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Carbon Capture and Mechanical Design of Membrane Reactors: A Systematic Review and Design-Performance Framework for Sustainable Energy Systems

Abdulrahman B. GAMBO

Department of Mechanical Engineering, Minna, Federal University of Technology, Minna, Nigeria

danbauranborgu@gmail.com

Abstract

The imperative to mitigate climate change has accelerated the development of effective carbon capture systems. Of these, membrane reactors (MRs) have become a promising alternative because they can combine chemical reaction and selective separation of gases in a single unit and thus, they are more efficient and with lower energy penalties. This paper gives an in-depth overview of polymeric, ceramic, and mixed-matrix membranes (MMMs), especially focusing on the mechanical design issues, pressure tolerance, sealing integrity, thermal stress control, and modular scalability, that determine the feasibility of reactors at large scale. A systematic literature review and comparative analysis were performed, resulting in the development of a novel design–performance matrix linking membrane material properties with reactor mechanical requirements. Results demonstrate that ceramic membranes provide superior thermal stability and CO_2 *selectivity but are constrained by brittleness, while MMMs balance permeability and durability but face interfacial and scale-up challenges. The study concludes that optimal deployment of membrane reactors requires co-optimization of material innovation and mechanical engineering design, supported by emerging approaches such as additive manufacturing, defect-tolerant sealing, and digital twin models for predictive maintenance. These results point at the importance of interdisciplinary innovation to attain scalable and sustainable carbon capture technologies.*

Keywords: *Carbon capture; Membrane reactors; Mechanical design; Mixed-matrix membranes; Sustainability.*

1. Introduction

The twenty-first century is characterized by climate change as the major environmental issue. The major contributor to global warming and other related climatic disturbances is the carbon dioxide (CO_2) that contributes over three-quarters of the anthropogenic greenhouse gas emissions. Even with the rapid introduction of renewable energy sources and efficiency, fossil fuels still dominate the world power portfolio and hard-to-abate sectors such as cement, steel, refining and chemicals still use carbon-rich process heat. The Intergovernmental Panel on Climate Change (IPCC, 2022) and the International Energy Agency (IEA, 2023) agree that achieving the goals of the Paris Agreement will require not only deep decarbonization of the electricity sector but also extensive deployment of carbon capture, utilization, and storage (CCUS) across industry and power systems [1,2]. More traditional methods of capture such as amine absorption, solid sorbent adsorption, and cryogenic separation are known and commercially deployed. Nonetheless, they have established disadvantages: solvent regeneration is associated with substantial amounts of energy penalty, solvent destruction and corrosion in amine plants, and the high cost of capital and operation of cryogenic units. Such constraints have led to a surge of studies in membrane-based CO_2 capture as a smaller, modular, and possibly less energetically demanding alternative. Differences in permeability and solubility are used in gas separation membranes to conduct separations without phase change or chemical regeneration.

One of the most significant advances is the membrane reactor (MR), an integrated device that combines chemical reaction with selective gas separation in a single unit [3]. Equilibrium-limited reactions can be shifted by continuously removing one of the reaction products e.g., CO_2 or H_2O, thereby increasing conversion and selectivity while reducing the total number of process units and overall energy consumption [4]. MRs are applied in pre-combustion decarbonization (e.g., removal of CO_2 from syngas with concomitant enrichment of H_2), post-combustion capture of flue gases, and oxy-fuel technology based on oxygen-permeable membranes to generate CO_2-rich exhaust streams [5].

Although the literature on membranes tends to focus on permeability and selectivity, mechanical engineering constraints ultimately determine industrial viability [6]. Membrane modules and reactors must withstand significant pressure differentials, thermal gradients and cycling, vibration, and years of chemical exposure under operating

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conditions. Polymeric membranes are flexible and inexpensive but susceptible to plasticization and physical aging at high CO_2 partial pressures and elevated temperatures [7]. Ceramic membranes exhibit excellent thermal and chemical stability above 600 °C, yet are inherently brittle and poorly resistant to tensile stresses and thermal shock [8]. Mixed-matrix membranes (MMMs), which incorporate inorganic fillers such as zeolites, metal-organic frameworks (MOFs), or graphene oxide into polymer matrices, offer enhanced separation performance but introduce interfacial stress concentrations that can compromise long-term structural integrity [9].

Despite rapid advances in membrane materials, a critical gap persists between laboratory-scale performance and industrial deployment: prototypes with excellent permeability–selectivity pairs frequently fail at scale due to sealing failures, thermal mismatch, flow maldistribution, and fatigue of joints and housings [10]. This work establishes a design performance framework that couples' membrane material properties with reactor mechanical requirements, thereby bridging materials science and mechanical engineering for scalable carbon capture. Specifically, this study contributes: (1) a systematic review of advances in polymeric, ceramic, MMM, and emerging membranes for CO_2 capture; (2) analysis of mechanical design constraints including pressure tolerance, thermal stress management, sealing integrity, and scalability; and (3) a structured design–performance matrix to guide technology application matching and system integration. By reframing membrane reactor development as a coupled material mechanics challenge, this study aims to accelerate the translation from bench-scale innovation to commercial carbon capture solutions aligned with net-zero pathways.

2. Literature Review

2.1 Membrane Reactors in Carbon Capture

Conventional CO_2 capture technologies amine absorption, solid sorbent adsorption, and cryogenic separation, are commercially validated but carry well-known drawbacks: high solvent-regeneration energy penalties, solvent degradation and corrosion in amine plants, and substantial capital and operating costs for cryogenic units [3,4]. These limitations have driven growing interest in membrane-based CO_2 capture as a compact, modular, and potentially less energy-intensive alternative, exploiting differences in permeability and solubility to achieve separation without phase change or chemical regeneration [5].

Membrane reactors (MRs) integrate reaction and separation in a single unit, enabling continuous removal of products such as CO_2 or H_2O to shift equilibrium-limited reactions, enhance conversion and selectivity, and reduce equipment count and total energy demand [3]. Applications span pre-combustion decarbonization (e.g., removal of CO_2 or enrichment of H_2 from syngas), post-combustion flue-gas capture, and oxy-fuel systems that use oxygen-permeable membranes to generate CO_2-rich exhaust streams [5].

Each capture pathway imposes distinct mechanical demands: pre-combustion systems require high-temperature, high-pressure operation; post-combustion applications demand selectivity and contaminant resistance at near-atmospheric conditions; and oxy-fuel systems necessitate thermal-cycling robustness and leak-free oxygen delivery. In pre-combustion configurations, membranes selectively permeate H_2 or retain CO_2 in high-pressure syngas; post-combustion systems target CO_2/N_2 separation of near-atmospheric flue gas, often in cascade arrangements; while oxy-fuel membranes supply O_2 to combustion, generating a CO_2-rich exhaust stream [5,8].

2.2 Polymeric Membranes

Commercial gas separation is dominated by polyimides, polysulfides, polybenzimidazoles (PBI), and polyether ether ketone (PEEK); these polymers are inexpensive, easy to process, and can be used with spiral-wound and hollow-fiber modules. Typical CO_2 permeabilities of 100–300 Barrer and CO_2/N_2 selectivities of 20–40 suit post-combustion capture when staged appropriately [7,11]. However, polymers face plasticization at elevated CO_2 partial pressures, physical aging that reduces free volume and permeability over time, and thermal limitations (usually < 200 °C). Reinforcement strategies include chemical cross-linking to restrict chain mobility, polymer blending to improve toughness, and thin-film composite architectures that deposit ultra-thin selective layers on porous supports to balance flux and strength. From a mechanical standpoint, polymeric membranes require reinforced housings and precise pressure control to prevent creep and deformation under sustained industrial pressure differentials [7].

2.3 Ceramic Membranes

Ceramic membranes, fabricated from alumina, zirconia, silica, or perovskite oxides, exhibit exceptional thermal and chemical stability above 600 °C and in chemically aggressive environments [8]. Their CO_2/N_2 selectivity of 50–150, controlled by microstructure and surface chemistry, exceeds that of most polymers, but ceramics are inherently brittle: highly resistant to compression yet susceptible to crack initiation at stress concentrators near seals and joints under tensile or impact loading [8,12]. Rapid thermal cycling can induce fracture through thermal shock. Design mitigation strategies include tape casting and extrusion of multilayer supports, composite ceramic architectures to improve fracture toughness, and additive manufacturing to tailor pore structures and minimize defect sensitivity [13]. Fracture-resistant seals and stress-relieved joints that accommodate thermal expansion mismatch between ceramic elements and metallic housings are prerequisite for successful deployment.

2.4 Mixed-Matrix Membranes (MMMs)

MMMs embed inorganic fillers, zeolites, MOFs, graphene oxide, carbon nanotubes, within polymer matrices to transcend the conventional permeability–selectivity trade-off. Reported CO_2 permeabilities of 200–600 Barrer and selectivities of 40–80 are common, with stability sometimes extending to 350–400 °C depending on matrix and filler [9,14]. The principal mechanical challenges are interfacial voids and poor adhesion that create non-selective leakage pathways, as well as thermal expansion mismatch that concentrates stress at the filler–matrix boundary under cycling. Advances include surface-functionalized fillers to improve compatibility, graded interlayers to smooth modulus transitions, and processing routes that promote uniform dispersion. Module designs for MMMs must mitigate interfacial stress via compliant seal concepts and geometries that avoid sharp corners and local strain amplification.

2.5 Hybrid and Emerging Membranes

Beyond polymers, ceramics, and MMMs, several emerging membrane concepts are pushing the boundaries of separation performance beyond what conventional approaches can achieve.

Ionic-liquid membranes exploit high CO_2 solubility, but they have poor mechanical stability and permeable properties. Carbon nanotubes (CNT) and graphene-made membranes have extraordinary theoretical permeability because of smooth nanochannels and atomic-scale pores, yet high intrinsic strength-to-weight ratios have been realized; scalable, defect-controlled fabrication is challenging. Bio-inspired membranes, which emulate selective ion-transport mechanisms found in nature, represent a promising emerging research direction. These technologies are promising but largely at laboratory or early pilot scale with unresolved integration and durability questions.

2.6 Mechanical Design Considerations

Successful membrane reactors demand mechanical reliability as much as separation performance. Key issues include: (i) pressure tolerance and structural integrity of supports and housings under 20–30 bar differentials; (ii) thermal stress management to accommodate expansion mismatch among membranes, seals, and metallic shells during cycles; (iii) sealing technologies, glass-ceramic seals, brazed joints, and compliant gaskets, that remain leak-tight after thousands of cycles; and (iv) scalability from flat-sheet coupons to spiral-wound or hollow-fiber modules with uniform flow distribution and acceptable pressure drop. Field experience shows that many pilot failures originate at seals and joints rather than in the membrane selective layer itself, underscoring the importance of reliability engineering.

2.7 Lessons from Pilot Studies

Industrial demonstrations provide practical insight. Polyimide-based post-combustion pilots have achieved capture efficiencies around 80–85% with reduced energy penalties relative to amines, yet experienced plasticization and performance decline at feed pressures above ~15 bar [11,15]. Ceramic modules for syngas decarbonization operated stably at 600–700 °C but exhibited seal degradation after ~1,000 thermal cycles [8,12]. EU Horizon projects on MOF-reinforced MMMs reported ~30–50% selectivity gains over baseline polymers while noting challenges in maintaining uniform filler dispersion and interfacial integrity at scale [9,14]. These outcomes affirm that material advances must be matched with robust sealing and module engineering to achieve durable, bankable performance.

3. Methodology

This study employed a systematic literature review (SLR) conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Page et al., 2021) [16] to synthesize evidence across materials and mechanical engineering aspects of membrane reactors for CO_2 capture. Searches were conducted in Scopus, Web of Science, Engineering Village, and IEEE Xplore using Boolean strings combining terms such as “membrane reactor”, “carbon capture”, “polymeric membrane”, “ceramic membrane”, “mixed-matrix membrane”, “mechanical durability”, “sealing”, and “thermal stress”. The review window focused on 2019–2025 to emphasize recent advances, with foundational earlier works included when necessary.

Inclusion criteria required peer-reviewed articles, conference papers, patents, or authoritative reports that presented quantitative performance data or mechanistic modelling relevant to reactor integration. Studies solely on polymer synthesis without mechanical relevance or lacking reproducible methods were excluded. From an initial corpus of 145 records, 52 high-quality sources were retained after abstract screening and full-text appraisal.

An analytical framework based on the Weighted Scoring Method (WSM), a multi-criteria decision making (MCDM) technique that aggregates normalized performance scores across criteria using equal weighting, was used to compare membrane classes across six dimensions: (1) CO_2 permeability (Barrer); (2) CO_2/N_2 selectivity; (3) maximum operating temperature; (4) mechanical strength and toughness; (5) pressure tolerance; and (6) scalability in module integration. Reported values were normalized using min-max scaling, rescaling each criterion to a 0–1 range relative to the minimum and maximum reported in the literature, to enable consistent cross-material comparison, acknowledging variability in test conditions across studies. To connect material performance to engineering feasibility, a design–performance matrix was developed that maps each membrane category to specific reactor requirements, e.g., ceramics to fracture-resistant seals, polymers to reinforced housings, MMMs to compliant sealing and optimized geometries. Finally, a bibliometric mapping with VOSviewer identified three research clusters, materials innovation, mechanical reliability, and system integration, highlighting the interdisciplinary nature of the field. Limitations of this approach include data heterogeneity, scarcity of long-term durability results at scale, and potential publication bias toward positive outcomes.

4. Results

The comparative analysis confirms pronounced trade-offs among membrane materials. No single class dominates across permeability, selectivity, thermal stability, mechanical durability, and scalability. Instead, performance niches emerge that align with specific carbon capture contexts. Key outcomes are summarized in Tables 1 and 2 and elaborated below, followed by observations on permeability–selectivity behavior, stress and sealing constraints, scalability, and representative case studies.

Table 1. Comparative performance of membrane materials for CO_2 capture

Membrane Type	**CO_2 Permeability (Barrer)**	**CO_2/N_2 Selectivity**	**Max Temp (°C)**	**Mechanical Traits**	**Key Challenges**
Polymeric	100–300	20–40	<200	Flexible, low-cost	Plasticization, aging
Ceramic	10–50	50–150	>600	Strong, brittle	Seal failures, cracking
MMMs	200–600	40–80	200–400	Balanced, tunable	Interfacial stress, dispersion
Hybrids	500–1000+	80–150	150–500	High potential	Scale-up, cost, stability

Table 2. Design–Performance Matrix linking material type with reactor mechanical requirements

Membrane Type	Reactor Requirement	Integration Challenge	Best Application
Polymeric	Reinforced housings	Plasticization, creep	Post-combustion
Ceramic	Fracture-resistant seals	Brittleness, thermal shock	Pre-combustion
MMMs	Optimized modules, compliant seals	Interfacial mismatch	Modular mid-temp
Hybrids	Advanced supports	Fabrication cost, uniformity	Oxy-fuel & H_2 systems

Permeability–selectivity trade-offs follow the Robeson upper-bound trend: polymers cluster at moderate permeability and selectivity; ceramics achieve high selectivity at lower permeabilities; while MMMs and emerging hybrids push the upper bound at the cost of increased mechanical and fabrication complexity. Stress analyses reported in the literature converge on sealing regions and joints as the most failure-prone locations. Polymeric membranes begin to deform at sustained differentials above ~15–20 bar; ceramics tolerate high temperatures and compressive loads but crack under tensile stress and rapid thermal cycling; MMM durability is strongly tied to filler–matrix adhesion quality, with micro-voids and debonding accelerating fatigue.

Scalability remains a decisive hurdle. Transitioning from flat-sheet laboratory coupons to spiral-wound or hollow-fiber modules introduces flow maldistribution, fouling propensity, and pressure-drop penalties. Computational fluid dynamics (CFD) studies indicate that optimized channel spacers and flow distributors can reduce pressure drop by 15–20% and improve stage cut uniformity [6]. Case studies reinforce these findings: polyimide-based flue-gas pilots reached roughly 85% capture with lower energy penalties than amines but suffered plasticization at higher pressures; ceramic syngas modules operated at 600–700 °C with strong selectivity yet experienced seal degradation after approximately 1,000 thermal cycles [8,12]; MOF–polyimide MMMs delivered 30–50% selectivity gains over neat polymers but encountered interfacial defects during scale-up fabrication.

Finally, emerging digital approaches, embedded sensors and digital twins, enable real-time state estimation and predictive maintenance. Studies report lifetime extensions on the order of 20–30% when operating envelopes are adaptively controlled to avoid conditions that accelerate crack initiation or plasticization [17]. These tools mark an important convergence of materials science, mechanical reliability, and data-driven operations.

5. Discussion

The results confirm that material performance must be co-optimized with mechanical reliability to deliver deployable membrane reactors. Polymers are attractive for post-combustion capture due to cost and manufacturability, yet their susceptibility to plasticization and thermal softening necessitates reinforced housings, conservative pressure staging, and in some cases protective coatings. Ceramics are natural candidates for pre-combustion and high-temperature service but will remain constrained by brittleness unless seal concepts and joint designs become far more defect-tolerant. MMMs offer a pragmatic middle ground, provided that interfacial engineering addresses adhesion and thermal mismatch at scale.

Scaling challenges are not merely engineering footnotes; they are central to techno-economic viability. Module geometry drives packing density and pressure drop, both of which feed back into capture cost. Manufacturing consistency, such as roll-to-roll coating uniformity for thin-film composite membranes or controlled filler dispersion in MMMs, is central to bridging laboratory performance and field reliability.

Issues of sustainability also make decisions more complex: polymer fabrication is fossil-based, ceramic sintering is energy-consuming, and high-tech fillers such as MOFs or graphene have non-trivial embodied effects. Rigorous life-cycle assessment (LCA) is therefore essential to ensure that capture benefits outweigh materials footprints.

A notable opportunity lies in the integration of digital twins and predictive reliability engineering. Finite-element models calibrated with operational data can forecast seal degradation or crack growth, enabling maintenance actions before failures cascade. When coupled with optimization and AI-based control, CFD can be used to find operating windows that reduce stress without loss of capture efficacy. Concurrently, additive manufacturing has the potential to create ceramic and composite structures to redistribute stress and reduce sensitivity to flaws, and novel sealants and compliant interfaces would absorb expansion differences thousands of thermal cycles.

Policy and industrial strategy should reflect these technical realities. Public funding targeted at pilot-scale demonstrations must include mechanical testing, seal qualification, and long-term durability evaluations, not solely membrane chemistry. Industry should budget for robust housings and instrumentation alongside novel selective layers. There is an utmost need to collaborate across disciplines: materials scientists, mechanical engineers, and data scientists need to collaborate to produce reactors that are not only efficient on paper but are also reliable in plants.

6. Conclusion

Membrane reactors are an emerging technology with potential to become a viable strategy to capture carbon; they are compact, modular and energy efficient and present an alternative to solvent systems. But success will rely on finding solutions to mechanical challenges - particularly sealing robustness and thermo-mechanical durability and scalable and reproducible fabrication. The design–performance matrix introduced in this work maps membrane types to reactor mechanical requirements and recasts technology selection as a joint materials–mechanics decision.

Future directions include: (1) hybrid membrane systems: combine ceramic backbones with polymer or MMM interlayers to balance toughness and thermal resilience; (2) defect-tolerant seals and joints with thousands of thermal cycles without leakage; (3) additive manufacturing to customize the pore architecture and minimize stress concentrations; (4) AI-enabled digital twins and predictive maintenance to extend lifetime and cost-reduction; and (5) comprehensive LCAs that quantify net climate benefits at scale. Such developments, pursued jointly, have the potential to commercialise, in a similar fashion, laboratory innovations in the shape of commercially viable membrane reactors that can contribute materially to net-zero ambitions worldwide.

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