO_2 and convert it into organic compounds in the presence of sunlight. Similarly, certain bacteria can fix carbon by assimilating CO_2 into their biomass.

Bioproducts and Bioremediation:

Microbial CCU holds promise for the production of bioproducts, such as biofuels, bioplastics, and biochemical [9]. Additionally, some microorganisms possess the ability to enhance soil fertility through the release of organic compounds, contributing to sustainable agriculture practices. Microbial carbon capture not only facilitates CO_2 removal but also offers a pathway to create valuable bio-based materials.

Genetic Engineering for Enhanced Carbon Assimilation:

Tailoring Organisms for Carbon Assimilation: Genetic engineering empowers scientists to tailor the genetic makeup of organisms to enhance their capacity for carbon assimilation. This involves modifying key metabolic pathways to optimize carbon fixation and utilization [45]. For instance, researchers are exploring ways to enhance the photosynthetic efficiency of plants or algae, allowing them to capture more CO_2 and convert it into biomass.

Synthetic Biology Approaches: Synthetic biology techniques enable the design of custom genetic circuits and pathways that optimize carbon assimilation in microorganisms [46]. This includes introducing novel enzymes or modifying existing ones to enhance their efficiency in fixing carbon. The aim is to create engineered organisms that can serve as efficient carbon sinks or be employed in biotechnological processes for carbon utilization.

6. EMERGING TRENDS IN CARBON CAPTURE TECHNOLOGIES:

The evolving landscape of carbon capture technologies is marked by innovative approaches that extend beyond traditional methods. This section explores three prominent emerging trends: Membrane-based separation processes, Nanotechnology applications in Carbon Capture and Utilization (CCU), and the Integration of CCU with industrial processes [47]. The (Table 1) provides a concise overview of various carbon capture technologies, their descriptions, and key advancements, offering a comparative perspective on their development.

Table 2. Advancements in Carbon Capture Technologies: A Comparative Overview

Carbon Capture Technology	Description	Advantages	Challenges
Absorption	Involves the use of solvents to absorb CO2 from flue gases or other sources.	- Mature technology - High capture efficiency - Applicable to various industries	- High energy consumption - Solvent degradation - Large footprint
Adsorption	Relies on solid sorbents to adsorb CO_2 molecules from gas streams.	- Can operate at ambient conditions - Potential for regeneration and reuse of sorbents - Suitable for low CO_2 concentration streams	- Limited sorbent capacity - Costly regeneration processes - Susceptible to impurities

Membrane Separation	Utilizes semi-permeable membranes to selectively separate CO_2 from gas mixtures.	- Energy-efficient - Compact and modular design - Scalable for various applications	- Limited by membrane selectivity - Vulnerable to fouling and degradation - Capital-intensive
Cryogenic Separation	Involves cooling gas mixtures to very low temperatures to separate CO_2 as a solid or liquid.	- High purity CO_2 capture - Well-established technology - Effective for high-pressure streams	- High energy consumption - Complex and expensive equipment - Requires large infrastructure
Direct Air Capture	Captures CO_2 directly from ambient air using chemical reactions or absorbents.	- Potential for carbon-negative emissions - Independent of CO_2 sources - Suitable for decentralized deployment	- Energy-intensive - Costly compared to point source capture - Limited by air CO_2 concentration

Membrane-Based Separation Processes:

Overview of Membrane-Based Carbon Capture: Membrane-based separation processes represent a paradigm shift in carbon capture, providing a more energy-efficient and economically viable alternative to traditional methods. Membrane technologies involve the use of selectively permeable membranes that allow the separation of CO_2 from other gases. These membranes can be designed to selectively transport CO_2, enabling its capture while allowing the passage of other gases [48]. This approach is particularly promising for point-source emissions, such as those from industrial facilities and power plants.

Advantages of Membrane-Based Capture:

Membrane-based carbon capture offers several advantages, including lower energy requirements, reduced footprint, and modular scalability. By sidestepping the need for energy-intensive solvent regeneration or adsorbent replacement, membrane technologies contribute to more sustainable and cost-effective carbon capture. Ongoing research focuses on developing high-performance membranes with enhanced selectivity and durability, thereby optimizing their application in diverse industrial settings.

Nanotechnology Applications in CCU:

Nanoparticles and Nanostructured Materials:

Nanotechnology presents innovative solutions for enhancing the efficiency and selectivity of carbon capture and utilization processes. Nanoparticles and nanostructured materials exhibit unique properties that can be harnessed for CO_2 adsorption, catalysis, and the design of advanced materials [49]. Metal-organic frameworks (MOFs), nanocatalysts, and engineered nanoparticles are examples of nanomaterials that hold promise for improving the performance of CCU technologies.

Nanoscale Catalysis for CO_2 Conversion:

Nanotechnology applications in CCU extend to catalysis, where nanocatalysts facilitate the conversion of captured CO_2 into valuable products [50]. The high surface area and tunable properties of nanocatalysts enable precise control over reaction pathways and product selectivity. Additionally, the integration of nanocatalysts with electrode materials in electrochemical CCU enhances overall efficiency. This convergence of nanotechnology and CCU represents a frontier for developing sustainable and economically viable carbon transformation processes.

Integration of CCU with Industrial Processes:

Symbiotic Integration of CCU:

The integration of CCU with industrial processes exemplifies a holistic and symbiotic approach to carbon management. Rather than treating CO_2 as a waste product, industries are exploring ways to incorporate CCU into their operations, thereby converting CO_2 into valuable resources [51]. This integration not only reduces the environmental impact of industrial activities but also creates a circular economy where carbon becomes a feedstock for the production of fuels, chemicals, and materials.

Combined Heat and Power (CHP) Systems:

The integration of CCU with Combined Heat and Power (CHP) systems exemplifies the synergy between carbon capture and energy generation [52,53]. CHP systems, which simultaneously produce electricity and useful heat, can utilize captured CO_2 in various processes. This integration enhances the overall energy efficiency of industrial operations while providing an avenue for sustainable carbon utilization.

These emerging trends in carbon capture technologies signify a dynamic shift toward more efficient, sustainable, and integrated approaches. Membrane-based separation processes offer a breakthrough in energy-efficient carbon capture, nanotechnology applications enhance the precision and effectiveness of CCU processes, and the integration of CCU with industrial processes exemplifies a synergistic approach toward a circular carbon economy. These trends underscore the ongoing efforts to revolutionize carbon capture and utilization, contributing to the imperative of mitigating climate change while fostering sustainable industrial practices.

7. LIFE CYCLE ASSESSMENT AND TECHNO-ECONOMIC ANALYSIS IN CARBON CAPTURE AND UTILIZATION (CCU):

The deployment of Carbon Capture and Utilization (CCU) technologies necessitates a comprehensive evaluation of both its environmental impact and economic feasibility. Life Cycle Assessment (LCA) and Techno-Economic Analysis (TEA) are two crucial methodologies employed to scrutinize these aspects [54,55]. This section explores the role of LCA and TEA in the context of CCU processes, highlighting their significance in assessing environmental impacts, economic feasibility, and making comparisons with traditional Carbon Capture and Storage (CCS).

Environmental Impact Assessment through Life Cycle Assessment (LCA):

LCA Methodology:

Life Cycle Assessment (LCA) is a holistic approach that evaluates the environmental impact of a product or process throughout its entire life cycle — from raw material extraction and manufacturing to use and disposal. In the context of CCU processes, LCA plays a pivotal role in quantifying the carbon footprint and identifying potential environmental hotspots associated with each stage of the process [56]. This includes assessing impacts on climate change, resource depletion, ecosystem quality, and human health.

Environmental Benefits and Trade-offs:

LCA enables a nuanced understanding of the environmental benefits and trade-offs associated with CCU. While CCU processes aim to mitigate CO_2 emissions by converting them into valuable products, LCA helps to quantify the net reduction in greenhouse gas emissions and assess other potential environmental impacts. Additionally, LCA can highlight areas for improvement and guide the optimization of CCU technologies to minimize their overall environmental footprint [57].

Economic Feasibility and Challenges through Techno-Economic Analysis (TEA):

TEA Methodology:

Techno-Economic Analysis (TEA) assesses the economic feasibility of a technology or process by evaluating the costs and benefits throughout its life cycle [58]. In the context of CCU, TEA considers factors such as capital and operating costs, revenue generation from products, and the overall economic viability of the technology. TEA helps stakeholders, including investors and policymakers, make informed decisions by quantifying the financial implications of implementing CCU processes.

Economic Challenges and Uncertainties:

TEA identifies economic challenges and uncertainties associated with CCU, helping stakeholders navigate potential risks [59]. Economic challenges may include the initial high capital costs of implementing CCU technologies, uncertainties in product markets, and fluctuations in energy prices. By incorporating sensitivity analyses and scenario assessments, TEA provides insights into the robustness of CCU processes under varying economic conditions.

Comparison with Traditional Carbon Capture and Storage (CCS):

Environmental and Economic Contrasts:

LCA and TEA facilitate a comprehensive comparison between CCU and traditional Carbon Capture and Storage (CCS). While both approaches aim to mitigate CO_2 emissions, they differ in their end goals and outputs [60]. CCU focuses on converting captured CO_2 into valuable products, contributing to a circular carbon economy, whereas CCS primarily involves the capture and storage of CO_2 underground [61]. LCA and TEA assist in evaluating the environmental and economic contrasts between these approaches, considering factors such as energy requirements, economic viability, and the potential for revenue generation from CCU-derived products.

Policy and Market Dynamics:

The comparison between CCU and CCS is influenced by policy frameworks, market dynamics, and societal preferences. LCA and TEA provide valuable insights into how each approach aligns with sustainability goals, regulatory frameworks, and economic incentives [57]. Assessing the environmental and economic performance of CCU and CCS helps inform policy decisions and industry strategies in the pursuit of a low-carbon future.

The integration of Life Cycle Assessment and Techno-Economic Analysis provides a comprehensive framework for evaluating the environmental and economic dimensions of Carbon Capture and Utilization processes [54,60]. These methodologies contribute crucial insights to enhance the sustainability and economic viability of CCU technologies, fostering informed decision-making in the transition towards a carbon-neutral and circular economy [62,63]. Additionally, the comparison with traditional Carbon Capture and Storage offers valuable perspectives on the relative merits and challenges of different carbon mitigation approaches.

8. POLICY AND REGULATORY LANDSCAPE IN CARBON CAPTURE AND UTILIZATION (CCU)

The policy and regulatory landscape plays a pivotal role in shaping the implementation and success of Carbon Capture and Utilization (CCU) technologies [64,65]. This section explores key aspects of the global initiatives, government incentives, and regulatory challenges in the field of CCU, along with potential solutions.

Global Initiatives and Agreements:

Paris Agreement and Climate Targets:

The Paris Agreement, a landmark international accord, sets the framework for global efforts to combat climate change [66]. Within this agreement, countries have committed to limiting global temperature increases to well below2 degrees Celsius above pre-industrial levels. CCU aligns with the goals of the Paris Agreement by providing a means to actively reduce and repurpose carbon dioxide emissions. International collaborations and initiatives under the Paris Agreement serve as catalysts for advancing CCU technologies on a global scale.

Mission Innovation and Breakthrough Energy:

Mission Innovation, a global initiative, brings together countries committed to doubling their investments in clean energy research and innovation [67]. CCU technologies fall within the purview of these investments, aiming to accelerate the development and deployment of breakthrough solutions. Complementary to this, initiatives like Breakthrough Energy Ventures, a private investment fund led by Bill Gates, focus on supporting and scaling innovations, including those in CCU, to address climate challenges.

Government Incentives for CCU Implementation:

Financial Incentives and Funding Programs:

Governments worldwide are instituting financial incentives and funding programs to stimulate the implementation of CCU technologies. This includes grants, subsidies, and tax credits to incentivize research, development, and commercial deployment of CCU projects [68]. Financial support fosters collaboration between industry and research institutions, encouraging innovation and the integration of CCU into existing industrial processes.

Carbon Pricing Mechanisms:

Carbon pricing, through mechanisms like carbon taxes or cap-and-trade systems, can create economic incentives for industries to adopt CCU [69,70]. By assigning a cost to carbon emissions, governments provide a financial motive for industries to invest in technologies that capture and utilize CO_2 [71]. This economic signal aligns market forces with environmental goals, driving the adoption of CCU as part of broader carbon mitigation strategies.Recent government initiatives for carbon capture and utilization (CCU) demonstrate a global commitment to advancing these technologies. In the United States, the Department of Energy allocated $3.5 billion under the Bipartisan Infrastructure Law to establish Regional Direct Air Capture Hubs, aiming to scale CO_2_22 removal solutions. Similarly, India’s NITIAayog launched a comprehensive CCUS Policy Framework, emphasizing innovative financing mechanisms like clean energy cesses and bonds, and promoting sector-specific CO_2_22 storage hubs for industries such as cement and steel. Incentives like the Production-Linked Incentive (PLI) scheme further encourage low-carbon product development. Meanwhile, the European Union supports projects like the Rotterdam CCS Cluster, integrating industrial CCU solutions for large-scale implementation.

Regulatory Challenges and Potential Solutions:

Uncertain Regulatory Frameworks:

One of the challenges in the regulatory landscape for CCU is the uncertainty surrounding standards and regulations. As CCU technologies evolve, regulatory frameworks may lag behind, posing challenges for permitting and compliance. Clear and adaptive regulatory guidelines are essential to provide a stable environment for industry stakeholders and to ensure that CCU technologies are deployed efficiently.

Cross-Border Regulatory Harmonization:

CCU projects often involve cross-border collaborations and the transport of captured CO_2 for utilization or storage [72]. Regulatory differences between regions can create barriers to the development of international CCU projects. Efforts to harmonize regulations and establish international standards can facilitate the smooth implementation of CCU technologies on a global scale.

Stakeholder Engagement and Public Perception:

CCU projects may face regulatory hurdles associated with stakeholder engagement and public perception. Transparency, effective communication, and public engagement are crucial for building trust and addressing concerns related to safety, environmental impact, and the socio-economic implications of CCU projects [73]. Regulatory frameworks that incorporate meaningful stakeholder participation can contribute to the social license needed for successful CCU deployment.

9. CASE STUDIES AND INDUSTRIAL APPLICATIONS OF CARBON CAPTURE AND UTILIZATION (CCU) TECHNOLOGIES:

Success Stories in CCU Implementations:

Carbon Cure Technologies (Concrete Industry):

Carbon Cure Technologies has successfully implemented CCU in the concrete industry. By injecting recycled CO_2 into the concrete mix during production, they not only reduce the carbon footprint of concrete but also enhance its strength [74]. This innovative approach has been adopted by numerous concrete producers globally, demonstrating the commercial viability of CCU in construction materials.

Carbon Clean Solutions (Industrial Emissions): Carbon Clean Solutions has developed and implemented CCU technologies for capturing CO_2 emissions from industrial processes. Their modular carbon capture units are designed to be cost-effective and scalable, making them suitable for integration into various industries. This approach has been demonstrated in applications such as natural gas processing and biogas upgrading.

Challenges Faced by Industries in Adopting CCU

High Capital Costs and Initial Investments:

One of the major challenges faced by industries in adopting CCU technologies is the high capital cost associated with the installation of carbon capture infrastructure [75]. The initial investments required for implementing CCU projects can be a barrier for industries, especially for small and medium-sized enterprises. Addressing this challenge often requires supportive government policies, incentives, and financial mechanisms to ease the burden on businesses.

Market and Product Acceptance:

The successful implementation of CCU is contingent on market demand for products derived from captured CO_2. Industries may face challenges in creating a market for CCU-derived products, especially when competing with traditional alternatives. Building consumer awareness and acceptance is crucial for establishing the market viability of CCU products.

Lessons Learned from Real-World Applications:

Integration with Existing Processes:

Real-world applications highlight the importance of integrating CCU technologies seamlessly into existing industrial processes. Retrofitting existing facilities to accommodate carbon capture units requires careful planning and engineering to ensure minimal disruption to ongoing operations [76]. Lessons learned emphasize the need for a comprehensive understanding of the host process and collaboration between technology providers and industrial stakeholders.

Sustainability Metrics and Reporting: CCU projects often involve sustainability goals beyond carbon capture, such as resource efficiency and circular economy principles. Lessons learned underscore the importance of developing robust metrics and reporting mechanisms to track and communicate the broader environmental and social impacts of CCU implementations. Transparent reporting enhances stakeholder engagement and facilitates compliance with sustainability standards.

Collaboration and Knowledge Sharing: Successful CCU implementations often involve collaboration between industry players, research institutions, and technology providers. Lessons learned emphasize the value of knowledge sharing, collaboration on research and development, and the creation of industry-specific networks. This collaborative approach accelerates the learning curve, fosters innovation, and facilitates the scale-up of CCU technologies.

10. FUTURE PROSPECTS AND RESEARCH DIRECTIONS IN CARBON CAPTURE AND UTILIZATION (CCU):

Technological Advancements on the Horizon:

Advanced Materials and Catalysts: Future prospects in CCU involve the development of advanced materials and catalysts with enhanced selectivity, stability, and efficiency. Innovations in materials science, such as the design of novel nanomaterials and catalysts, will play a critical role in improving the performance of CCU processes [77]. This includes the exploration of new classes of materials and the optimization of existing ones for enhanced CO_2 capture, conversion, and utilization.

Electrochemical and Photocatalytic Technologies:

Technological advancements are expected in the realm of electrochemical and photocatalytic technologies for CO_2 reduction. Improvements in electrode materials, catalyst design, and reactor configurations will contribute to the efficiency and scalability of electrochemical CCU. Similarly, developments in photocatalysis, driven by renewable energy sources, hold promise for sustainable and energy-efficient CO_2 conversion.

Key Challenges and Opportunities for Further Research:

Scalability and Integration with Industrial Processes: One of the key challenges is to enhance the scalability of CCU technologies and their seamless integration with existing industrial processes. Research in this direction should address the engineering and logistical aspects of scaling up CCU, considering factors such as continuous operation, modular design, and compatibility with diverse industrial settings.

Economic Viability and Market Adoption: Research needs to focus on improving the economic viability of CCU technologies to ensure their widespread adoption. This includes cost reduction strategies, optimization of energy consumption, and the development of market-driven incentives. Understanding and overcoming the barriers to market adoption, such as creating demand for CCU-derived products, will be crucial for the success of these technologies.

Sustainability Assessment Beyond Carbon Footprint: While CCU primarily addresses carbon mitigation, future research should expand the sustainability assessment to include broader environmental, social, and economic dimensions. Life cycle assessments should encompass a comprehensive evaluation of the environmental impact of CCU processes, considering factors such as resource use, ecosystem impact, and social implications.

The Role of CCU in a Sustainable Future:

Circular Carbon Economy and Resource Efficiency: CCU plays a pivotal role in transitioning towards a circular carbon economy, where carbon is considered a valuable resource rather than a waste product [78]. Research should further explore how CCU can contribute to resource efficiency, circularity, and the creation of closed-loop systems within various industries.

Integration with Renewable Energy Sources: The integration of CCU with renewable energy sources is critical for achieving a sustainable future. Future research should explore synergies between CCU and renewable energy technologies, including the use of excess renewable energy for electrochemical CO_2 reduction and the development of integrated systems that combine CCU with renewable energy production.

Policy Frameworks and International Collaboration: To unlock the full potential of CCU, there is a need for supportive policy frameworks and international collaboration. Research should contribute to the development of policies that incentivize CCU adoption, streamline regulatory processes, and foster collaboration between governments, industries, and research institutions on a global scale [79].

In summary, the future of CCU is marked by exciting technological advancements, ongoing research to address challenges, and a crucial role in contributing to a sustainable future. The interdisciplinary nature of CCU research, spanning chemistry, materials science, engineering, and policy studies, underscores the need for collaborative efforts to drive innovation and bring about transformative changes in the way we approach carbon management.

11. CONCLUSION

In the exploration of Carbon Capture and Utilization (CCU), key findings reveal a dynamic landscape marked by technological advancements, successful implementations, challenges, and the pivotal role of policy frameworks. The synthesis of information yields critical insights that shape the path forward for CCU.

Key Findings:

Technological Advancements: The field of CCU is witnessing significant strides in technological advancements, particularly in materials science, catalysis, and electrochemical and photocatalytic processes. Innovations in advanced materials and catalysts are poised to enhance the efficiency and selectivity of CO_2 capture and conversion.

Successful Implementations: Success stories from companies like CarbonCure Technologies and Carbon Clean Solutions demonstrate the practical application of CCU across diverse industries, including concrete production and industrial emissions reduction. These implementations underscore the commercial viability of CCU technologies.

Challenges and Opportunities: Challenges faced by industries include high capital costs, market acceptance, and uncertainties in regulatory frameworks. Opportunities lie in addressing these challenges through financial incentives, market creation, and adaptive regulatory approaches. The circular carbon economy and resource efficiency present promising avenues for further research.

Policy and Regulatory Landscape: Global initiatives, such as the Paris Agreement and Mission Innovation, provide a framework for international collaboration. Government incentives, including financial support and carbon pricing mechanisms, play a crucial role in driving CCU adoption. Regulatory challenges, including uncertain frameworks and cross-border harmonization, require attention for the seamless deployment of CCU technologies.

Recommendations for Future Research and Development:

Advanced Materials and Catalysts: Future research should focus on the development of advanced materials and catalysts with improved properties for CO_2 capture and conversion. This includes exploring nanomaterials, innovative catalyst designs, and scalable synthesis methods.

Scalability and Integration: Addressing the challenge of scalability is critical for the widespread adoption of CCU. Research should emphasize engineering solutions that enhance scalability and seamless integration with diverse industrial processes.

Economic Viability: Research should target strategies for improving the economic viability of CCU technologies. This includes cost reduction measures, optimization of energy consumption, and creating market demand for CCU-derived products.

Sustainability Assessment: Expand the scope of sustainability assessments beyond carbon footprints. Research should encompass comprehensive evaluations of the environmental, social, and economic impacts of CCU processes.

Circular Carbon Economy: Further exploration is needed on how CCU can contribute to the development of a circular carbon economy, promoting resource efficiency and closed-loop systems within various industries.

Renewable Energy Integration: Investigate synergies between CCU and renewable energy sources. This includes utilizing excess renewable energy for electrochemical CO_2 reduction and developing integrated systems that combine CCU with renewable energy production.

Policy Frameworks: Research should contribute to the development of supportive policy frameworks that incentivize CCU adoption. This includes streamlining regulatory processes, fostering international collaboration, and aligning policies with sustainability goals.

In conclusion, the future of CCU is dynamic and holds immense potential for contributing to a sustainable and low-carbon future. The recommendations for future research and development outlined here provide a roadmap for harnessing this potential, addressing challenges, and advancing CCU technologies towards broader adoption and impact. The collaborative efforts of researchers, industry stakeholders, and policy makers are essential in realizing the transformative potential of CCU for mitigating climate change and creating a more sustainable industrial landscape.

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IZVOD

NOVE STRATEGIJE U UPOTREBI I KORIŠĆENJU UGLJENIKA: HEMIJSKA PERSPEKTIVA

Sve veća pretnja od klimatskih promena zahteva inovativne pristupe za ublažavanje emisija ugljenika, a hvatanje i korišćenje ugljenika (CCU) se pojavilo kao paradigma koja obećava. Članak počinje pregledom trenutnog pejzaža emisije ugljenika, naglašavajući kritičnu ulogu CCU u ublažavanju klimatskih promena. Katalizatori igraju ključnu ulogu u CCU, a pregled razmatra najsavremenije razvoje u katalitičkim materijalima i dizajnu, nudeći mehaničke uvide u katalizovane reakcije. Biološke strategije, kao što su bioenergija sa hvatanjem i skladištenjem ugljenika (BECCS) i mikrobno hvatanje ugljenika, istražuju se zajedno sa genetskim inženjeringom za poboljšanu asimilaciju ugljenika. Procena životnog ciklusa i tehno-ekonomska analiza se ispituju da bi se procenili ekološki i ekonomski aspekti CCU. Završava se perspektivom koja je okrenuta budućnosti, izlažući buduće izglede i pravce istraživanja u CCU. Ovaj pregled ima za cilj da pruži vredan resurs za istraživače, kreatore politike i profesionalce iz industrije koji rade na održivoj budućnosti sa niskim sadržajem ugljenika.

Ključne reči: *održiva hemija; elektrohemijska redukcija; Industrijsko korišćenje ugljenika; nanotehnologija u CCU.*

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Ali Akbar: https://orcid.org/0009-0002-9155-7308
Abhilekha Sharma: https://orcid.org/0000-0003-0153-1340
Abhirup Mitra: https://orcid.org/0000-0002-2696-7223
Richa Saxena: https://orcid.org/0000-0002-9229-9235
Dipti Bharti: https://orcid.org/0000-0001-5658-2749
Richa Sharma: https://orcid.org/0000-0001-9747-0700