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Review Article

ELECTROCHEMICAL CARBON DIOXIDE (CO_2) CAPTURE WITH IONIC LIQUIDS: PROCESS DESIGN AND SCALE-UP

REUBEN PAMBANI[1*], ANSAR BILYAMINU ADAM[2], MUSA YAHAYA ABUBAKAR[3]

[1]Department of Chemical Engineering, Federal University Wukari, Taraba State, Nigeria. [2]Department of Chemistry, Federal University Wukari, Taraba State, Nigeria. [3]Department of Industrial Chemistry, Federal University Wukari, Taraba State, Nigeria
*Corresponding author: Reuben Pambani; *Email: reubenpambani@fuwukari.edu.ng

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ABSTRACT

Ionic liquids are tunable, low volatile and energy efficient, which make them promising materials for electrochemical CO_2 capture as an alternative to the conventional carbon capture. The application of this process relies on the specific physicochemical properties of ionic liquid (IL)s: high solubility to CO2 and electrochemical stability, which allows ionic liquid (IL)s to reversibly absorb and release carbon dioxide as a result of changing potential under the specified conditions. Thermal energy doubts are reduced compared to traditional amine-based methods, leading to higher compatibility with renewable electricity sources. This work carries out a comprehensive analysis of reactor configurations, mass transport dynamics, ionic liquid (IL) regeneration strategies and cost-effectiveness of this process for industrial deployment. The paper describes how special attention is given to the optimization of electrode materials, cell geometry, and process integration for scalable operations. Novel approach is technoeconomically modelled and lifecycle analysis is addressed to highlight advantages and bottlenecks when scaling is needed. The study shows a path forward for turning CO_2 capture from an energy-intensive, energy-input-requiring process to one that becomes part of the solution to the global decarbonization problem.

Keywords: Electrochemical CO_2 capture, Ionic liquids, Process design, Scale-up, Sustainable technology

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INTRODUCTION

The climate crisis is becoming more intense, and with that, global systems are under huge pressure to accelerate the transition towards net zero emissions. Effective carbon capture technologies have become one of the key approaches in climate mitigation strategies that rely on the remaining most abundant anthropogenic greenhouse gas, carbon dioxide (CO_2). Amine scrubbing has reached commercial scale but has been limited by high thermal regeneration costs and solvent degradation, in addition to solvent corrosivity, because of which the process does not have the most favorable operational and environmental performance [1]. The electrochemical approach not only fends off emissions per se but also provides a huge opportunity to deploy in a decentralized fashion with scalability all the way from industrial, through commercial, to residential settings [2]. The operating energy consumption of electrochemical systems can be below 1 GJ/ton CO_2, much improved over the 2–4 GJ per ton CO_2 required in thermal processes [3].

Ionic Liquids (ionic liquids (ILs))-organic salts that are liquid at or near room temperature-are a pivotal enabler of this innovation. Due to negligible vapor pressure, high thermal stability, wide electrochemical windows, and customizable molecular structure, ionic liquids (ILs) possess unique physicochemical properties. Due to these features, these systems would be ideal for selective CO_2 binding and electrochemical reversibility without solvent loss or fouling-both of which are major limitations prohibiting traditional systems [4]. The redox properties of ionic liquids (ILs) can be manipulated to enable the reversible binding of CO_2 under defined voltage inputs.

Furthermore, an interesting synergy arises from integrating IL-based electrochemical systems with renewable energy power grids, in which both the materials and operation conditions/functions are well matched. Such systems are designed to operate with high efficiency under intermittent power conditions so that CO_2 capture could be dynamically matched to the availability of solar or wind power. This adaptability pointed out by [5] will be equally important for future energy infrastructures that go beyond capacity to include flexibility and resilience. Furthermore, coupling CO_2 capture with the on-site electrochemical conversion (for instance, syngas, formic acid, methanol) can allow closed-loop systems that simultaneously sequester and valorize the carbon [6].

This platform could be versatile and not only be supportive in the climate mitigation direction but also be supportive in compliance with green chemistry and circular economy principles. Electrochemical capture is IL-based and can be tuned for flue gases to ambient air sources, and the modular nature of its deployment can target various sectors, such as steel and cement to data centers and agriculture. And that's why, according to [7], this field is an intersection of chemistry, materials science, and renewable engineering and is redefining what is technically and economically possible in CO_2 capture.

In this study, we present a systematic study of electrochemical CO_2 capture using designed ionic liquids in terms of Faradaic efficiency, capture capacity, stability, and energy consumption. We wish to establish a new design framework for scalable, sustainable, and economically viable CO_2 management systems through the study of the IL composition and its correlation with the electrochemical parameters.

Search Criteria

This review was based on literature sourced from databases such as Scopus, Web of Science, ScienceDirect, PubMed, and Google Scholar. Keywords included terms related to electrochemical CO_2 capture, ionic liquids, renewable energy integration, and techno-economic assessments. The search was limited to peer-reviewed publications from 2019 to 2024, with a focus on experimental data, system-level analyses, and high-impact journals. Seminal works outside this range were also included when necessary to support foundational concepts.

Role of ionic liquids in CO_2 capture

The sub-limits of access to this element and high chemical costs pose challenges for carbon capture technology. In contrast to conventional aqueous amines that experience extreme volatility and heat degradation, as well as enormous regenerative energy requirements, ILs are proposed as non-volatile, electrochemically stable, and extremely CO_2-philic mediums for reversible capture processes.

Among other outstanding features, they constitute one of the most remarkable IL properties: exceptional CO_2 solubility, particularly and purposely in task-specific ILs that contain functional groups like amines, carboxylates, or azolium moieties. These groups can chemically interact with CO_2; the resulting stable but reversible adducts, in turn, increase selectivity and capacity [8]. Moreover, the molecular ability to tailor ILs for process requirements is possible, including the solubility, viscosity, and electrochemical properties [9].

An additional important advantage is that ILs have a wide electrochemical window, enabling the application of large potentials without solvent breakdown. The stability of ILs is well suited to electrochemical CO_2 capture, wherein the redox active species in the IL can be exploited for the specific and controlled binding and release of CO_2 based on voltage. As an example, quinones and metal-organic complexes containing ILs have achieved high Faradaic efficiencies and long durability at multiple capture and release cycles [10].

Also, ILs have negligible vapor pressure, which prevents solvent loss due to solvent evaporation and results in minimal environmental hazards and process obsolescence. As a result, IL-based systems are very attractive for long-term, continuous operation for both point-source and direct air capture [11].

All of these properties together collectively make ILs ideal candidates for carbon capture systems based on future-generation technologies. They are perfectly compatible with renewable electricity, have robust chemical resilience, and have the capability to be customized [12]. Underline how the synergy between ILs and electrochemical platforms allows the development of new systems, hardly based on energy-efficient, compact, and modular CO_2 separation systems, amenable to being seamlessly integrated into future carbon management infrastructures.

Mechanisms of electrochemical CO_2 capture using ionic liquids

This motor of electrochemical CO_2 capture using ionic liquids (ILs) is based on reversible redox reactions for binding and releasing carbon dioxide. Because of their wide electrochemical windows and the ability to solubilize redox active species, ILs represent an excellent medium from which to develop energy-efficient CO_2 manipulation schemes.

The central redox active molecule or functional group of the process is either dissolved in or covalently attached to the IL and can be electrochemically switched between a CO2 reactive and inert redox state. At a specific potential, CO_2 in the surrounding gas stream is captured by the IL chemically binding to it. Upon reversing the potential, the bound CO_2 is shed, and the original species are returned for reuse in the next cycle. By driving these separations with voltage instead of temperature, this voltage-driven control allows community-level capture and absorption of energy with substantial energy advantages compared to the existing temperature swing absorption system [2].

For instance, quinone-functionalized ILs are widely used, wherein the quinone moiety is electrochemically reduced to form a nucleophilic species, which reacts readily with CO_2 to form respective carbonate or carbamate adducts. Upon reoxidation, the quinone regenerated carries a pure CO_2 due to adduct dissociation [13]. The interaction is highly selective and reversible and thus allows the system to cycle repeatedly with little input energy.

In addition, ILs improve CO_2 and ion diffusion owing to their high CO_2 solubility and ionic conductivity. These characteristics greatly enhance the kinetics of the capture process and thereby lower the system resistance and raise the overall efficiency [14]. Moreover, the low volatility of ILs guarantees long-term operational stability without the danger of evaporation of the solvent or environmental contamination.

Electrochemical EL systems, upon the release of CO_2 are inherently modular and scalable, which is something that is important for decentralized applications like direct air capture (DAC) or electrochemical CO_2 fixation integrated with renewable energy sources. For example, an example of such a scenario could be a solar-powered electrochemical cell utilizing ILs to convey off-grid CO_2 removal with very little infrastructure that was recently tried in the pilot studies [15].

ILs' tunable chemistry, electrochemical responsiveness, and low environmental footprint combine to provide a transformative platform for carbon capture. As pointed out by [12], this electrochemical route eliminates the energy penalty and, at the same time, circumvents the disadvantages of post-combustion carbon capture by providing compact, mobile, and effective means for carbon management in many industrial and environmental settings.

Process design considerations

For the design of an electrochemical CO_2 capture system based on ionic liquids (ILs), these disciplines need to be synergistically combined to reveal electrochemistry and material science elements together with fluid dynamics. Electrochemical designs are not like standard solvent-based systems, as the variables to control them are voltage, not pressure. While this opens up new possibilities, it also presents challenges-to be tackled with great precision in order to realize the full potential of IL-based capture.

Reactor configuration: enabling triple-phase interaction

An effective reactor configuration is one that provides most of the interface between the gas (CO_2), liquid (IL), and solid (electrode) phases. The critical zone examined in this interface is the zone where CO_2 molecules are dissolved into an ionic medium and finally interact with the electrochemically active species at the electrode surface. In particular, flow-through or gas diffusion electrode (GDE)-based configurations are attractive because they enable rapid CO_2 absorption and also minimize mass transport limitations. As pointed out by [14], the gas-liquid contact efficiency can be increased up to 40% with microstructured flow fields when compared to a flat electrode configuration.

Mass transport: navigating viscosity and diffusivity

Despite their richness in functionality, ionic liquids are known to have high viscosities, which hinder mass transport. As a result, there is a need for deliberate engineering of diffusion-layer thickness, flow rates, and turbulence-inducing geometries. It has been demonstrated that pulsatile flow or microbubble dispersion can greatly speed up CO_2 migration towards reactive zones [16]. Further, selection of ILs with lower viscosity and/or the use of co-solvents can improve the diffusivity of both CO_2 and redox active species without affecting the electrochemical stability.

Electrochemical protocols: controlling capture and release

Electrochemical capture mechanism is controlled by redox processes of reactive species occurring in the IL medium. One prototypical case that can be discussed is quinone-based systems.

$$Q+2e^{-}+2H+\leftrightarrow QH_2$$

$$QH_2+CO_2\rightarrow QH_2\cdot CO_2$$

In the reduction step, the quinone (Q) is reduced to hydroquinone (QH_2) electrochemically that could react with CO_2 to form a reversible adduct. When the applied voltage is reversed, QH_2 is again oxidized back into Q, expelling CO_2. Such a mechanism allows for simple voltage toggling to generate well-defined capture and release cycles with high precision. However, as described by [2], electrochemical cycling can also provide a unique pathway to synchronize capture with fluctuating renewable energy inputs and thus control the operation of real-time carbon management operations.

Electrode selection and geometry: performance anchors

Both reaction kinetics and overall energy efficiency of the system depend highly on electrode material and structure. However, carbon nanotubes, graphene composites, or functionalized porous carbons possess high surface area, tunable hydrophobicity, and good electrochemical stability. Furthermore, 3D-structured electrodes, including interdigitated arrays or foams, contact more of the IL and decrease resistance as well as promote bubble detachment when desorbing. Vertical graphene electrodes showed better diffusion and reactive accessibility of the vertically aligned graphene electrodes and resulted in CO_2 reduction rates that were over 60% improved upon previous vertically seeded graphene electrodes, as reported by [13].

System integration and scalability: from lab to field

In order to make CO_2 capture design successful, beyond lab-scale proof of concept, it is necessary for this technology to be operated within modular, scalable architectures. This encompasses full integration with power sources (solar or wind), automated cycling protocol execution, and rugged thermal control. Secondly, the electrochemical IL systems are inherently closed-loop in nature, reducing loss of solvent, especially in the more severe or exotic environments. They showed [15] that a pilot setup for cyclic removal of CO_2 over 100+hours was possible with little loss of performance.

Scale-up strategies

A number of key engineering issues must be addressed in scaling up an electrochemical CO_2 capture process from the laboratory to industrial applications. These challenges include reactor design, process sustainability, to ensure that the technology is cost effective, efficient and robust over long period of operation. The following are some strategies to overcome these challenges to gap between proof of concept research and large scale deployment.

Modular reactor design: enabling flexible expansion

Reactor design is a requirement for scalability with no loss in performance for industrial-scale applications. As an example, modular reactor systems are advantageous since they can grow incrementally with variable CO_2 capture rates. Generally, these systems are parallel or serially interconnected systems, which provide flexibility with respect to fluctuations of supply of renewable energy sources as well as changing CO_2 concentrations. Modularity allows for easier maintenance too, as the reactor units can be more easily serviced or replaced without interrupting the entire system. Therefore, modularity in reactor design has demonstrated over a 30% reduction of operational downtime for scale-up processes, as shown by [4], and is known to be crucial in commercial applications.

IL regeneration cycles that are efficient as enablers to long term viability

Current challenges with ionic liquid-based CO_2 capture are to use ILs with high performance, especially in terms of their capability of performing well under regeneration cycles. IL regeneration of the absorbed CO_2 consists of heating or providing electrochemical potential to purge the captured CO_2 and regenerate IL for the next cycle. It is necessary to make the process efficient and energy-conserving and to minimize the degradation. However, in practice, ILs may suffer from decomposition or accumulation of impurities after a number of cycles under the relevant conditions of capacity and selectivity. In order to reduce this, IL regeneration cycles must be optimized in such a way that it reduces energy input and maximizes recovery rate [10]. Have recently suggested integrating a hybrid regeneration system that combines thermal and electrochemical methods and therefore lowers energy consumption and extends IL depot life. This kind of strategy will increase the sustainability of electrochemical CO_2 capture systems and make them work for years.

Minimizing the material degradation: ensuring system-lasting

For the successful operation of CO_2 capture systems, a critical factor is the material degradation, in particular of electrodes and ionic liquids. However, the on-and-off cycling of CO_2 sorption and release on both electrodes, by means of continuous electrochemical cycling, uses up both electrodes and ILs, leading to excessive wear and tear, accompanied by a reduction in efficiency and increased maintenance costs. The advent of highly durable carbon-based composites or metal-organic frameworks (MOFs) serves as an advance in electrode materials, enabling the electrodes to resist corrosion and foul less, thus lengthening their lifespan [16]. Likewise, choosing ILs with inherent chemical stability and low volatility preserves their performance many capture and release cycles. Besides, incorporating the ability of self-healing or regenerating material into the system was able to further reduce the effect of material degradation, as shown in the work by [17], where a carbon-n-n-based electrode with self-healing capability did not show any performance drop at 500 cycles.

Adaptability to existing infrastructure: facilitating seamless integration

The need for the scaling up of electrochemical CO_2 capture technologies and integrating them into existing industrial infrastructures is one of its main components. CO_2 capture systems should be designed to maximize technical performance compatibility with current processes and power systems. As an example, the system should be able to adapt to changing availability of electricity provided by renewable resources like solar or wind for integration of electrochemical CO_2 capture with renewable energy sources. Couplingctrochemical systems with energy storage units, such as batteries or capacitors, may be more effective in load balancing and, thus, lessen demand whenever renewable energy generation is low so that CO_2 capture can still occur [13]. Furthermore, systems need to be designed to fit into the context of existing flue gas streams, or indeed carbon capture systems, in industrial installations such that changes to their infrastructure are minimal. All of these factors allow electrochemical CO_2 capture systems to be scaled up economically and with environmental impact.

Techno-economic and environmental assessment

The techno-economic and environmental assessment of CO_2 electrochemical capture systems is performed on a comprehensive level. This assessment thus informs financial feasibility, environmental impact, and driving decisions such as investing in the technology, implementing new policy, or modifying existing policy for investors, policymakers, and other industry stakeholders. For the assessment of the viability of this technology, the following key elements are important.

Techno-economic modeling: estimating capital and operating costs

Electrochemical CO_2 capture systems are among the technologies with which techno-economic modeling must be conducted to estimate the initial capital costs and ongoing operating expenses. This enables researchers and industry professionals to assess the cost competitiveness of the technology compared to other methods of CO_2 capture, such as amine scrubbing or membrane-based technologies. Finally, this model takes into account reactor size, material costs, energy requirements, maintenance and labor costs, and expected system lifetime. Optimization of system performance in terms of cost-effectiveness and sustainability can be achieved by means of simulation of different design configurations and operating scenarios.

Capital expenditure (capital expenditure (CAPEX)) includes costs of buying reactors, electrolyzers, ionic liquids, etc., while operational expenditure (operational expenditure (OPEX)) includes energy consumption, labor, and material regeneration [18] states a study that using renewable energy sources for electrochemical CO_2 capture can greatly reduce the operating cost as renewable electricity is typically cheaper than conventional grid power. On the other hand, IL regeneration and system durability also determine the system's long-term operational cost. Techno-economic analyses of these factors have the potential of offering insights into the payback period and break-even points for industrial-scale CO_2 capture plants.

Lifecycle analysis ion and environmental impacts

Electrochemical CO_2 capture technology is without question in need of a methodology with which to assess environmental performance, and that methodology is lifecycle analysis (LCA). LCA takes into account all stages of the technology's lifecycle, from material extraction and production to operation and disposal. Four maps of the environmental footprint of the capturer system approach to provide a very comprehensive picture of how much the CO_2 footprint will be reduced and other environmental impacts, including water use, energy consumption, and potential for toxicity.

An integral part of LCA the net CO_2 reduction that the system delivers, i. e., taking into account those CO_2 that have been captured d any CO_2 generated in the process. LCA can show whether the energy needed to power the system actually overcomes the CO_2 captured, making the technology unviable. In a recent work by [14], a combination of electrochemical CO_2 capture with the use of renewable energy lowers the life-cycle carbon footprint of the capture process down to a net zero carbon balance. In addition, LCA addresses the impact of IL degradation, hazardous byproducts if made, and the closed loop and end-of-life management of the materials. Bio-based ionic liquids is an example where it can lead to significant environmental burden associated with disposal.

Integration of techno-economic and environmental assessments: achieving commercial viability

Techno-economic and environmental assessments are integrated to provide a framework for commercial viability assessment of electrochemical CO_2 capture technologies. The assessments provide a wholesome view of the financial sustainability and environmental benefits overall, allowing stakeholders to make the right decisions in regards to whether they need to invest in or adopt the technology at a larger scale. For instance, despite possibly being costly to initialize, the prospects of significant long-term operational savings and environmental benefits (especially when linked with renewable energy sources) can give a favorable I

Moreover, if one is able to integrate these assessments with regulatory considerations, e. g., carbon pricing and emissions trading schemes, the commercial outlook improves further. Due to incentives or subsidies from governments and international organizations for technologies that reducebon emissions, this will help businesses to lower the financial burden of push and pull strategies. s. s. Green energy policies of governments are seen by [19] as a key enabler for the adoption of CO_2-capturing technologies like demand reduction, demand shifting, or relieving an initial cost barrier and promoting market adoption.

CONCLUSION

The electrochemical method of CO_2 capture using ionic liquids (ILs) is presented as an energy-efficient and sustainable carbon capture. High CO_2 solubility, electrochemical stability, and low volatilization make the process suitable for reversible CO_2 capture under electrochemical control at low energy. The system is also described in terms of some key aspects such as reactor design, electrode material selection, and mass transport optimization for scalable and efficient operation. Scale-up strategies and modular reactor designs as well as IL regeneration cycles for industrial applications are also discussed,, and a techno-economic and environmental assessment of the technology is presented to determine commercial viability. This work represents a contribution towards the goal of decarbonization as it presents a sustainable and low-cost solution for CO_2 capture, which opens the door for the industrial adoption of this innovative technology on a large scale.

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AUTHORS CONTRIBUTIONS

Reuben Pambani led the research design, manuscript coordination, and overall writing.

Ansar Bilyaminu Adam conducted the literature review and contributed to technical analysis and formatting.

Musa Yahaya Abubakar supported data interpretation and reviewed the manuscript, focusing on scalability and techno-economic aspects.

CONFLICT OF INTERESTS

Declared none

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