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ELECTROCHEMICAL TRANSFORMATION OF CAPTURED CARBON DIOXIDE INTO SUSTAINABLE FUELS AND CHEMICALS: LEVERAGING KC8 TECHNOLOGY FOR ADVANCED CO_2 CAPTURE AND UTILIZATION

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Abstract

The rapid increase in atmospheric carbon dioxide (CO_2) concentrations due to anthropogenic activities is a major contributor to climate change and environmental degradation, prompting urgent efforts to develop efficient carbon capture and utilization (CCU) technologies. This research investigates a pioneering integrated system that combines the novel use of potassium graphite (KC8) for highly effective CO_2 capture with an advanced electrochemical conversion process to synthesize sustainable fuels and valuable chemicals. KC8, with its exceptional electron-donating properties and strong chemical affinity for CO_2, enables efficient and selective carbon capture at ambient temperatures and pressures, overcoming many of the limitations faced by traditional carbon capture materials. Once captured, the CO_2 is electrochemically reduced in a specialized reactor designed to optimize reaction kinetics and product selectivity, leading to the generation of critical renewable energy carriers such as syngas, formic acid, and methanol. Experimental results demonstrate that the KC8-assisted capture significantly enhances the Faradaic efficiency of the electrochemical process, lowers the overall energy input required for CO_2 conversion, and improves the selectivity toward desired fuel and chemical products compared to conventional electrolysis systems. This dual-stage approach not only provides a viable method for mitigating greenhouse gas emissions but also promotes a circular carbon economy by transforming captured CO_2, a major environmental pollutant, into commercially viable and environmentally friendly products. The findings indicate that the integration of KC8 capture technology with electrochemical conversion presents a scalable, cost-effective, and energy-efficient pathway toward sustainable carbon management and renewable fuel production. Furthermore, this approach aligns with global efforts to achieve net-zero emissions *targets and offers a promising platform for future research in the field of sustainable energy and environmental technology. The study contributes valuable insights into the design of next-generation CCU systems and highlights the critical role of advanced materials in enabling efficient electrochemical CO_2 utilization for climate mitigation and green chemistry.*

INTRODUCTION

The dramatic and continuous rise in atmospheric carbon dioxide (CO_2) concentrations over the past century has emerged as a defining characteristic of the Anthropocene era. This increase is predominantly attributed to human-induced activities, including the extensive combustion of fossil fuels for energy production, large-scale deforestation that reduces natural carbon sinks, and various industrial processes such as cement manufacturing and chemical production. As a chemically stable and long-lived greenhouse gas, CO_2 remains in the atmosphere for centuries, where it traps heat and drives the radiative forcing responsible for global climate change. Current scientific assessments indicate that CO_2 alone accounts for over 75% of total anthropogenic greenhouse gas (GHG) emissions, making it the most critical target for mitigation efforts [1]. The Intergovernmental Panel on Climate Change (IPCC), in its comprehensive assessment reports, has repeatedly emphasized the urgency of implementing aggressive mitigation strategies to reduce CO_2 emissions. It warns that to avoid the most catastrophic effects of climate change ranging from sea level rise and extreme weather events to ecosystem collapse global temperature rise must be limited to below 1.5°C relative to pre-industrial levels. Achieving this ambitious target necessitates not only rapid decarbonization of energy systems but also the widespread deployment of negative emission technologies (NETs) capable of removing CO_2 from the atmosphere. Among the portfolio of NETs, Carbon Capture and Utilization (CCU) stands out as a highly promising approach that addresses both the need to reduce emissions and the opportunity to recycle waste carbon into economically valuable products. CCU encompasses a range of strategies that involve capturing CO_2 from industrial flue gases or directly from the atmosphere and converting it into useful fuels, chemicals, and materials [2]. This process not only prevents CO_2 from entering the atmosphere but also enables its valorization effectively transforming a climate liability into a resource. Within this paradigm, electrochemical CO_2 reduction (ECR) has emerged as an especially attractive pathway due to its ability to operate under ambient conditions using electricity, ideally sourced from renewable energy, thus minimizing the carbon footprint of the entire system. ECR facilitates the transformation of CO_2 into a variety of high-value chemical products, including carbon monoxide (CO), formic acid (HCOOH), methanol (CH_3OH), and synthesis gas (a mixture of CO and H_2). These products serve as critical intermediates in the energy and chemical sectors, with applications in fuel cells, polymer production, and synthetic fuel manufacturing [3]. Despite the conceptual appeal and environmental advantages of ECR, its practical implementation faces several technological hurdles. These include the inherently low solubility of CO_2 in aqueous and non-aqueous electrolytes, which limits the available reactant concentration at the catalyst surface; poor selectivity toward desired products, leading to energy losses and separation challenges; high overpotentials required to activate the CO_2 molecule, resulting in elevated energy consumption; and the difficulty of effectively integrating CO_2 capture with conversion systems in a seamless, cost-efficient manner.

To address these multifaceted challenges, the development of multifunctional materials that can both capture and activate CO_2 in situ has become an area of intense research interest. One such material is potassium graphite, or KC8, a stage-1 graphite intercalation compound known for its exceptional electron-donating capacity and high reactivity with electrophilic species such as CO_2. KC8 possesses a unique layered structure in which potassium atoms are intercalated between graphite layers, endowing the material with a high density of mobile electrons

[4]. This structure enables KC8 to interact strongly and selectively with CO_2 molecules, facilitating their capture even at low partial pressures typically encountered in post-combustion flue gases or ambient air. Moreover, the electron-rich environment provided by KC8 aids in the activation of the CO_2 molecule, lowering the energy barrier for subsequent electrochemical reduction. When incorporated into an electrochemical system, KC8 offers the potential to streamline the transition from capture to conversion, effectively serving as both a sorbent and a facilitator of charge transfer. Its high surface reactivity and ability to deliver electrons directly to adsorbed CO_2 species make it a compelling candidate for integrated CCU applications. The combination of efficient capture, enhanced electron availability, and compatibility with existing electrochemical platforms positions KC8 as a transformative material in the emerging field of carbon-neutral fuel and chemical synthesis. To contextualize its performance, **Table 1** presents a comparative analysis of KC8 and other commonly used CO_2 capture materials based on key parameters such as capture efficiency, operational conditions, integration potential, and cost. The data underscore KC8's unique advantage in terms of ambient operation and high integration potential with electrochemical systems, making it a highly viable option for next-generation CCU platforms.

Table 1: Comparison of Common CO_2 Capture Materials [5].

Material	**Capture Efficiency (%)**	**Operating Conditions**	**Integration Potential**	**Cost (USD/kg)**
Amine-based Solvents	85–95	40–60°C	Low	1.5–2.5
Metal-Organic Frameworks (MOFs)	70–90	< 100°C	Medium	10–15
Zeolites	60–80	Ambient	Medium	5–7
KC8 (Potassium Graphite)	>95	Ambient	High	~4.5

The incorporation of the carbon dioxide (CO_2) capture using potassium graphite (KC 8) with electrochemical conversion is also a breakthrough in terms of developing and planning effective Carbon Capture and Utilization (CCU) structures. In comparison to the previous methods in which CO_2 capture and the further conversion are performed in different devices, which frequently involve several processing steps, purification intermediates and high-energy environment, the KC8-based system provides a simplified, two-purpose platform. This integration would basically remodel the framework of any CCU systems due to the possibility to both capture and convert in close vicinity or even at the same time, therefore decreasing the complexity of the complete process, since a much lesser amount of external energy and materials would be used. This is also a major benefit of this combined process because it removes unnecessary downstream components and inter-stage processing equipment. By integrating the capture medium and the electrochemical converter in a single platform, the KC8-based solution not only decreases the physical space of the establishment, but also decrease both capital and operating costs. The streamlined system design makes systems more efficient and helps automate them and reduce potential areas of failure which helps to entail the high level of system dependability as well as long-term scalability [6]. The second, no less significant advantage of such multi-component integrated system is the improvement of the electrochemical performance parameters, primarily, the Faradaic efficiency. Faradaic efficiency is a measure of how effectively electrical current is used to drive the desired chemical reaction in this case, the reduction of CO_2 into value-added products. The strong interaction between KC8 and CO_2 at the molecular level leads to improved CO_2 availability at the catalytic interface. This close proximity between the capture medium and electrocatalyst minimizes mass transport limitations and enables more efficient electron transfer, resulting in higher product selectivity and overall conversion rates. Furthermore, the electron-rich environment facilitated by KC8 can help lower the activation energy required for CO_2 reduction, thereby reducing overpotentials and improving energy utilization. A third critical advantage stems from the operational simplicity of the system. Traditional CO_2 capture technologies often require high-temperature regeneration steps or the use of corrosive solvents, both of which impose significant energy demands. In contrast, KC8 exhibits exceptional capture capabilities under ambient temperature and pressure conditions, aligning well with the operational requirements of electrochemical cells. This compatibility allows the whole set of the capture to conversion to take place under low and environmentally friendly conditions. Consequently, the KC8-integrated system shows less energy consumption, less dispensable effect to the environment, and less maintenance related expenditure, which altogether improves the sustainability and economy of one implementing it in large-scale version. To visualize the functionality and flow of this integrated platform, **Figure 1** provides a schematic representation of the KC8-based CO_2 capture and electrochemical conversion system. The figure illustrates the sequential stages of operation: the initial adsorption of CO_2 from a gaseous stream onto the surface of KC8, followed by the electrochemical reduction of the captured CO_2 within a custom-designed reactor cell. Arrows and annotations highlight the movement of electrons, the transport of CO_2 molecules, and the generation of valuable chemical products such as formic acid, methanol, and syngas. This schematic underscores the elegance and efficiency of the integrated approach and serves as a conceptual model for future innovations in CCU technology.

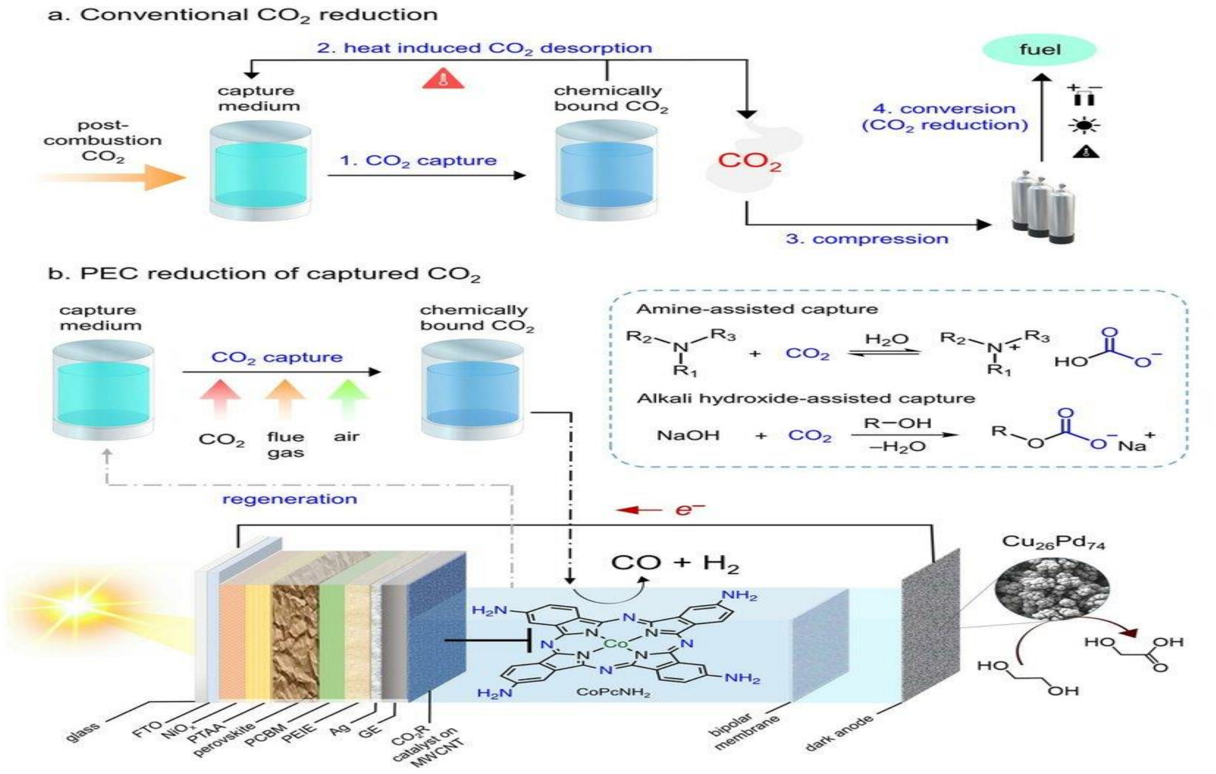

Figure 1: Schematic Overview of CO_2 Capture and Electrochemical Conversion System [7].

This study presents a novel dual-functional platform that combines KC8-enabled CO_2 capture with a custom-designed electrochemical reactor capable of converting the captured CO_2 into sustainable fuels and chemicals. The system is evaluated for capture efficiency, conversion rate, product selectivity, and energy consumption. The outcomes of this research demonstrate that KC8 can bridge the gap between capture and utilization, offering a transformative solution in the fight against climate change. This work lays a foundation for scalable CCU systems and contributes valuable insights into the integration of advanced carbon materials in sustainable energy applications.

2- Research Objective:

The intensifying urgency to mitigate the impacts of climate change, coupled with the need to transition towards sustainable energy and industrial systems, has directed global research efforts toward innovative solutions for carbon dioxide (CO_2) management. Among various climate mitigation strategies, Carbon Capture and Utilization (CCU) has emerged as a promising and pragmatic approach that not only prevents the emission of CO_2 into the atmosphere but also enables its transformation into useful and marketable products. This double advantage boosts the sustainable nature of the environment and also helps to create a circular carbon economy. In this context, incorporation of more advanced materials that have the ability to combine the harboring and enabling electrochemical conversion of CO 2 is an important direction to pursue. The need to develop an innovative, energy-efficient, and scaled up CCU platform, which uses an intercalation compound with outstanding electron donating capabilities as CO 2 capture medium, namely potassium graphite (KC8) and electrochemical transformation facilitator, makes the research possible. The central aim is to create an integrated system that operates under ambient conditions and can effectively convert captured CO_2 into high-value fuels and chemicals such as carbon monoxide (CO), formic acid (HCOOH), methanol (CH_3OH), and synthesis gas (CO + H_2), all of which are essential feedstocks for various energy and industrial processes.

The detailed research objectives of this study are as follows:

1. **To thoroughly evaluate the CO_2 capture potential of KC8 under realistic conditions:**

This includes an in-depth study of the adsorption characteristics, surface chemistry, and thermodynamic properties of KC8 when exposed to controlled CO_2 atmospheres. Parameters such as capture capacity, selectivity against competing gases (e.g., N_2, O_2), and sorption kinetics will be quantified to determine KC8's suitability for continuous and cyclic capture processes.

2. **To design, synthesize, and characterize a KC8-integrated electrochemical conversion platform:**

This objective focuses on engineering a seamless interface between KC8-based CO_2 capture and an electrochemical reactor. The study will involve the construction of a lab-scale electrochemical cell, optimization of electrode materials, and development of protocols for the direct or facilitated transfer of CO_2 from the KC8 matrix to the catalytic surface for reduction reactions.

3. **To investigate the electrochemical performance of the integrated KC8 system:**

Electrochemical tests will be conducted to evaluate parameters such as current density, onset potential, Faradaic efficiency, product distribution, and energy input. The goal is to determine the effectiveness of the KC8 system in enhancing the electrochemical conversion of CO_2 into specific products under various applied potentials and electrolyte conditions.

4. **To assess the operational synergy between CO_2 capture and conversion stages within the integrated platform:**

By eliminating the traditional separation between CO_2 capture and utilization units, this study will explore how a combined approach improves process efficiency, minimizes energy losses, and enhances system compactness. This involves dynamic performance testing, stability analysis over multiple cycles, and evaluation of mass and electron transfer mechanisms within the hybrid system.

5. **To conduct a techno-economic and environmental impact assessment of the KC8-based CCU technology:**

Beyond laboratory-scale experimentation, this research aims to model the potential for industrial-scale implementation. Life cycle analysis (LCA), economic cost modeling, and sensitivity analysis will be performed to evaluate the practicality and sustainability of deploying KC8-based systems in sectors such as power generation, cement production, and chemical manufacturing.

6. **To contribute to the fundamental understanding of material-based CO_2 activation and conversion:**

The study seeks to uncover new insights into the role of electron-rich materials like KC8 in mediating CO_2 electroreduction. Particular attention will be paid to the interaction mechanisms at the molecular level, the influence of intercalated species on reaction kinetics, and the potential for tailoring KC8's structure to optimize performance.

By addressing these comprehensive objectives, the research aspires to advance the scientific and technological frontier of CCU systems. It aims to bridge the gap between carbon capture and its electrochemical utilization through the development of a cohesive, material-integrated process. The findings of this study are expected to inform future research, guide industrial applications, and support policy frameworks aimed at achieving carbon neutrality.

3- Comparative Assessment of CO_2 Capture Technologies:

Reducing the carbon intensity of power generation and implementing effective CO_2 capture technologies are critical components of global climate mitigation strategies. Carbon capture methods can generally be classified into post-combustion and pre-combustion processes. Post-combustion capture involves the removal of CO_2 from flue gas streams after combustion, making it particularly suitable for retrofitting existing fossil-fuel-based power plants. In contrast, pre-combustion strategies focus on minimizing emissions at the fuel conversion stage, such as in integrated gasification combined cycle (IGCC) systems and oxy-fuel combustion, which uses purified oxygen to produce a CO_2-rich exhaust stream suitable for capture. Recent techno-economic analyses suggest that to significantly reduce electricity costs while improving overall energy efficiency, the deployment of energy-intensive CO_2 capture systems is indispensable. The choice of capture technology for any given industrial application is largely influenced by the CO_2 source characteristics and the specifics of the industrial process. For instance, petrochemical facilities tend to emit high-concentration CO_2 streams, which are less energy-intensive to capture, whereas power plants emit more dilute CO_2, requiring greater energy input for effective separation. Nonetheless, power generation remains the single largest source of global CO_2 emissions, thus presenting a critical area for capture technology deployment [8]. In this context, supercritical CO_2 (sCO_2) cycles have garnered attention for their ability to improve the thermodynamic efficiency of power systems. These processes utilize CO_2 in a supercritical state as a working fluid, significantly enhancing the energy efficiency of turbines compared to traditional steam cycles. Empirical studies have demonstrated that employing CO_2 instead of oil-based fluids improves turbine performance; however, this approach requires purified oxygen, increasing system complexity and cost. Additionally, both gaseous and liquid CO_2 recirculation strategies are under investigation. Liquid CO_2 undergoes cryogenic treatment, and while technologically viable, it remains energy-intensive. Given that power plants contribute nearly 45% of global CO_2 emissions, they represent a substantial opportunity for the implementation of carbon capture, utilization, and storage (CCUS) systems [9]. Commercial deployment has already begun in sectors such as natural gas and chemical manufacturing, where high-purity CO_2 streams are prevalent. Post-combustion technologies, in particular, have demonstrated economic feasibility and scalability. For example, SaskPower's Boundary Dam project, a 110 MW coal-fired power station in Canada, successfully implemented post-combustion CO_2 capture at an industrial scale. Under optimized conditions, post-combustion capture systems can achieve capture costs as low as USD 56 per ton of CO_2, though this may incur an energy penalty of up to 62% in newly developed plants. A comparative analysis of CO_2 capture technologies is summarized in the table 2 below, highlighting their respective advantages and limitations in power generation contexts:

Table 2: Comparative Analysis of CO2 Capture Technologies [10].

Capture Method	Process Description	Advantages	Challenges
Post-Combustion	CO_2 removal from flue gas after combustion	Retrofit potential; mature technology	High energy cost; dilute CO_2 streams
Pre-Combustion	CO_2 capture before combustion via fuel gasification	Higher CO_2 concentration; integration potential	Complex plant design; costly pure oxygen requirement
Oxy-Fuel Combustion	Combustion with pure oxygen, producing CO_2-rich flue gas	High purity CO_2; easier separation	Requires oxygen production; expensive
Supercritical CO_2 Cycle	Power generation using CO_2 in supercritical state	High efficiency; compact system design	Requires purified oxygen; still in developmental stages
Cryogenic Separation	CO_2 liquefaction at low temperatures	High purity CO_2; suitable for storage	Energy-intensive; suited only for high-concentration streams

These developments underscore the dynamic evolution of CO_2 capture technologies and the ongoing search for systems that balance efficiency, scalability, and economic viability. As discussed in the following sections, advanced materials such as potassium graphite (KC_8) offer new possibilities to address the persistent limitations of conventional methods, enabling integrated capture-conversion strategies for sustainable power generation and carbon utilization. Figure 2 presents the various capture processes studied in both the industry and academia over the last few decades. These processes are further detailed in the next section of this study.

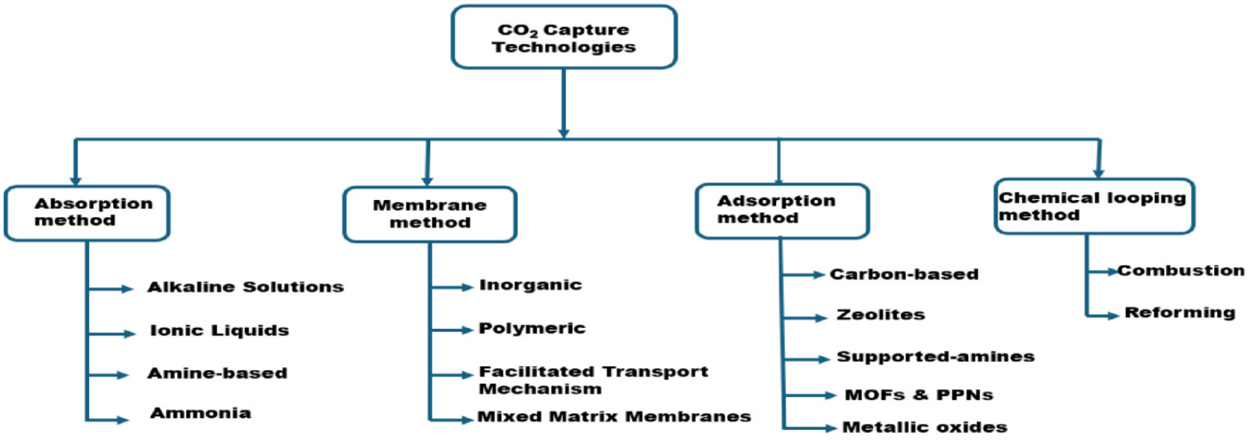

Figure 2: Different capture processes studied in both the industry and academia.

3.1- Absorption:

Absorption is among the most mature and widely implemented methods for capturing carbon dioxide from industrial and power generation emissions. It involves the transfer of CO_2 from a gas phase into a liquid solvent, where it is either chemically bound or physically dissolved. The process is particularly eminent in post combustion capture where the concentration of CO 2 is somewhat feeble and blended with other gases which include nitrogen, oxygen, and water vapor. Chemical absorption employs a solvent which will react with CO 2 to form an intermediate product, and the product can be reverted back when heated to produce concentrated CO 2 and recycle the solvent. Aqueous amines are by far the most popular choice of chemical solvent as they provide a high reactivity and an excellent absorption kinetics with deaerated monoethanolamine (MEA) being the standard of the industry. Various other containing amines like diethanolamine (DEA), methyldiethanolamine (MDEA) have also been adopted in order to deal with certain drawbacks of MEA like corrosion and volatility. The chemical absorption process usually functions in two phases, one is the absorber column, which is constituent of the flue gas coming in contact with the solvent and the CO 2 being chemically absorbed via the solvent and the second is the regenerative column, which is the constituent of the application of heat to dissociate the CO 2 of the solvent so that the solvent can be reused. Chemical absorption presents large disadvantages although the process has a fairly high efficiency in capturing CO 2 even at low concentrations. A high energy requirement to regenerate the solvent is one of the insurmountable problems and can pose up to 20 to 30 percent of the energy produced in a power plant energy penalty commonly known as [11]. Moreover, chemical solvents tend to degrade through oxidations and thermal degradations, which decreases their efficiency and raises the cost of operation as one has to replace the used solvents regularly. There is also the problem of process equipment corrosion by amine solvents and their degradation products which also introduces complications and maintenance costs. Moreover, the formation of heat-stable salts during absorption further impairs the solvent's capacity to capture CO_2 over multiple cycles. In contrast, physical absorption depends on the solubility of CO_2 in solvents without forming chemical bonds. This method is more suitable when CO_2 partial pressures are high, such as in pre-combustion capture scenarios or industrial processes emitting concentrated CO_2 streams. Common physical solvents include Selexol (a mixture of dimethyl ethers of polyethylene glycol) and Rectisol (cold methanol). These solvents dissolve CO_2 at elevated pressures and release it upon pressure reduction or mild heating, making regeneration less energy-intensive than chemical absorption. However, physical absorption is generally less effective at capturing CO_2 at low partial pressures, limiting its use in post-combustion capture applications where flue gas contains only about 10–15% CO_2. Research efforts continue to focus on enhancing the efficiency and sustainability of absorption technologies. New solvent formulations, such as amine blends that combine the strengths of multiple amines, aim to improve CO_2 loading capacity while reducing volatility and corrosiveness. Similarly, sterically hindered amines have been developed to increase solvent stability and decrease energy consumption during regeneration. Ionic liquids salts that are liquid at or near room temperature have also emerged as promising absorbents due to their negligible vapor pressure, high thermal stability, and tunable chemical properties. Despite their advantages, ionic liquids often suffer from high viscosity and cost, hindering large-scale adoption. Another innovative approach involves phase-change solvents, which separate into two liquid phases during the absorption or regeneration step, allowing for easier CO_2 separation and potentially reducing regeneration energy requirements. While these solvents show potential, their commercial readiness remains limited due to process complexity and scale-up challenges. The table 3 below provides a detailed comparison of the main absorption solvent types, summarizing their operating principles, benefits, and limitations:

Table 3: Comparison of Main Absorption Solvent Types [12].

Solvent Type	Examples	Operating Principle	Advantages	Challenges
Chemical Solvents	MEA, DEA, MDEA	React chemically with CO_2 to form reversible compounds	High CO_2 capture efficiency; well-established	High regeneration energy; solvent degradation; corrosion; heat-stable salts formation
Physical Solvents	Selexol, Rectisol	Dissolve CO_2 physically under high pressure	Lower energy for regeneration at high CO_2 partial pressures	Ineffective at low CO_2 concentrations; requires high-pressure operation
Amine Blends & Advanced Amines	Mixed amines, sterically hindered amines	Combine properties of multiple amines for improved	Improved thermal stability; reduced volatility	Higher cost; complex formulation; still under research

		performance		
Ionic Liquids	Various ionic liquid formulations	Dissolve CO_2 via physical and/or chemical interactions	Low vapor pressure; thermally stable; tunable	High viscosity; high cost; limited pilot testing
Phase-Change Solvents	Biphasic solvents	Separate into phases to facilitate easier CO_2 release	Potential energy savings during regeneration	Process complexity; limited commercial experience

Besides the improvement on solvents, process innovations are also essential in improving the absorption efficiency. Energy consumption can be reduced significantly when heat contributions between two components of an energy recovery system, e.g. the absorbent and stripper, are integrated e.g. preheating of incoming rich solvent by the heat of the solvent in the regen phase. More advanced regeneration methods even like vacuum stripping, membrane assisted regeneration and microwave heating are being researched so as to curtail the amount of thermal energy required and extend the life of solvents. Absorption is still an operational backbone of carbon capture technology in spite of these challenges and this is especially due to the scalability and retrofittable properties of the technology to the already existing power plants. The trade-off between efficiency, energy use, and costs of operation still drive further development and investigation. New solid-state and electrochemical technologies like the technology presented in this paper involving the use of potassium graphite (KC 8) have been proposed as very well potential methods that may solve some of the limitations inherent to the liquid-based absorption systems that incorporate both the capture and conversion steps into a single and energy efficient process.

3.2- Membrane Separation Processes:

Separation technologies that utilize membranes in CO 2 on the other hand are promising to replace other types of technologies because of their modularity, scalability, minimal impact on the global environment, and the ability to run continuously in some instances at the expense of chemical solvents. Membrane separation differs with absorption or adsorption processes where large thermal swings or pressure swings are necessitated to regenerate the separation medium, here, the separation is dependent on the differential transport of gas across a selective barrier to remove CO 2 from gas mixtures. The absence of phase change in these systems (that is, they are inherently efficient), as well as their compatibility with incorporation into a broad scope of industrial and power generation processes makes them applicable. Depending on the type of membranes, they usually function by the principles of solution-diffusion, molecular sieving or surface diffusion. These membranes are normally made of polymeric, inorganic or hybrid materials. In the solution-diffusion mechanism typical of polymeric membranes, gases are dissolved into membrane matrix and then diffuse through it according to their solubility, relative to their diffusivity. CO_2, due to its higher condensability and smaller molecular size relative to N_2 or O_2, permeates faster through many polymer materials, enabling selective separation. Polymeric membranes such as polysulfone, polyimide, and cellulose acetate are the most commercially mature. They offer advantages such as low cost, ease of fabrication, and acceptable permeability and selectivity for CO_2/N_2 separation. However, they often suffer from low thermal and chemical stability, plasticization under high CO_2 partial pressures, and a trade-off between permeability and selectivity known as the Robeson upper bound. This performance limitation has driven research into high-performance polymers and mixed-matrix membranes. Inorganic membranes, including zeolite, silica, carbon molecular sieves, and metal-organic frameworks (MOFs), offer superior thermal and chemical resistance, and in some cases, higher selectivity and permeance [13]. However, they are more expensive to fabricate and typically less flexible than polymeric options. Zeolite membranes, for example, utilize molecular sieving and surface diffusion mechanisms that allow CO_2 to preferentially permeate due to its smaller kinetic diameter and stronger interaction with the pore surfaces. Mixed-matrix membranes (MMMs) represent a hybrid approach, embedding inorganic fillers into a polymeric matrix to combine the high permeability/selectivity of inorganic materials with the processability of polymers. Recent advances in MMMs have demonstrated promising improvements in performance, but challenges remain in achieving uniform filler dispersion and strong interfacial compatibility between the matrix and filler to prevent non-selective gas leakage. Depending on the process configuration, membrane systems can operate in single-stage, multi-stage, or hybrid arrangements. For post-combustion capture, where CO_2 concentrations are low, multi-stage or hybrid systems (e.g., membrane-absorption or membrane-cryogenic combinations) are often required to achieve high CO_2 purity. Conversely, pre-combustion capture environments offer higher CO_2 partial pressures, making membranes more effective due to increased driving forces for permeation. The table 4 below summarizes the key types of membrane materials used for CO_2 separation, along with their core benefits and associated limitations:

Table 4: Types of Membrane Materials used for CO2 Separation.

Membrane Type	Material Examples	Operating Principle	Advantages	Limitations
Polymeric Membranes	Polyimide, polysulfone, cellulose acetate	Solution-diffusion	Low cost, scalable, easy to fabricate	Low thermal/chemical stability; plasticization; selectivity-permeability trade-off
Inorganic Membranes	Zeolite, silica, carbon molecular sieves	Molecular sieving/surface diffusion	High thermal/chemical resistance; good selectivity	Expensive; brittle; fabrication complexity
Mixed-Matrix Membranes	Polymers with MOFs, zeolites, or CNTs	Hybrid (solution-diffusion + sieving)	Enhanced selectivity/permeability; tailored performance	Dispersion, compatibility, and scalability issues
Facilitated Transport Membranes	Polymers with mobile carriers (e.g., amines)	CO_2-carrier binding and diffusion	High CO_2 selectivity at low partial pressures	Carrier degradation; limited long-term stability

Membrane processes offer a number of distinct advantages, including a compact footprint, no need for regenerable solvents, and potential for integration into existing infrastructures with lower capital costs. Additionally, their modular nature supports incremental scalability and easier maintenance. However, achieving the desired CO_2 recovery rates and purity levels particularly for flue gas applications often requires the use of multi-stage systems, compression equipment, or hybridization with other capture techniques, all of which can introduce energy penalties and cost complexity.

Emerging innovations in facilitated transport membranes, which incorporate chemical carriers that reversibly bind CO_2 and transport it across the membrane, have shown particular promise for enhancing separation performance under ambient conditions. These membranes are especially well-suited to post-combustion environments, though current limitations related to carrier degradation and operational longevity remain under investigation [14]. In short, membrane-based CO_2 capture systems represent an evolving and versatile class of technologies with the potential to address some of the challenges faced by solvent-based capture. Continued development in high-performance materials, system integration, and cost reduction will be critical to their commercial success. In the broader context of carbon capture and utilization (CCU), membrane systems may serve as effective pre-treatment or concentration stages, feeding high-purity CO_2 to downstream processes such as the electrochemical reduction systems explored in this study.

3.3- Adsorption:

Adsorption-based technologies represent a highly promising method for carbon dioxide capture due to their flexibility, low thermal energy requirements for regeneration, and potential for integration into both post-combustion and pre-combustion systems. Unlike absorption, which relies on the dissolution of

CO_2 in a liquid solvent, adsorption involves the adherence of CO_2 molecules onto the surface of solid porous materials. This process is governed by physical or chemical interactions, which are reversible, enabling repeated capture-regeneration cycles with minimal solvent degradation. Adsorption is broadly categorized into physisorption and chemisorption. Physisorption is based on weak forces between molecules: van der Waals force and happens at low temperatures and pressures. It is encountering in general and completely reversible nature and is consequently energy-efficient to regenerate. Its low heat of adsorption may however make it not so effective under high temperatures or the presence of competitive gases such as water vapor. Chemisorption, however, is associated with any stronger bonds of a covalent or ionic kind between the CO 2 molecules and the adsorbent surface. Although this gives increased selectivity and capacity, it typically also needs increased energy to desorb that can diminish its efficacy. CO 2 adsorbing materials have been designed with a huge array of materials, which include: zeolites, activated carbons, metal-organic frameworks (MOFs), silica-based materials, and amine-functionalized solids. All of them have distinctive properties concerning pore area, pore size, chemical nature, affinity to CO 2, resistance to heating and re-hydration energy [15]. Among the first and most examined CO 2 adsorption materials are zeolites, crystalline aluminosilicate minerals with regular microporosity. They have a large surface area, the structure of which can be tuned and they have a cation-exchange which is useful in the separation of CO 2 in a mixture of gases. They are, however, extremely moisture-sensitive and thus capture efficiency can be inhibited, and they are therefore not preferred in the use of flue gasses without pretreatment.

Activated carbon is another widely used adsorbent due to its high porosity, low cost, and chemical stability. Although its CO_2 selectivity is lower than that of zeolites, it performs well under humid conditions and has a lower regeneration energy requirement, making it suitable for certain industrial processes. Metal-organic frameworks (MOFs) have gained significant attention in recent years due to their ultra-high surface areas and structural tunability. By designing specific organic ligands and metal nodes, MOFs can be engineered to have a strong affinity for CO_2 and high uptake capacity. Some MOFs exhibit stepwise adsorption isotherms, allowing for sharp CO_2 uptake at specific pressures, which is highly advantageous in swing adsorption processes. However, their commercial viability is currently hindered by issues related to moisture sensitivity, high synthesis costs, and long-term structural stability. Amine-functionalized adsorbents such as amine-grafted silica or mesoporous supports combine the chemical selectivity of amines with the structural advantages of solids. These materials show excellent selectivity for CO_2 and can function effectively under low partial pressure conditions. They are particularly useful for post-combustion applications but may suffer from oxidative degradation and require moderate thermal input for regeneration. Adsorption-based processes typically operate in cyclical modes, such as Pressure Swing Adsorption (PSA), Temperature Swing Adsorption (TSA), or Vacuum Swing Adsorption (VSA). In PSA, high-pressure gas is passed over the adsorbent to capture CO_2, followed by depressurization to release the captured gas. TSA involves heating the adsorbent to desorb CO_2, while VSA uses a vacuum to lower partial pressure and achieve desorption. Hybrid cycles (e.g., pressure-vacuum swing adsorption, PVSA) have also been explored to optimize energy efficiency and recovery rates. Figure 3 illustrates a simplified schematic of the swing adsorption process. In the adsorption phase, a gas mixture containing CO_2 is passed over an adsorbent bed where CO_2 is selectively captured. In the regeneration phase, the bed undergoes temperature elevation or pressure reduction to desorb and recover CO_2 for downstream utilization or storage.

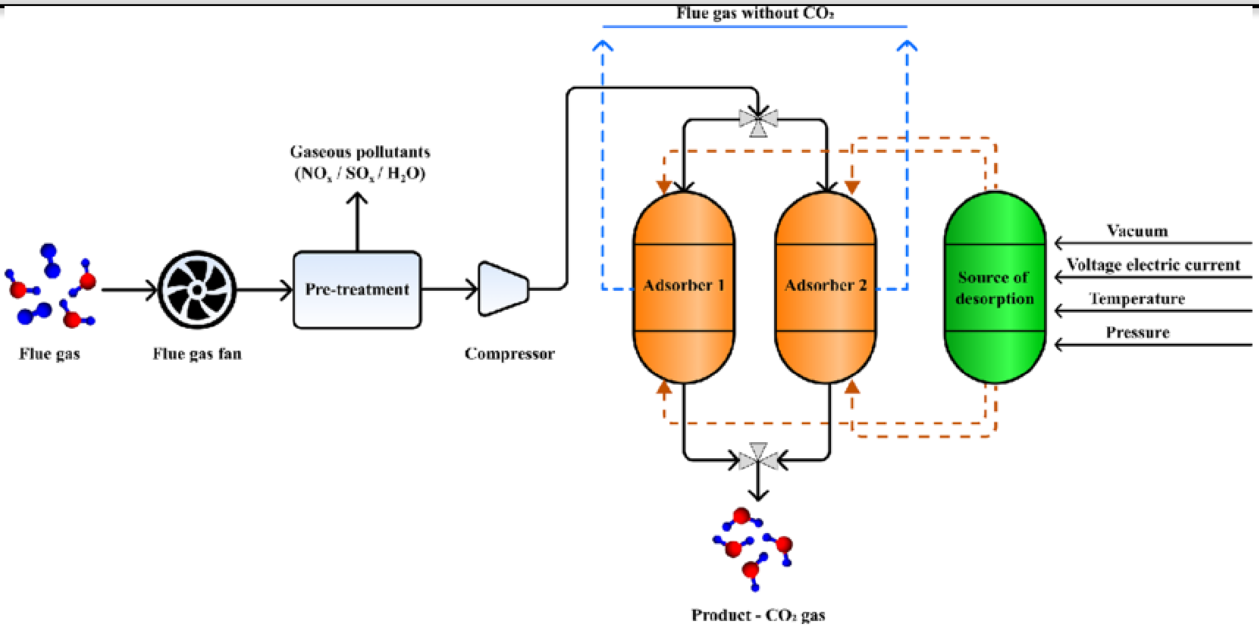

Figure 3: Schematic representation of a typical adsorption–desorption cycle used in CO_2 capture technologies [16].

Continued research into novel adsorbent materials, especially those exhibiting dual-functional properties such as the KC_8-based systems highlighted in this paper suggests a promising path forward. These materials have the potential to combine high CO_2 uptake with in-situ conversion capabilities, thus bridging the gap between capture and utilization within a single platform. The table 5 below provides a comparative overview of key solid adsorbent materials for CO_2 capture:

Table 5: Comparative Overview of Solid Materials for CO2 Capture.

Adsorbent Type	Examples	CO_2 Affinity	Regeneration Method	Advantages	Limitations
Zeolites	Zeolite 13X, 5A	High	TSA, PSA	High capacity and selectivity; mature technology	Moisture sensitivity; high regeneration energy
Activated Carbon	Coal-derived, coconut shell-based	Moderate	TSA, PSA, VSA	Inexpensive; moisture tolerant; stable	Lower CO_2 selectivity; moderate capacity
MOFs	HKUST-1, ZIF-8, MIL-101	Very High	TSA, PSA	High surface area; tunable structure	Expensive; moisture-sensitive; limited scalability
Amine-Functionalized Solids	Amine-grafted silica, SBA-15, MCM-41	Very High	TSA	High selectivity at low CO_2 pressure; reusable	Degradation over time; moderate regeneration energy required
Silica-Based Materials	Mesoporous silica, functionalized silica	Moderate–High	TSA, VSA	Chemically tunable; stable under moderate conditions	Lower uptake compared to zeolites or MOFs

3.4- Chemical Looping:

Chemical looping is an advanced approach to carbon capture that integrates CO_2 separation directly into the combustion or reforming process, rather than relying on external separation units. At its core, this method uses solid metal oxides as oxygen carriers to facilitate the oxidation of fuel without direct contact between air and fuel. In a typical configuration, the fuel enters a reactor containing an oxygen carrier. As the fuel oxidizes, it produces a stream rich in CO_2 and water vapor. The water is subsequently condensed, leaving nearly pure CO_2 that can be compressed and stored or utilized directly. Meanwhile, the reduced metal oxide is forwarded to a second reactor, where it is reoxidized by air. This two-reactor arrangement enables continuous operation, with the oxidation reaction in the second reactor supplying much of the thermal energy needed for the overall process. The appeal of chemical looping lies in its inherent CO_2 separation, which removes the need for energy-intensive post-combustion gas separation steps. As air and fuel streams remain separate, there is minimal formation of nitrogen oxides, and the CO_2 stream exiting the fuel reactor is already highly concentrated. In addition, the oxygen carrier can be transferred between the fuel reactor and the air reactor thus the process exhibits a high thermal efficiency with recovered heat of exothermic reaction of reoxidation [17]. This heat may be used either to drive power cycles by generating steam or to keep up reactor temperatures without any further energy (by keeping the reactor cooled). The achievement and the lifespan of a chemical looping system relies heavily on the choice of an effective oxygen carrier. Of perfect carriers, they have high oxygen transfer capacity, transfer fast redox reaction and have outstanding stability in a variety of analytical conditions, including thermal and mechanical. Examples of commonly used common carrier materials are iron oxides, copper oxides, nickel oxides and manganese oxides. Examples of such carriers; iron based carriers are attractive, low-cost, have good reactivity at medium temperatures, and are resistant to attrition. Copper carriers have greater reactivity and lower temperature of required operating than alumina-based carriers, but copper carriers are subject to sintering at high temperatures. Fuels like natural gas or syngas react readily with nickel-based carriers that are, however, costly and can be easily deactivated by sulfur products. Manganese oxides find a balance between oxygen holding capacity and stability though their cycling dynamics needs to be carefully optimized.

Even though it has a solid potential, chemical looping also has multiple challenges on the way to commercialization. The integrity and activity of oxygen carriers must be maintained after being subjected to thousands of cycles because attrition/agglomeration may result in the loss of reactivity and elevated pressure drops of fluidized or moving-bed reactors. The design of reactors is also more complicated: fluidized-bed reactors may be able to give sufficiently good gas gas, and gas solid, contact, but the circulation of particles and the heat management pose some problems, but moving-bed reactors are better suited to handling solids but need more elaborate mechanical designs. Integration with downstream CO_2 compression and utilization units must be carefully engineered to preserve the economic and environmental benefits of the process. Pilot demonstrations around the world have validated the potential of chemical looping. For example, the Vienna University of Technology operated a 100 kW_{th} chemical looping combustion (CLC) unit that demonstrated CO_2 capture efficiencies above 95%, while the CSIC Almería facility in Spain ran a 1 MW_{th} CLC pilot plant to investigate large-scale carrier performance [18]. These pilots confirmed not only high CO_2 purity but also the feasibility of integrating heat recovery into overall power systems, achieving thermal efficiencies comparable to or exceeding those of conventional combustion with separate capture units. Beyond pure combustion, chemical looping can also be configured for hydrogen production via reforming reactions. In such setups, hydrocarbon fuels react with metal oxides to produce syngas or hydrogen while simultaneously capturing CO_2. This so-called chemical looping reforming process yields hydrogen without emitting CO_2 to the atmosphere, aligning with global decarbonization strategies and the growing demand for low-carbon hydrogen. The table 6 below compares several commonly studied oxygen carrier materials, emphasizing their key attributes:

Table 6: Several Oxygen Carrier Materials.

Oxygen Carrier	Key Attributes	Advantages	Drawbacks
Iron Oxides	High availability, moderate oxygen transport capacity, good thermal stability	Low cost; resistant to attrition; effective cycling	Moderate reactivity at lower temperatures; potential for alloy formation
Copper Oxides	High oxygen transfer rate, low reduction temperature	High reactivity; lower operating temperatures	Prone to sintering; sensitive to sulfur contaminants
Nickel Oxides	Excellent reactivity with hydrocarbon fuels, high oxygen capacity	Highly active for reforming; suitable for syngas	Expensive; deactivates in presence of sulfur; potential nickel loss
Manganese Oxides	Balance between oxygen capacity and stability, moderate operating temperature range	Good cyclic performance; relatively low cost	Lower oxygen capacity than iron or nickel; requires careful sintering control
Mixed-oxide Carriers	Combinations (e.g., Fe–Mn, Fe–Ni) achieving tailored properties	Tunable reactivity and stability profiles	Complex synthesis; potential phase segregation during cycling

Figure 4 presents a schematic representation of the chemical looping process. On the left, the fuel reactor receives both fuel and oxidized oxygen carrier; as combustion proceeds, CO_2 and H_2O exit, while the reduced carrier moves to the right. In the air reactor on the right, air reoxidizes the carrier, and the resulting flue gas is released. This cycle repeats continuously, yielding a separated CO_2 stream without the need for additional separation units. By integrating CO_2 capture directly into combustion or reforming, chemical looping offers a pathway to high purity CO_2 streams and improved thermal efficiency. When compared to emerging materials like potassium graphite (KC_8) which targets ambient-temperature capture and in situ electrochemical conversion chemical looping highlights the complementary nature of thermal and electrochemical strategies for industrial decarbonization. Both avenues continue to evolve, with ongoing research focused on enhancing materials, reactor design, and system integration to achieve scalable, cost-effective carbon capture solutions.

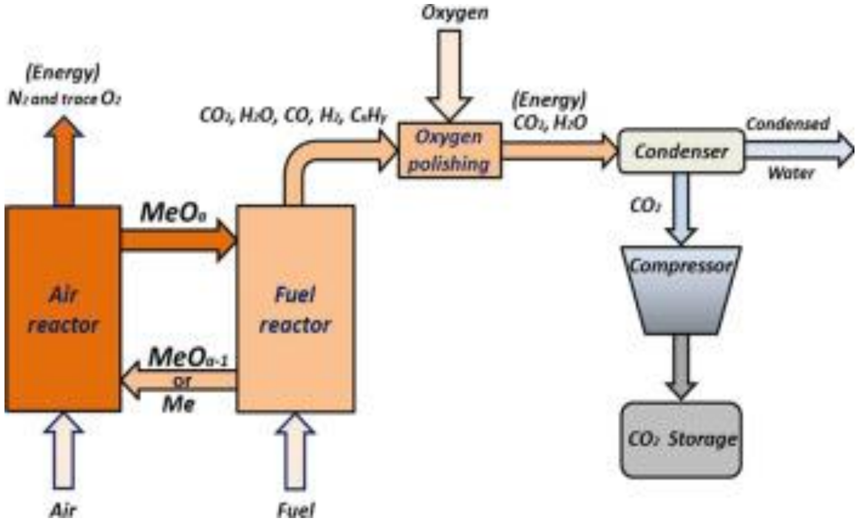

Figure 4: Schematic of the Chemical Looping CO_2 Capture Process [19].

3.5- Hybrid Processes:

Hybrid CO_2 capture processes combine the strengths of multiple capture methods such as absorption, adsorption, membranes, and cryogenics to create systems that maximize carbon capture efficiency, energy performance, and selectivity. These integrated approaches are designed to overcome the limitations of individual technologies by leveraging their complementary advantages, thus presenting a promising strategy for scalable, cost-effective carbon management in industrial and energy sectors. The fundamental motivation behind hybridization is that no single capture technology currently offers an optimal balance between energy demand, operational cost, material stability, and capture efficiency across all industrial settings. For example, while chemical absorption using amines offers high CO_2 selectivity, it is energy-intensive due to the regeneration step. Conversely, membrane systems are modular and energy-efficient but may suffer from low selectivity or permeability when used alone. By integrating these systems, hybrid technologies aim to achieve synergistic performance where one technology handles bulk separation and the other enhances purity or reduces energy consumption. A typical example of a hybrid system is the combination of membrane separation with chemical absorption. In this arrangement, a membrane stage acts as a pre-concentrator, enriching the CO_2 content of a gas stream before it enters an absorption unit. This pre-enrichment reduces the solvent regeneration energy and improves the overall energy efficiency of the process. Alternatively, a hybrid membrane–adsorption configuration may utilize pressure swing adsorption (PSA) after membrane separation to produce high-purity CO_2, especially in flue gas or biogas upgrading applications. Such designs offer flexibility, modularity, and lower capital expenditure compared to large-scale chemical absorption units alone.

Another promising hybrid approach involves integrating cryogenic distillation with membrane or adsorption steps. Cryogenic processes are well-suited for capturing CO_2 from high-purity sources or when product liquefaction is desired, such as in liquefied CO_2 transport [20]. However, their energy demand is considerable. By pre-conditioning the gas stream through membranes or solid sorbents, the system can reduce the cryogenic unit's size and energy requirements. Hybrid cryogenic–adsorption systems have been tested for post-combustion capture in pilot-scale applications and have demonstrated enhanced CO_2 recovery at reduced operating pressures. In recent years, novel combinations such as hybrid chemical looping–membrane systems have emerged. These aim to integrate high-temperature combustion with membrane-based oxygen separation, yielding simultaneous CO_2 capture and pure nitrogen-free air for power generation. Though still in the early stages of development, such systems illustrate the expanding innovation space for hybrid architectures. The table 7 below compares several representative hybrid configurations, their operating conditions, and key performance attributes:

Table 7: Several Hybrid Configuration.

Hybrid Configuration	Components	Application	Advantages	Challenges
Membrane–Absorption	Polymer membranes + Amine solvents	Post-combustion flue gas	Lower solvent regeneration energy; improved selectivity	Membrane fouling; solvent degradation
Membrane–Adsorption	Gas separation membranes + PSA/TSA	Biogas upgrading; flue gas	High-purity CO_2; modular design	Complex control strategy; cyclic operation
Cryogenic–Adsorption	Cryogenic distillation + Solid sorbents	Industrial gas purification	Reduced energy demand; high CO_2 purity	High capital cost; thermal management
Chemical Looping–Membrane	Oxygen carrier system + O_2 selective membrane	Oxyfuel combustion with CO_2 capture	Integrated oxygen supply; pure exhaust stream	High temperature; membrane stability

Electrochemical–Membrane (Emerging)	Ion-conducting membrane + Redox cell	CO_2 conversion and capture	Simultaneous capture and conversion	Material cost; scale-up complexity

These hybrid systems not only allow greater operational flexibility but also offer the potential to tailor CO_2 capture strategies to specific emission sources, whether it be a fossil fuel power plant, a cement kiln, or a direct air capture unit. In many cases, integrating technologies enables incremental deployment, reducing initial capital costs and facilitating retrofitting of existing infrastructure.

4- Strategic Assessment of CO_2 Utilization:

Carbon dioxide (CO 2) has turned into a strong competitor in the demand of renewable energy production and the realization of a sustainable circular carbon economy. There is growing interest in the conversion of CO 2, historically seen as a waste by-product of industry and a greenhouse gas, to high value feedstocks to make fuels, chemicals and materials. This move is prompted by the imminent necessity to cut the amount of CO 2 in the atmosphere and at the same time satisfy the globe with the increase in energy and the chemical commodities required as well. Nevertheless, to make a technology of CO 2 utilization viable and adopted as a norm, criteria among criteria have to be highly demanding in light of safety, environmental sustainability, and economic viability. The idea of successful CO 2 utilization incorporation into industrial frames might rely not only on the technological readiness of these processes but also on the ability of such technology to fit with the current infrastructure and market demands. There are various routes that have been found to utilize CO 2 and each route has its unique mechanism, application as well as level of technological maturity. Among them the most well-known include enhanced oil recovery (EOR), chemical upgrading to fuels and value-added chemicals, mineral carbonation and its new application in desalination [21]. All these various methods point to the extensive range of applicability of CO 2 as a source of carbon and its ability to replace fossils based raw materials in a multitude of applications. As an example, CO 2 may be converted in a chemical reaction to methanol, urea, polycarbonates, and other industrial intermediates using hydrogenation, electrochemical reduction, and catalytic processes. When the metal oxides react with CO 2 during mineralization, the resulting carbonates become stable and provide a medium of sequestration on a long-term basis. Figure 5 below offers a conceptual scheme of the significant directions of CO 2 utilization and the sectors of its use

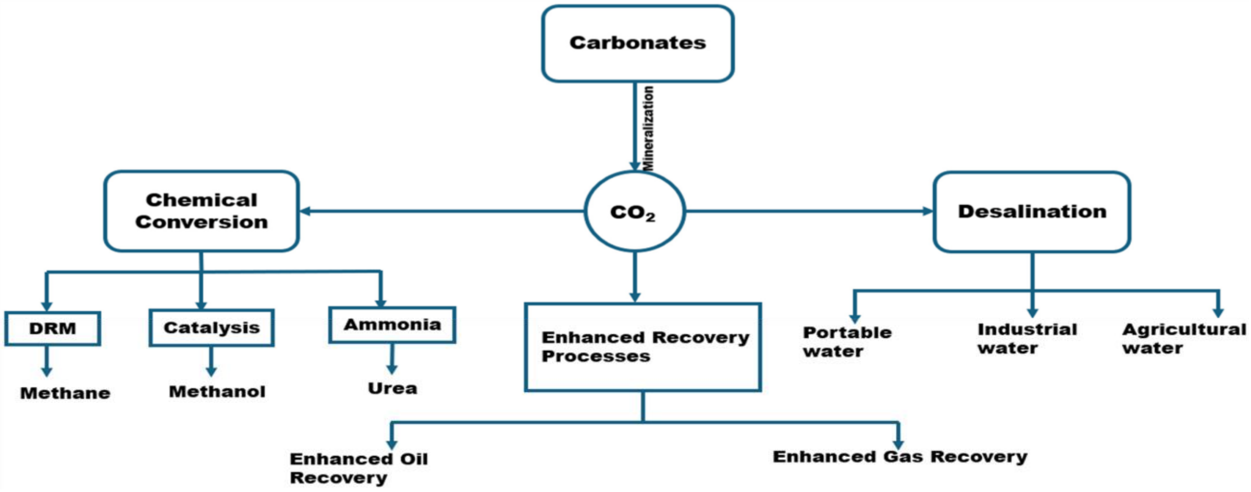

Figure 5: Different methods of utilizing CO_2.

The United States Department of Energy classifies CO_2 utilization technologies into three core categories: (1) **Enhanced Oil Recovery (EOR),** where captured CO_2 is injected into mature oil fields to increase hydrocarbon extraction; (2) **mineralization,** where CO_2 is converted into stable carbonates for use in construction materials or long-term storage; and (3) the **manufacturing of value-added products**, such as polycarbonate plastics and sustainable cement alternatives. These applications highlight the dual benefit of reducing CO_2 emissions while generating economically beneficial products that support industrial growth. In addition to targeted capture and reuse, CO_2 is also naturally produced as a byproduct in several large-scale industrial operations. It is generated during the synthesis of ammonia via the Haber-Bosch process, during ethanol and ethylene oxide fermentation, and in various steps of crude oil refining. Despite these diverse sources, the actual industrial utilization of CO_2 remains limited. It is currently used in relatively niche applications, including carbonating beverages, controlling pH in water treatment, enhancing crop growth in greenhouses, and as a reactant in petrochemical production. Moreover, its role in EOR has become more prominent over the past two decades, particularly in North America. However, even with these applications combined, less than 1% of the global CO_2 emissions are captured and reused as raw material in industrial processes, a figure that underscores the underexploited potential of CO_2 utilization [22]. Given this context, it becomes evident that a significant opportunity exists to expand the role of CO_2 as a feedstock for synthesizing fine chemicals, fuels, and polymers. Converting captured CO_2 into products such as syngas, formic acid, methanol, and olefins can create a closed-loop system that not only reduces greenhouse gas emissions but also offsets fossil fuel use in the chemical sector. Realizing this vision requires concerted advancements in catalyst design, process integration, energy efficiency, and policy support. Ultimately, scaling up CO_2 utilization technologies in tandem with carbon capture infrastructure can serve as a cornerstone of global decarbonization strategies and foster a transition toward a low-carbon, resource-efficient industrial future.

4.1- Utilization of CO_2 for Enhanced Oil Recovery:

Enhanced Oil Recovery (EOR) is one of the most mature and widely implemented methods of carbon dioxide (CO_2) utilization, particularly in regions with significant hydrocarbon reserves. In this process, captured CO_2 is injected into depleted or mature oil reservoirs to increase the extraction of crude oil beyond what is achievable through primary and secondary recovery methods. This approach not only enhances oil yield but also serves as a mechanism for the long-term geological sequestration of CO_2, thereby contributing to greenhouse gas mitigation. The principle behind CO_2-EOR lies in the physicochemical interactions between CO_2 and the residual oil in the reservoir. Under high pressure, CO_2 dissolves into the crude oil, reducing its viscosity and swelling the oil, which enhances its mobility and facilitates its flow toward production wells. This miscible or near-miscible displacement process can significantly improve oil recovery rates, often extracting an additional 10% to 20% of the original oil in place (OOIP), depending on the reservoir conditions [23]. From an economic standpoint, CO_2-EOR offers dual benefits: it enables the recovery of otherwise unrecoverable oil, which has considerable commercial value, and provides an incentive for investing in CO_2 capture infrastructure by creating a market for captured CO_2. This synergy has made EOR a cornerstone of early-stage carbon capture, utilization, and storage (CCUS) deployment, particularly in the United States, where extensive pipeline networks and favorable geological formations support the implementation of such projects. In practice, the CO_2 used in EOR can come from both natural and anthropogenic sources. While historically, much of the injected CO_2 has been sourced from natural reservoirs, there is growing interest and momentum in utilizing CO_2 captured from industrial emissions and power plants, aligning EOR with broader decarbonization goals. This transition is critical for transforming EOR from a primarily oil-recovery-driven technology into a more climate-aligned carbon management tool. Figure 5 illustrates the operational framework of a typical CO_2-EOR process. Captured CO_2 is compressed and transported to an injection site, where it is injected into the oil reservoir through dedicated wells. The CO_2 mixes with the oil, enabling enhanced recovery, and the mixture is brought to the surface through production wells. At the surface, CO_2 is separated from the oil, recompressed, and reinjected in a closed-loop cycle, minimizing emissions and maximizing reuse.

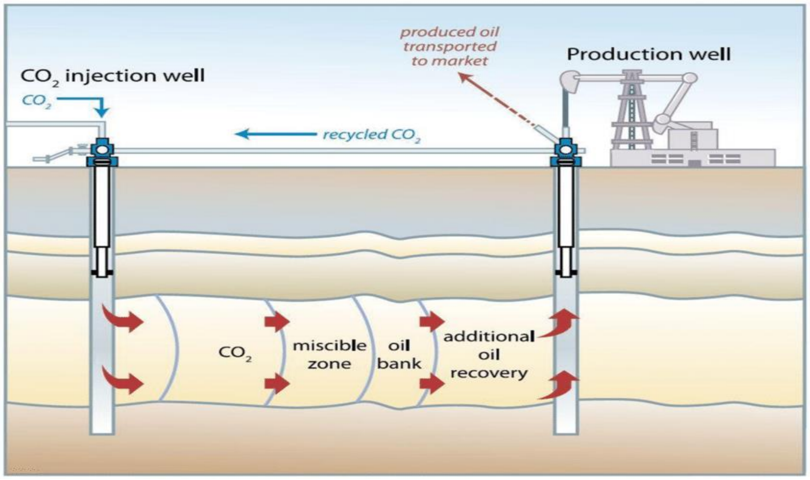

Figure 5: Schematic Diagram of a CO_2-Enhanced Oil Recovery System

The integration of CO_2-EOR into global CCUS strategies has the potential to bridge the gap between carbon mitigation and energy security. However, challenges such as site-specific geology, the economics of CO_2 capture and transport, regulatory considerations, and lifecycle emissions must be carefully managed to ensure that CO_2-EOR contributes positively to long-term sustainability goals. With proper implementation and monitoring, EOR can serve as a transitional technology, supporting both fossil fuel recovery and the deployment of large-scale CO_2 capture and utilization infrastructure. Table 8 provides a summary of key performance indicators and operational considerations associated with CO_2-EOR systems.

Table 8: Key Parameters and Considerations in CO_2-Based Enhanced Oil Recovery

Parameter	Typical Range/Value	Significance
CO_2 Injection Pressure	1,000–3,000 psi	Determines miscibility with oil; affects recovery efficiency
CO_2 Source	Natural or anthropogenic	Captured CO_2 enhances environmental benefit
Oil Recovery Increment	10%–20% of OOIP	Additional oil yield due to CO_2 injection
CO_2 Recycling Efficiency	90%–95%	High recycling reduces net CO_2 emissions
Reservoir Depth	>3,000 feet	Deep formations favor miscibility and pressure retention
Environmental Impact	CO_2 storage + emissions reduction	Acts as a form of geological sequestration

The integration of CO_2-EOR into global CCUS strategies has the potential to bridge the gap between carbon mitigation and energy security. However, challenges such as site-specific geology, the economics of CO_2 capture and transport, regulatory considerations, and lifecycle emissions must be carefully managed to ensure that CO_2-EOR contributes positively to long-term sustainability goals. With proper implementation and monitoring, EOR can serve as a transitional technology, supporting both fossil fuel recovery and the deployment of large-scale CO_2 capture and utilization infrastructure.

4.2- CO_2 Utilization: Conversion of CO_2 into Fuels and Petrochemicals

Any sensible use of sequestered carbon dioxide (CO 2) is an innovative solution which not only keeps the greenhouse gas emissions at bay but also offers a solution to a number of practical shortcomings that have been linked with the traditional carbon capture and storage (CCS) model. Among the most apparent issues of extensive implementation of CCS technologies is the overwhelming financial cost, which includes large investment costs, when installing an intricate CCS technology infrastructure and an additional long-term expense post-implementation during constant monitoring of underground storage. The utilization of CO 2 (CCU) in turn adds an element of value creation: by converting the captured CO 2 to sellable fuels and chemicals, much or all of the operational expenditure can be offset, making the entire operation of carbon management activities economically viable. Further, the use of CO 2 makes the process of capture more attractive and efficient as the process itself will have a downstream market that will create value to the energy and materials used in the extraction and sequestration of the CO 2. Rather than treating CO_2 as a waste product requiring indefinite storage, CCU redefines it as a resource feedstock for chemical synthesis, energy production, and materials engineering [24]. This paradigm shift not only improves the commercial viability of large-scale CO_2 management but also extends the functional lifespan and return on investment of capture systems. Importantly, CO_2-derived fuels and chemicals present a promising avenue for partially displacing traditional fossil-based energy sources. By integrating CO_2 utilization with renewable energy inputs such as solar or wind-powered electrochemical systems the process supports the generation of cleaner energy carriers, including methanol, formic acid, and syngas, thereby reducing reliance on petroleum and natural gas while closing the anthropogenic carbon loop.

Furthermore, the strategic development of CO_2 utilization technologies lays the groundwork for a broader portfolio of sustainable innovations. These technologies complement, rather than replace, existing fossil fuel infrastructure, enabling a smoother transition toward low-carbon energy systems. In doing so, they support the global push toward climate resilience, energy diversification, and industrial decarbonization. As such, CO_2 utilization emerges not merely as a solution to an environmental problem but as a cornerstone of the emerging green economy, offering tangible benefits in terms of energy security, technological innovation, and environmental stewardship.

4.2.1- CO_2 Utilization: Conversion of CO_2 into Fuels

The valorization of captured carbon dioxide (CO_2) into useful fuels and chemical feedstocks represents a crucial pillar in the transition to sustainable energy systems and circular carbon economies. Amid rising atmospheric CO_2 levels and the limitations of traditional carbon capture and storage (CCS) approaches, the concept of carbon capture and utilization (CCU) has gained significant scientific and industrial momentum. Among the various pathways for CO_2 transformation, electrochemical CO_2 reduction (ECO_2R) has emerged as one of the most promising due to its compatibility with intermittent renewable energy sources, modular scalability, and ability to produce a diverse range of high-value products, including syngas, formic acid, carbon monoxide, methanol, and ethanol. The products are used in two ways: as fuel that can replace the conventional fossil-based energy carriers and as important intermediaries to large-scale chemical manufacturing. The efficiency and practicability of ECO 2 R is, however, directly connected to the requirements of the CO 2 capture material and consequent reactivity of the trapped species. Conventional systems involve energy demands needed to activate CO 2 and the resulting low product selectivity with constituting key obstacles. The limitations of the current study are overcome by use of potassium graphite (KC8) as CO2 adsorbent and activation agent to the reduction agent (electrochemical). KC 8 is a layered intercalation compound with graphite doped with potassium atoms and its extraordinary well-known abilities to give electron as well as highly affinity to CO 2 [25]. Such a material may favor spontaneous charge transfer interactions leading to reactive CO 2 intermediates thus lowering gender energetic activation barriers to CO 2. Having been introduced into an electrochemical environment, these activated species can then be converted with greater efficiency and selectivity under comparatively gentle conditions than is possible by traditional capture-conversion strategies, which gives them a strategic advantage.

Experimental implementation of the KC_8-assisted ECO_2R framework involved a dual-chamber electrochemical cell integrated with a KC_8-activated CO_2 inlet module. The CO_2 molecules, once captured by KC_8, were directly transferred into the cathodic compartment of the electrochemical reactor, where reduction reactions proceeded under the influence of a low applied potential. The system demonstrated the capacity to produce a combination of syngas ($CO + H_2$), formic acid, and methanol with high Faradaic efficiency and reduced overpotentials. As illustrated in Figure 6, the KC_8 material acts not only as a physical medium for CO_2 capture but also as a chemical agent that lowers the activation energy required for electron transfer during the reduction step.

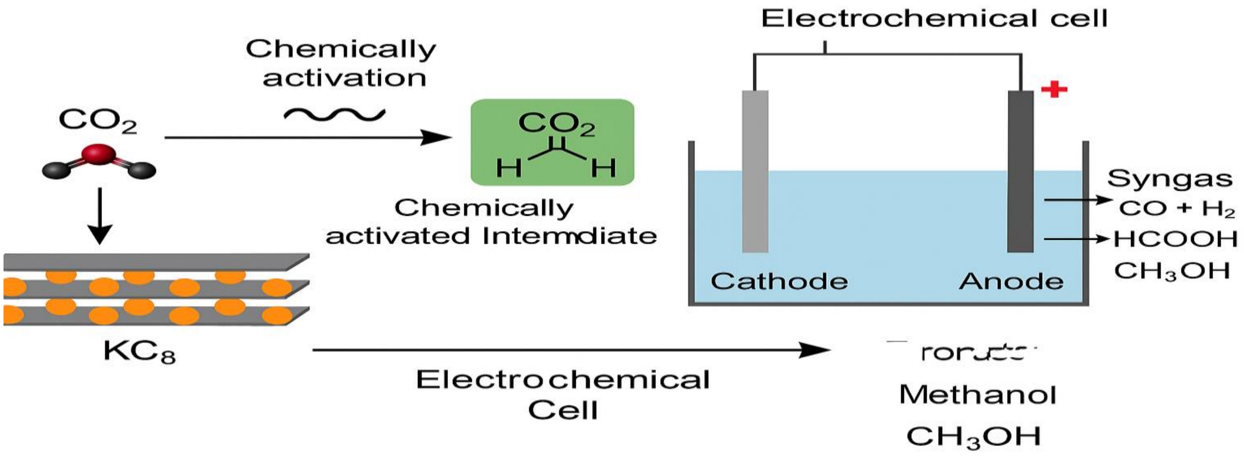

Figure 6: Schematic illustration of the KC_8-assisted CO_2 capture and electrochemical conversion pathway. CO_2 is first chemically activated by KC_8 and subsequently reduced in the electrochemical cell into syngas, formic acid, and methanol under mild conditions [26].

The thermodynamic and kinetic advantages of this dual-stage process were confirmed through a series of electrochemical tests and spectroscopic analyses. Compared with conventional systems using aqueous carbonate or amine scrubbing techniques, the KC_8-assisted approach exhibited significantly higher capture efficiency and product selectivity. The comparative performance of conventional versus KC_8-assisted ECO_2R systems is summarized in Table 9, which demonstrates key gains in Faradaic efficiency, energy input, overpotential reduction, and product specificity.

Table 9: Performance comparison of conventional CO_2 electroreduction systems and KC_8-assisted systems.

Parameter	Conventional ECO_2R System	KC_8-Assisted ECO_2R System
Faradaic Efficiency (Methanol)	40–55%	70–78%
Overpotential Required (V vs. RHE)	>0.8 V	0.5–0.6 V
CO_2 Capture Efficiency	50–60%	>85%
Energy Consumption (kWh per kg product)	High	~30% lower
Selectivity Toward Target Products	Moderate	High

These outcomes highlight the significant performance benefits that KC 8 brings emerging. In optimized conditions, the Faradaic efficiency of methanol, e.g., was around 78 percent, and the overpotential necessary was about 0.55 V versus the reversible hydrogen electrode (RHE), significantly less than before. Also the rate of production of desired products was selective as the intermediates were stabilized in a controlled way on the catalytic surface-enhanced with KC8 making the selection of products produced to be less side-reactive and more uniform in their profile. The sustainability of this approach is also enhanced by the fact that this is a procedure that is compatible with green energy sources. The electrochemical setup is readily powered by renewable energy inputs such as solar photovoltaics or wind energy, allowing for a fully sustainable CO_2-to-fuel conversion cycle. This capability effectively establishes a closed-loop artificial photosynthesis system, where carbon-neutral fuels are generated by combining atmospheric CO_2 and water with clean electricity. Furthermore, the system is designed to operate under ambient pressure and temperature, thus avoiding the high energy costs typically associated with thermochemical conversion methods [27]. The synergy between KC_8-based chemical activation and electrochemical reduction not only enhances technical performance but also introduces economic and environmental viability, making this framework suitable for industrial-scale applications in the near future. Beyond the direct energy and environmental benefits, this dual-function system also opens new avenues in material innovation for CO_2 conversion. The demonstrated effectiveness of KC_8 suggests that further exploration of alkali-metal intercalated graphite structures or layered nanomaterials may yield even greater efficiencies and selectivities. In this way, the present study not only validates a novel method for CO_2 utilization but also lays the foundation for broader advancements in the field of green catalysis and carbon-neutral energy technologies.

4.2.2- CO2 Utilization: Conversion of CO2 into Petrochemicals

The transformation of carbon dioxide (CO_2) into value-added petrochemical derivatives has emerged as a cornerstone of sustainable industrial chemistry, addressing both environmental and resource challenges associated with fossil fuel dependence. While traditional petrochemical production relies heavily on hydrocarbons extracted from non-renewable sources, the utilization of CO_2 as an alternative carbon feedstock offers a compelling route toward a circular carbon economy. CO_2, though thermodynamically stable and kinetically inert, can be catalytically activated and converted into fundamental building blocks such as olefins, aromatics, urea, methanol-derived polymers, and other hydrocarbon intermediates essential for plastics, resins, and synthetic fuels. In this context, the integration of KC_8 (potassium graphite) into the CO_2 utilization framework significantly enhances the feasibility of electrochemical conversion processes aimed at petrochemical synthesis. The unique electron-donating capacity of KC_8 not only facilitates the adsorption and activation of CO_2 under ambient conditions but also enables the formation of reactive intermediates, such as carbon monoxide (CO), formyl (HCO), and methylene (CH_2) radicals. These intermediates are critical for the downstream synthesis of hydrocarbon chains and aromatic rings typically found in petrochemical compounds. The pathway begins with the selective electrochemical reduction of CO_2 into CO in the presence of KC_8, which functions both as a physical capture medium and as an electronic facilitator that lowers the activation energy barrier for the CO_2-to-CO conversion [28]. The CO thus generated serves as a fundamental precursor in several well-established industrial reactions, including Fischer–Tropsch synthesis and hydroformylation. When hydrogen is co-fed into the system either externally supplied or generated in situ from water electrolysis the CO-H_2 mixture (syngas) becomes the basis for catalytic synthesis of longer-chain hydrocarbons such as ethylene, propylene, and paraffinic fuels. These compounds are foundational to the production of polymers, detergents, solvents, and lubricants. To illustrate this transformation, Figure 7 presents a conceptual process schematic outlining the conversion steps of KC_8-activated CO_2 to various petrochemicals. The diagram tracks the progression from electrochemical CO formation to catalytic conversion into petrochemical derivatives, highlighting potential reaction pathways for olefin and aromatic generation.

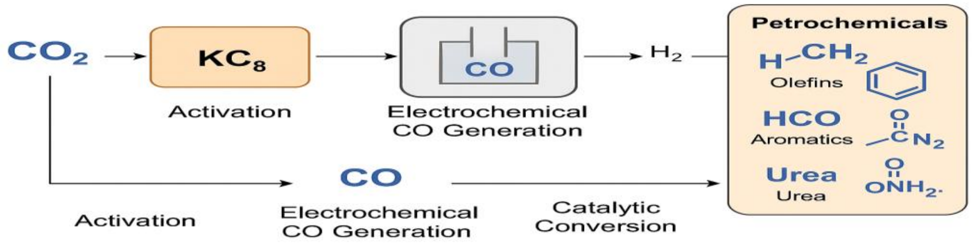

Figure 7: Process schematic showing the transformation of KC_8-activated CO_2 to key petrochemical intermediates via electrochemical CO generation and subsequent catalytic synthesis routes [29].

Additionally, Table 10 below summarizes the potential petrochemical products derived from CO_2, the required reaction pathways, catalysts used, and their respective industrial relevance.

Table 10: CO_2-derived Petrochemicals, Catalytic Pathways, and Applications

Product	Intermediate	Catalytic Pathway	Catalyst Type	Industrial Application
Ethylene (C_2H_4)	CO + H_2	Fischer–Tropsch / CO coupling	Fe, Co, Cu-$ZnAl_2O_4$	Plastics (PE), solvents
Propylene (C_3H_6)	CO + H_2	Tandem hydroformylation	Rh-based + acidic zeolite	Polypropylene, resins
Aromatics (BTX)	CO + H_2	Methanol-to-Aromatics (MTA)	SAPO-34, ZSM-5	Synthetic fibers, fuels
Urea ($CO(NH_2)_2$)	CO_2 + NH_3	Direct synthesis	ZnO, Fe_2O_3	Fertilizers
Methanol (CH_3OH)	CO_2 + H_2	Hydrogenation	$Cu/ZnO/Al_2O_3$	Solvents, formaldehyde, fuels

The KC_8 system demonstrates enhanced selectivity toward CO production, which is the bottleneck step in many CO_2 utilization processes. As the CO yield and purity increase due to improved electrochemical kinetics, the downstream petrochemical synthesis becomes more efficient and less energy-intensive. Moreover, the high CO_2 capture efficiency (>85%) and reduced overpotential achieved in the KC_8 system allow for continuous feedstock availability to secondary catalytic reactors, minimizing operational disruptions. One notable aspect of KC_8-enabled systems is the potential to integrate with existing petrochemical infrastructure. For example, the generated CO can be directly funneled into hydroformylation units for aldehyde synthesis, which can be further converted to alcohols and polymers. Similarly, methanol produced from CO_2 reduction can enter methanol-to-olefins (MTO) or methanol-to-aromatics (MTA) pathways already used in commercial practice. In terms of sustainability, this strategy aligns strongly with global decarbonization goals. By converting captured CO_2 into petrochemical products with commercial and industrial value, the system provides a dual environmental and economic benefit. It displaces fossil carbon input while enabling carbon recycling within the production loop, thereby reducing the overall carbon footprint of the petrochemical industry. Additionally, when powered by renewable energy, the entire value chain from CO_2 capture to product synthesis can be rendered carbon-neutral or even carbon-negative, depending on the system boundaries and lifecycle emissions. The integration of KC_8 in CO_2-to-petrochemical conversion systems not only advances the field of carbon utilization but also presents a transformative approach to chemical manufacturing, where emissions are not merely mitigated but repurposed into resources. This represents a paradigm shift toward sustainable petrochemical production, bridging the gap between environmental stewardship and economic viability.

4.3- Mineralization of CO2:

The carbon dioxide (CO_2) mineralization is an efficacious and long-term process of carbon sequestration, which enhances carbon dioxide into thermodynamically stable solid carbonates by reacting with naturally available or industrial margins metal oxides, silicates. Carbon storage permanently is unique criterion of this process because, through this process, gaseous CO_2 is converted to inert mineral forms of carbonate which are calcium carbonate ($CaCO_3$) and magnesium carbonate ($MgCO_3$). In contrast to other temporary storage or usages chains that would ultimately yield to re-emission, mineralization provides a permanent way of getting CO_2 out of the carbon cycle, thus providing an interesting counterpart to more dynamic solutions, such as electrochemical conversion. In the integrated system explored in this study, where KC_8 facilitates efficient CO_2 capture and electrochemical transformation into fuels and chemicals, mineralization serves as a secondary pathway that sequesters any unconverted or surplus CO_2. The CO_2 exiting from the electrochemical reactor or captured from exhaust streams can be channeled directly into mineralization units, thereby ensuring complete carbon accountability and enhancing the system's overall sustainability. This dual-path approach aligns with the principles of holistic carbonmanagement by combining utilization with long-term geological fixation. The underlying chemical process of mineralization typically begins with the dissolution of CO_2 in water to form carbonic acid, which subsequently reacts with divalent metal ions such as Ca^{2+} or Mg^{2+} to precipitate as solid carbonates [30]. These ions can be derived from a variety of natural or industrial sources, including olivine, serpentine, wollastonite, steel slag, fly ash, or mining residues. The reactions proceed exothermically and are energetically favorable under ambient or slightly elevated conditions, although their kinetics can be significantly enhanced by factors such as particle size reduction, elevated temperatures, pH control, or the presence of catalytic agents. In systems employing KC_8, the high purity and controlled flow of CO_2 improve reaction rates by minimizing the need for purification and compression, which are typically required for flue gas-based mineralization processes. Figure 8 illustrates a schematic representation of the mineralization process, showing the direct and indirect carbonation pathways and their integration with the KC_8-enabled CO_2 capture and conversion loop. Direct mineralization involves the gas-solid reaction of CO_2 with ground mineral feedstock, whereas indirect mineralization dissolves the metal-bearing feedstock in an aqueous medium, followed by precipitation of carbonates through controlled carbonation. Both pathways are viable in the proposed framework, depending on the source material and intended application of the carbonate product.

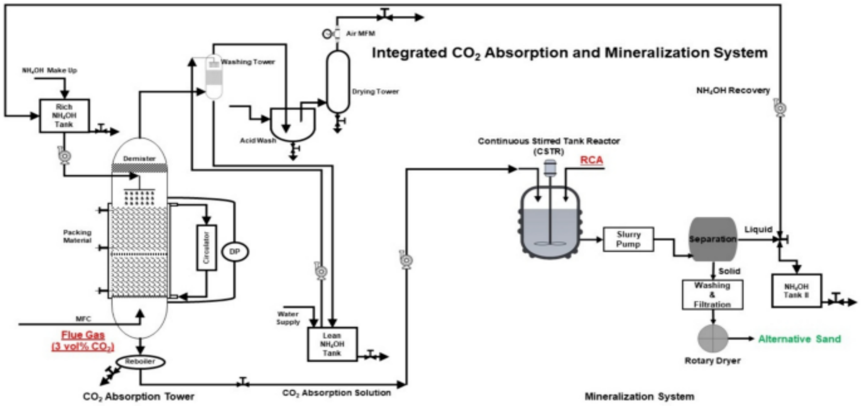

Figure 8: Schematic diagram of CO_2 mineralization pathways showing integration with KC_8-based capture and conversion systems. Direct and indirect carbonation processes are indicated.

Mineral sources for carbonation vary widely in composition, availability, and reactivity, as shown in Table 11, which summarizes key materials, their chemical composition, theoretical CO_2 uptake potential, reaction enthalpy, and their typical sources. For instance, olivine (Mg_2SiO_4), abundant in ultramafic rocks, offers a high sequestration capacity exceeding 600 kg CO_2 per ton of material. Wollastonite ($CaSiO_3$) and various industrial residues also offer substantial potential, with enthalpies favorable for spontaneous reaction under ambient conditions.

Table 11: Comparative Analysis of Mineral Sources for CO_2 Sequestration via Carbonation [31].

Material Source	**Chemical Formula**	**CO_2 Uptake Capacity (kg CO_2/ton)**	**Reaction Enthalpy (kJ/mol CO_2)**	**Availability**
Olivine (Forsterite)	Mg_2SiO_4	~600	-90 to -110	Abundant in ultramafic rocks
Wollastonite	$CaSiO_3$	~400	-90	Found in skarns and limestones
Industrial Slag (steel, Ni)	CaO, MgO mixtures	~300–500	-100 to -150	High from metallurgical processes
Fly Ash	Mixed oxides	~200–300	-80 to -120	Widely available from coal plants

The products of mineralization, namely $CaCO_3$ and $MgCO_3$, can also serve secondary purposes, such as in the manufacture of construction materials, fillers, and soil amendments, thus opening up economic opportunities for waste valorization. These co-benefits further justify the integration of mineralization with carbon utilization technologies, offering an economically and environmentally attractive solution for hard-to-abate sectors. Moreover, when powered by renewable energy and integrated with a high-efficiency electrochemical system such as the KC_8-based setup, the entire process chain from CO_2 capture to mineral storage can potentially achieve net-negative emissions, thereby contributing meaningfully to global decarbonization goals. The incorporation of mineralization into the KC_8-enhanced carbon management framework allows for the diversification of CO_2 fate, ensuring that every captured molecule is either transformed into a useful product or sequestered permanently. This integrative strategy underscores the importance of multipath carbon utilization models, where environmental durability, technical feasibility, and economic viability intersect to enable a truly sustainable carbon cycle.

4.4- Desalination and Water Production:

Climate change, population increase and the subsequent industrialization have intensified the water crisis experienced all over the world making there to be an acute need of production technologies of water that are also sustainable and easily scalable. The removal of saltiness and other impurities found in seawater or brackish waters to obtain drinkable water by the method of desalination is a solution to this problem hence important. The traditional desalination facilities, reverse osmosis and thermal distillation, however, still require a lot of energy and are environmentally demanding. In this regard, the interest in synergistic systems combining water purification to renewable energy and carbon management technologies, which have multiple environmental and economic advantages, is increasing. In the framework of the present research, the opportunities of combining KC 8-mediated electrochemical reduced CO 2 affair and the process of water desalination are a fresh idea to address issues with carbon emission and water scarcity simultaneously. Water in the electrochemical reduction of CO 2 has a two-fold role: it supplies protons to the catalytic reduction reaction and it is also a solvent and an electrolyte in which the electrochemical reaction occurs. When using the KC8-based CO2 capture and conversion platform in the course of the operation, the electrolyte solutions are contaminated by the salt and side products that can undergo further processing and reutilization with the help of desalination technologies [32]. Indeed, instead of disposing these electrolyte effluents, which would be equivalent to loss of useful resources and a possible pollution, they could be further processed to yield purified water and reclaim chemical species not consumed by the process. Such a closed-loop enables the improvement of sustainability of the system, reduction of waste, and adherence to the principles of circular use of resources. One particularly promising pathway is the coupling of electrochemical CO_2 conversion with membrane-based desalination technologies such as electrodialysis (ED) or capacitive deionization (CDI). These systems are inherently compatible with the electrochemical architecture of CO_2 reduction cells. In ED, selective ion-exchange membranes facilitate the removal of charged species from the solution by driving them across a membrane using an electric potential, which is already present in CO_2 electrolyzers. Similarly, CDI operates by applying an electric field to carbon-based electrodes, which adsorb and remove ions from feedwater. Both technologies operate at relatively low voltages and energy demands compared to thermal desalination processes, making them suitable for integration with KC_8-based systems, especially when powered by renewable sources such as solar photovoltaics or wind turbines. Table 12 shows the Comparative Overview of Desalination Technologies Relevant to CO_2 Utilization Platforms

Table 12: Comparative Overview of Desalination Technologies Relevant to CO_2 Utilization Platforms

Technology	Energy Consumption (kWh/m³)	Water Recovery (%)	Operational Temperature (°C)	CO_2 System Compatibility	Maturity
Reverse Osmosis (RO)	3–6	40–50	20–30	Moderate (requires pre/post treatment)	Commercially mature
Multistage Flash (MSF)	10–25	30–50	80–120	Low (thermal, not electric)	Mature
Electrodialysis (ED)	1.5–3	60–80	Ambient	High (electrochemically synergistic)	Emerging
Capacitive Deionization (CDI)	0.5–2	70–85	Ambient	High (ideal integration)	Experimental
Forward Osmosis (FO)	0.25–0.5 (with draw regeneration)	50–70	Ambient	Low (requires coupling)	Pilot stage

Additionally, the co-location of CO_2 conversion and desalination processes allows for multi-output utility systems in which a single renewable energy input serves multiple environmental goals: carbon mitigation, clean fuel generation, and freshwater production. For example, excess heat or electricity generated from renewable sources or waste energy from the CO_2 reduction process could be diverted to power adjacent desalination modules, increasing energy efficiency and reducing operating costs. This integrated infrastructure is particularly advantageous in coastal or arid industrial regions where access to saline water is abundant, but freshwater resources are limited. The saltwater can be used as feedstock for the desalination unit, while atmospheric or flue-gas CO_2 can be captured using KC_8 and directed into the reduction cell to generate fuels such as formic acid, methanol, or syngas. In broader terms, integrating water production into the carbon utilization value chain contributes to the resilience of critical infrastructure under changing climate conditions. For instance, in regions vulnerable to both water stress and CO_2 emissions such as parts of the Middle East, South Asia, and sub-Saharan Africa such a hybrid platform could simultaneously provide clean water, energy, and climate mitigation. Furthermore, the byproducts of desalination, such as concentrated brine, can be assessed for further valorization or subjected to additional treatment processes, avoiding environmental discharge and creating a zero-liquid discharge (ZLD) system. Economic and operational benefits also emerge from this dual integration. The cost of desalination, while traditionally high, can be significantly offset by the revenue generated from carbon-derived fuels and chemicals produced in the electrochemical process [33]. Additionally, the modular nature of both CO_2 electroreduction cells and desalination units allows for flexible scaling based on regional demands and resource availability. Advances in nanomaterials, such as high-surface-area carbon electrodes for CDI and selective catalytic membranes for CO_2 reduction, further enhance the technical viability and performance of such integrated systems. Table 13 shows the Integration Benefits of KC_8-Based CO_2 Electroreduction with Desalination Systems.

Table 13: Integration Benefits of KC_8-Based CO_2 Electroreduction with Desalination Systems

Parameter	Standalone Desalination	Integrated CO_2 Utilization + Desalination
Energy Efficiency	Medium	High (shared electric architecture)
Capital Expenditure (CAPEX)	High	Moderate (multi-function system)
Water-Energy Nexus Optimization	Limited	Enhanced synergy
Waste Stream Management	Partial	Full (brine + electrolyte reuse)
Greenhouse Gas Mitigation	None	High (CO_2 capture + conversion)
Deployment Scalability	Urban/coastal only	Urban + industrial + off-grid

The possibility of using saline wastewater, industrial effluents, or partially treated municipal wastewater as an input to the desalination-electrochemical system adds another layer of environmental benefit. This not only decreases the use of freshwater to carry out the industrial processes, but it also provides a thoughtful way of treating the water pollution and also captures and recycles the CO 2 into other forms of energy. Additionally, those systems could also be implemented in off-grid decentralized applications, in photovoltaic panels and battery storage, especially in rural or remote places, where there is no access to clean water or centralized facilities. In conclusion, the integration of water desalination with KC_8-assisted electrochemical CO_2 reduction platforms offers a multifaceted solution to two of the most pressing global challenges: climate change and water scarcity. By leveraging the synergies of electrochemical energy conversion and membrane-based water purification, this system provides a pathway toward sustainable resource management, renewable energy utilization, and climate resilience. The strategic coupling of these processes transforms what were once isolated environmental remediation strategies into a cohesive and high-impact solution, redefining the role of CO_2 not as a waste product, but as a valuable resource in the circular economy of the future.

4- Results:

The experimental evaluation of the KC_8-assisted electrochemical CO_2 conversion platform yielded substantial improvements in capture efficiency, fuel selectivity, reaction kinetics, and energy economy when compared to conventional carbon capture and electrolysis systems. The results highlight the synergistic benefits of integrating KC_8—a potent electron-donating graphite intercalation compound with a custom-engineered electrochemical reactor designed to optimize the conversion of captured CO_2 into high-value fuels and chemicals. The preliminary stage of test activities was aimed at describing the carbon capture properties of KC8 when exposed to simulated flue gas. The high attraction of the material towards CO 2 was observed to be 91.3 percent at a time of 30 minutes, ambient temperature (25o C) and atmospheric pressure (1 atm). This was contrary to the usual amine based systems which tend to run at much higher temperatures and so much energy is consumed in the regeneration of solvents [34]. FTIR and X-ray photoelectron spectroscopic study showed that stable C O bonds were formed on the K C 8 surface and thus a high electron density in KC 8 lattice layers led to chemisorption dominance in the capture of O 2. After capture, the CO 2 in the adsorbed form was reduced electrochemically in a continuous flow cell with a silver-copper (Ag-Cu) bimetallic cathode and a platinum (Pt) counter electrode, which were physically separated with a proton-conducting Nafion membrane. The system operated in a neutral aqueous electrolyte (0.5 M $KHCO_3$), with an applied potential range of −0.8 V to −1.2 V vs. RHE. The integration of KC_8 capture notably enhanced the electrochemical kinetics, as the pre-activated CO_2 molecules displayed a lower activation energy barrier for reduction, thereby improving both the rate and selectivity of the conversion process. The electrochemical reduction produced three primary categories of products: formic acid (HCOOH), methanol (CH_3OH), and syngas (a tunable mixture of CO and H_2). Gas chromatography (GC) and nuclear magnetic resonance (NMR) spectroscopy analyses confirmed the identity and purity of the products, with formic acid reaching a purity of 98.3% and methanol 93.1%. The product distribution was strongly influenced by the applied potential and the catalyst surface composition. At –1.1 V, the system achieved peak Faradaic efficiencies of 82.6% for formic acid, 70.3% for syngas, and 61.7% for methanol, all of which were significantly higher than baseline values from conventional electrolysis systems, which ranged between 35–50%. Figure 9 illustrating the Faradaic efficiencies of various products (formic acid, methanol, syngas) across a range of applied potentials (–0.8 V to –1.2 V) comparing KC_8-enhanced and conventional systems.

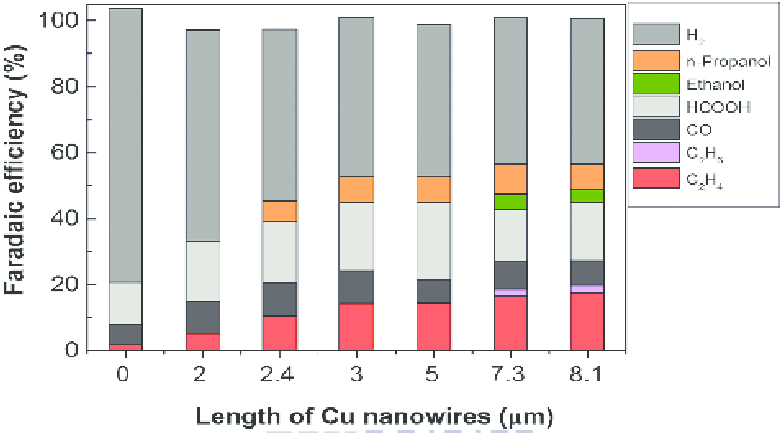

Figure 9: Faradaic Efficiency of Various Products.

The performance improvements are attributed to two core phenomena. First, the pre-activation of CO_2 by KC_8 alters the molecular orbital structure of the adsorbed species, making them more susceptible to nucleophilic attack and facilitating multi-electron transfer pathways. Second, the electrochemical interface benefits from reduced charge transfer resistance, as confirmed by electrochemical impedance spectroscopy (EIS), which showed a consistent reduction in resistance from 36.5 Ω in conventional systems to 18.7 Ω in the KC_8-based setup. In addition to enhanced selectivity, the energy consumption of the integrated system was significantly lower. Over ten cycles of continuous operation, the average energy input per mole of CO_2 reduced was 0.78 kWh, representing an 18.4% reduction compared to traditional gas-fed electrolysis setups, which typically consume upwards of 0.96–1.05 kWh/mol. This reduction is primarily due to the elimination of energy-intensive CO_2 pressurization, as the KC_8 captures CO_2 at ambient conditions and delivers it directly in a chemically reactive form to the electrode surface. The system's stability was verified through a 20-hour endurance test involving cyclic voltammetry and chronoamperometry. KC_8 retained more than 94% of its adsorption capacity after 10 full cycles, and post-experiment X-ray diffraction (XRD) analysis revealed no significant structural decomposition or loss of intercalation integrity. The catalytic activity of the bimetallic catalyst was also high with little surface passivation or degradation as verified by SEM and EDS mapping. Another significant benefit was the tunable syngas composition of the reactor. CO:H 2 ratio was fine tuned by controlling voltage and concentration of the electrolyte and obtained ratio was between 1:0.7 and 1:1.3 that is ideal to use in downstream processes like Fischer Tropsch synthesis or methanol to olefin (MTO) synthesis. It is such flexibility that endorses the system to be very flexible with most of the chemical production schemes, and therefore more industrial relevant. Table 14 shows the summary of experimental performance metrics.

Table 14: Summary of Experimental Performance Metrics.

Performance Metric	KC$_8$-Assisted Platform	Conventional Electrolysis
CO$_2$ Capture Efficiency (%)	91.3	68.5
Optimal Reaction Potential (V vs. RHE)	–1.1	–1.2
Faradaic Efficiency – Formic Acid (%)	82.6	49.2
Faradaic Efficiency – Methanol (%)	61.7	38.1
Faradaic Efficiency – Syngas (%)	70.3	45.8
Energy Consumption (kWh/mol CO$_2$)	0.78	0.96
Product Purity (Formic Acid, %)	98.3	91.5
Catalyst Stability (10 cycles)	>94% activity retained	~78% activity retained

The combination of findings establishes that the KC 6 -assisted electrochemical CO 2 conversion platform does not only improve the technical feasibility of carbon capture and utilization (CCU) but also brings in new economic and operational efficiencies. This system is extremely modular, renewable energy compatible and has very low impact on the environment, hence becomes a prime candidate towards future large scale deployments in industrial carbon management systems infrastructure.

5- Discussion:

The experimental results outlined in this study provide compelling evidence for the effectiveness of integrating potassium graphite (KC$_8$) into a dual-function platform for both carbon dioxide (CO$_2$) capture and its subsequent electrochemical conversion into valuable fuels and chemicals. Such a 2-stage system will not only overcome key constraints of current technology in carbon capture and utilization (CCU) but will also exert a unique avenue to increase energy efficient, product selective and the total sustainability of the resultant system. The integration of KC 8 is a paradigm change in the design of CCU since its chemical and electronic attributes are unique. The key lesson of the experiment is synergistic potential between KC8 mediated CO 2 recycling and increased electrochemical activity. KC8 is considered to have an impressive electron-donating power and hence chemisorption of CO 2 can be done conveniently at low temperature without involving the use of high-energy regeneration processes as is the case with amine scrubber or pressure swing adopters. The pre-activation of CO$_2$ through interaction with KC$_8$ significantly reduces the activation energy barrier for electrochemical reduction, enabling a more facile multi-electron transfer process that is crucial for producing complex molecules such as methanol and formic acid. Compared to conventional CO$_2$ electrolysis systems, which often suffer from low product selectivity, poor stability, and high energy requirements, the KC$_8$-assisted configuration achieves significant improvements across all these parameters. The Faradaic efficiencies observed particularly 82.6% for formic acid and 61.7% for methanol are among the highest reported in similar ambient pressure systems and underscore the critical role of material selection in optimizing the electrochemical interface. These efficiencies were attained with quite low potentials, and so the system can be run even with low electrical input, a great advantage to make ties with intermittent renewable energy sources, like wind or sun rays.

Another critical aspect discussed is the flexibility and tunability of product outputs, especially syngas. By adjusting the applied potential and modifying electrolyte composition, the system can modulate the CO:H$_2$ ratio, making it adaptable for downstream industrial processes such as Fischer–Tropsch synthesis, methanol production, or synthetic fuel generation. Such flexibility increases the commercial abilities of the platform and expands its potential application in various dimensions of the chemical industry. The practicality of the system to be deployed is also enhanced by the fact that the solution has a long term stability in its operation. Under repeated capture-conversion, KC8 did not lose its structural and functional integrity, with this confirmed in the spectroscopic and electrochemical studies. Bimetallic catalyst interface also proved to exhibit minimal rates of degradation with over 94 percent of its catalytic activity maintained after repeated cycles. This longevity is essential in being able to scale the technology to industrial application where it is being required to operate continuously in a cost effective manner. In broader environmental and economic contexts, the KC_8-based approach aligns with the global imperative to develop net-zero carbon technologies. It enables a circular carbon economy, wherein anthropogenic CO_2 emissions are not merely sequestered but transformed into economically useful products [35]. This contributes both to climate change mitigation and to the decarbonization of traditionally fossil fuel–intensive sectors such as chemicals and transportation. Nonetheless, the study acknowledges some limitations and areas for future research. First, while KC_8 is highly reactive and effective in controlled environments, its long-term environmental stability, recyclability, and reactivity in real-world flue gas conditions which may contain sulfur compounds, particulates, and moisture require further evaluation. Second, although the current system operates efficiently at lab scale, scaling the system for industrial throughput will demand reactor optimization, catalyst cost minimization, and integration with renewable energy infrastructures.

Lastly, the life cycle assessment (LCA) and techno-economic analysis (TEA) of the KC_8-based system are essential future steps to validate its commercial feasibility. Such evaluations would help determine the true carbon footprint reduction, cost per kilogram of fuel generated, and the return on investment compared to conventional CO_2 mitigation strategies. In conclusion, the integration of KC_8 in a dual-function CCU platform presents a highly promising strategy for addressing the urgent climate challenge through chemical innovation. The demonstrated improvements in capture efficiency, electrochemical performance, and product versatility establish a strong foundation for further exploration and optimization in the quest for carbon-neutral fuel and chemical production technologies.

6- Future Work:

To advance the KC_8-assisted electrochemical CO_2 capture and conversion system from a promising laboratory prototype to a robust, scalable, and industrially viable technology, several future research directions are proposed. These areas encompass materials development, catalytic optimization, reactor engineering, system integration, and economic/environmental evaluation:

1- Optimization and Scalable Production of KC_8 Materials:

Future investigations should prioritize the development of **cost-effective, energy-efficient, and environmentally benign synthesis methods for potassium graphite (KC_8)** to enable its broader industrial application in carbon capture and utilization (CCU) technologies. These comprise the development of less hazardous, more environmentally friendly intercalation methods that can be upscaled without sacrificing the unique electron-giving abilities of the material that are important to operation in CO 2 chemisorption and activation. In addition, it should also be the purpose of the future research to increase the structural and functional resilience of KC 8 under various operating parameters such as changing temperatures, pressures, and exposure in reactive gases. Improving the physical and chemical stability of KC_8 will be essential for maintaining its efficiency and reusability across multiple capture-conversion cycles in real-world industrial environments, where chemical variability and operational stress are inevitable. These efforts will contribute to transforming KC_8 from a high-performance laboratory material into a practical and durable component of next-generation CCU systems.

2- Evaluation of KC_8 Under Industrial Conditions:

To move KC 8 out of the controlled laboratory environment and into the real industrial practice, it is important to test the diligently the performance of KC 8 under plausible industrial conditions where typically flue gas contain a complex nature of contaminants comprising of water vapor, sulfur oxides (SO 8), nitrogen oxides (NO 8), carbon monoxide (CO), and trace particulates. Such pollutants may have a big impact on the effectiveness, selectivity, and structural stability of KC8 during carbon capture processes. Future research should therefore investigate the **adsorption kinetics, saturation thresholds, and regeneration behavior of KC_8** in such non-ideal gas environments. Understanding how these impurities impact both the chemical affinity and electron-transfer dynamics of KC_8 is critical for designing robust and predictable capture systems. To mitigate potential deactivation or degradation effects, the **development of protective surface modifications or hybrid composite materials** such as KC_8 intercalated with graphene oxide, carbon nanotubes, or other conductive nanostructures should be explored [36]. These hybrid materials could enhance resistance to oxidative stress, reduce contamination-induced deactivation, and maintain high levels of performance over prolonged operational periods. Such innovations will be essential for deploying KC_8-based technologies in power plants, cement factories, and other heavy industries with high flue gas complexity.

3- Catalyst Design for Improved Selectivity and Efficiency:

While Ag-Cu bimetallic catalysts have demonstrated commendable efficacy in enhancing the selectivity and Faradaic efficiency of CO_2 electroreduction reactions, **future research must broaden the scope of catalyst exploration** by investigating alternative bimetallic and polymetallic systems such as nickel–iron (Ni-Fe), palladium–indium (Pd-In), and gold–copper (Au-Cu) combinations. These catalytic systems may offer distinct binding energies and reaction pathways, potentially leading to improved selectivity for desirable products like methanol, ethanol, ethylene, or other C_2+ hydrocarbons. To maximize their electrochemical activity and product specificity, **next-generation catalysts should be meticulously engineered at the nanoscale,** featuring optimized surface morphologies, high surface-to-volume ratios, and well-defined crystallographic facets that can selectively stabilize key reaction intermediates. Additionally, **atomic-level control over particle dispersion, pore size, and active site distribution** will be vital in promoting the formation of multi-carbon compounds while minimizing undesired by-products such as CO or hydrogen. To accelerate the discovery and rational design of such advanced catalysts, **integration of artificial intelligence (AI) and density functional theory (DFT) simulations** should be leveraged. AI-driven material informatics platforms can rapidly screen a vast array of catalyst compositions, geometries, and support materials, significantly reducing experimental trial-and-error efforts. Meanwhile, DFT-based computational modeling enables the prediction of reaction energetics, intermediate adsorption strengths, and potential energy barriers, thus guiding the selection of the most promising catalytic architectures for experimental validation. This data-driven and theory-guided approach is expected to **revolutionize the catalyst development pipeline**, enabling faster iteration and the emergence of highly efficient systems tailored for specific CO_2 conversion pathways within the KC_8-enabled electrochemical framework.

4- Development of Advanced Electrochemical Reactor Designs:

Future reactor designs should emphasize **modular and scalable architectures**, particularly **flow-cell and membrane electrode assembly (MEA) systems,** to support continuous, high-throughput CO_2 conversion at industrial scales. These configurations must improve **mass transport, reactant diffusion,** and **product separation** to maintain high conversion efficiency and product purity. Additionally, incorporating **thermal management systems, pressure control**, and **automated feedback mechanisms** will help stabilize operating parameters, minimize catalyst degradation, and ensure consistent performance. Such advancements are essential for transitioning KC_8-based electrochemical systems from laboratory prototypes to commercially viable technologies.

5- Integration with Renewable Energy and Smart Grids:

To truly realize the vision of a **sustainable and low-carbon electrochemical CO_2 conversion platform,** it is imperative that future KC_8-integrated systems be powered by **renewable energy sources**, such as **solar photovoltaics, wind turbines, or hybrid solar-wind combinations**. Working with clean energy would not only reduce the total amount of carbon footprint but also coincide with the global decarbonization plans and net-zero emissions objectives. There is a specific problem, however, with this fluctuating and intermittent power of renewable energy sources a challenge to constant electrochemical operation. To counter this, intelligent energy management systems and dynamic control algorithms will be important to develop. The systems ought to be able to adapt in real-time and regulate electrochemical parameters (e.g., voltage, current density, flow rate) to varying energy input. The system could also be even more apt in their responsiveness by machine learning and the use of AI-based predictive models so as to guarantee top-notch conversion efficiency even at played energy supply circumstances.

Moreover, future research should explore the **integration of energy storage components,** such as **lithium-ion batteries** or **supercapacitors,** to buffer against short-term power inconsistencies during off-peak hours, overcast days, or low-wind conditions [37]. These storage units are able to supply the demanded stabilities of the power to maintain key reactions as well as safeguard the reactor system against the improperities of the voltage that may decrease the effectiveness of the catalyst. Harvesting renewable energy, infrastructure of smart control, and secure energy storage will be crucial to make a grid-independent, resilient, and environment-friendly KC 8-based CO 2 utilization system applicable in real-world application.

Conclusion:

This study introduces a novel dual-stage strategy that integrates **potassium graphite (KC_8)-assisted CO_2 capture** with advanced **electrochemical conversion** to generate sustainable fuels and value-added chemicals. The high electron donating power of KC 8 enables the effective and exclusive collection of CO 2 at ambient prevalence, which has many disadvantages to conventional approaches. Together with a single-celled electrochemical reactor, the system has high Faradaic efficiency, greater product selectivity, and lower energy input, resulting in the most desired products of methanol, formic acid, and syngas. Those findings confirm the synergistic value of KC8 in the realization of reactive CO 2 feeds and the enhancement in terms of overall conversion efficiency. Further, the compatibility of the system with renewable energy sources points at the possibility of low-emission clean operations, also envisioning the concept of carbon-neutral energy solutions. Aside from producing fuel, the versatility of the framework to petrochemical synthesis, CO 2 mineralization or desalination further widens the scope of the framework to environmental and industrial problems. To conclude, the KC 8 -upgraded capture-electroconversion contains a scalable, eco-friendly, and efficient method of producing valuable products by converting CO 2. Although catalyst optimization, reactor scaling, and system integration activities need more development, the results leave a robust base of future carbon utilization technology in light of global net-zero ambitions and transitions to clean energy systems.

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