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Nanostructured Materials for Carbon Dioxide Capture and Greenhouse Gas Mitigation: Mechanisms Performance and Sustainability

Pankaj Kumar

Department of Physics, Akal University, Talwandi Sabo, Bathinda, Punjab, 151302, India

ABSTRACT

This review examines the role of nanostructured materials including MOFs, COFs, zeolites, mesoporous silicas, carbon-based nanostructures, polymeric membranes, and nanocomposites in advancing scalable CO2 capture and greenhouse gas mitigation. By enabling precise engineering of pore architecture, active-site density, and surface chemistry, these materials optimize key mechanisms such as physisorption, chemisorption, amine functionalization, and molecular sieving. Their operational performance is systematically evaluated across diverse applications, ranging from industrial flue gas and natural gas processing to direct air capture (DAC), under varying operational parameters including temperature, pressure, humidity, and competitive gas streams. Crucially, the authors bridge the gap between bench-scale adsorption capacity and practical process engineering, highlighting metrics such as pressure drop, sorbent productivity, heat and mass transfer, and regeneration energy. Beyond capture efficiency, the review assesses life-cycle sustainability, addressing cyclic stability, manufacturing costs, environmental toxicity, and end-of-life management. Emerging paradigms including machine-learning-driven discovery, hybrid nanocomposites, structured adsorbents, electrochemical capture, and integrated capture-conversion systems are highlighted. Ultimately, the review proposes a sustainability-oriented framework emphasizing that nanostructured sorbents can effectively support global decarbonization only when evaluated through full life-cycle impacts, low regeneration penalties, and permanent downstream carbon storage or utilization.

***Corresponding author**

Pankaj Kumar, Department of Physics, Akal University, Talwandi Sabo, Bathinda, Punjab, 151302, India.

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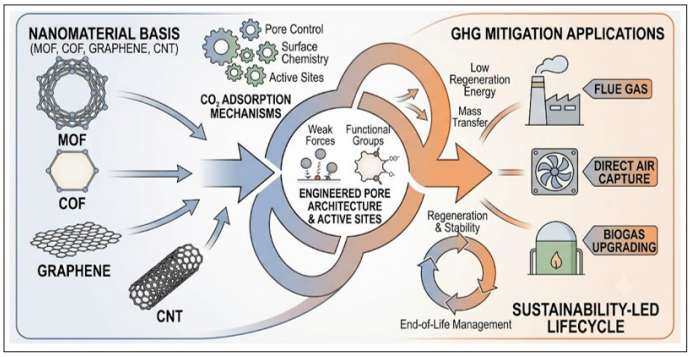
Graphical Abstract



Introduction

Greenhouse Gas Emissions and the Need for Advanced Capture Materials

Anthropogenic greenhouse gas emissions have intensified the need for technologies that can reduce emissions at industrial sources and remove CO_2 already present in the atmosphere. Carbon dioxide is released primarily through fossil-fuel combustion, cement production, industrial heating, and land-use change. Other greenhouse gases, including methane (CH_4) and nitrous oxide (N_2O), contribute substantially to radiative forcing and require complementary mitigation strategies [1]. Carbon capture and storage, carbon capture and utilization, and direct air capture have therefore become important components of broader climate mitigation pathways.

Conventional post-combustion capture frequently relies on aqueous amine solvents, particularly monoethanolamine-based systems. These technologies can capture CO2 from relatively dilute gas streams, but solvent regeneration requires substantial heat, while solvent degradation, corrosion, and water management can increase operating costs. Solid adsorption, selective membranes, cryogenic separation, and mineral carbonation offer alternative or complementary approaches [2]. However, no single separation technology is universally optimal because the required performance depends on the CO_2 concentration, gas composition, pressure, temperature, moisture content, and intended destination of the captured carbon.

Nanostructured materials have attracted interest because nanoscale engineering can increase the accessibility of active sites and enable control over molecular interactions. Microporous frameworks can discriminate between gases according to molecular size and adsorption affinity, while amine-functionalized surfaces can chemically bind CO_2. Carbonaceous nanomaterials can provide conductive networks and adjustable surface chemistry, and polymeric nanocomposites can combine gas permeability with improved mechanical properties [3]. Nevertheless, a high specific surface area or large equilibrium uptake does not automatically

establish industrial superiority. A material that adsorbs CO_2 strongly may require excessive energy for regeneration. Similarly, a highly porous powder may perform poorly after pelletization because of pore blockage, reduced diffusivity, or mechanical degradation. The central scientific challenge is therefore to optimize the complete relationship between material structure, adsorption mechanism, separation performance, regeneration, and environmental impact.

Nanostructuring Matters

Nanostructuring changes the spatial distribution of adsorption sites, diffusion pathways, and chemical functionalities. In microporous materials, pores smaller than approximately 2 nm can generate overlapping adsorption potentials from opposing pore walls, increasing the affinity for CO_2 at low partial pressures. Mesoporous materials, with pores approximately 2-50 nm in diameter, often provide improved transport pathways and space for amine loading. Hierarchical structures combine micropores for adsorption with larger pores for rapid mass transfer. Surface functionalization provides an additional mechanism for improving selectivity [4].

Amine groups interact chemically with CO_2, whereas nitrogen-containing heterocycles, ionic groups, open metal sites, and polar surface functionalities can alter adsorption enthalpy and molecular discrimination. In membrane materials, nanoscale fillers may modify free volume, diffusion pathways, and polymer filler interactions, although poorly controlled interfaces can create nonselective defects. These effects must be distinguished from purely geometric surface-area enhancement. The useful capacity of a sorbent depends on the number of accessible sites, their binding strength, and the difference between adsorption at the feed conditions and desorption at regeneration conditions. Consequently, rational materials design must account for both thermodynamics and transport.

Fundamentals of CO_2 Capture and Nanostructured Adsorbents

Capture Pathways and Separation Requirements

CO_2 capture can be categorized into pre-combustion capture, post-combustion capture, oxy-fuel combustion, and direct air capture. Pre-combustion streams may contain CO2 at elevated pressure, whereas post-combustion flue gases generally contain CO_2 diluted by nitrogen, water vapour, and other components. DAC faces the most demanding concentration constraint because the target gas is present at only a few hundred parts per million in ambient air. The optimal material consequently depends on the thermodynamic driving force and the separation duty [5]. High-pressure applications may benefit from physical adsorption, while dilute streams often require strong chemical affinity or carefully engineered selective interactions. In every case, the captured CO_2 must be recovered at a useful purity and pressure without consuming an excessive fraction of the energy or emissions savings that the capture process is intended to deliver.

Physisorption

Physisorption occurs through relatively weak intermolecular interactions, including van der Waals forces, electrostatic interactions, and confinement-induced adsorption potentials. It is commonly reversible and can be regenerated through pressure reduction, temperature increase, or changes in gas composition [6]. Physisorption is particularly relevant to MOFs, zeolites, activated carbons, COFs, and selected porous organic polymers. Its principal advantages are reversibility and the possibility of relatively low-temperature regeneration. Its limitations include reduced affinity at very low CO_2 partial pressure, competition with water and other gases, and the need to maintain sufficient selectivity under actual process conditions.

Classification of Nanostructured Materials for CO_2 Capture

Metal-Organic Frameworks

MOFs are crystalline porous materials constructed from metal-containing nodes connected by organic linkers. Their modular structures allow systematic adjustment of pore size, topology, functional groups, and metal coordination environments. This tunability makes them attractive candidates for gas separation and CO2 capture. The capture behaviour of MOFs depends on the pore aperture, surface polarity, framework flexibility, and the presence of open metal sites. Unsaturated metal centres can strengthen interactions with CO2, while amine-bearing linkers or post-synthetic functionalization can enhance affinity at low partial pressures. Materials such as selected Mg, Zn, Al, and Zr-based frameworks have been investigated for different carbon capture duties, although their stability and manufacturing requirements differ substantially [7].

A central challenge is that idealized performance measured using pure CO_2 may not persist in humid flue gas. Water molecules can occupy active sites, alter framework flexibility, or compete with CO_2 for adsorption. Some MOFs undergo hydrolysis or structural changes under prolonged exposure to moisture or acidic impurities. Others possess improved hydrothermal stability but may require expensive linkers or complex synthesis conditions. Amine-functionalized MOFs are particularly promising because they combine chemically active binding sites with a porous host [8]. Recent reviews have highlighted the importance of functionalization, moisture tolerance, synthesis costs, and industrial shaping for moving MOF adsorbents beyond laboratory testing. The practical value of a MOF should therefore be judged by working capacity, selectivity, cyclic stability, synthesis yield, pellet strength, and regeneration duty rather than BET surface area alone.

Covalent Organic Frameworks

COFs are porous crystalline networks formed through covalent bonds between organic building blocks. Their low framework density, adjustable pore chemistry, and potential for metal-free synthesis make them attractive for applications requiring controlled adsorption sites. Nitrogen-rich COFs can provide polar environments that favour CO_2 interactions. Amine-functionalized frameworks can introduce chemically reactive sites, while the periodic pore architecture can facilitate transport when pore connectivity and crystallinity are suitable. Selected COFs may also support catalytic functions, allowing captured CO_2 to be converted into chemical products [8].

However, COFs exhibit varying degrees of moisture stability, hydrolytic resistance, and mechanical robustness. Some frameworks require expensive monomers, high-boiling solvents, catalysts, or prolonged synthesis and purification. The retention of accessible porosity after pelletization or incorporation into a polymer matrix is also a major consideration. For practical applications, the main research priority is not simply increasing the number of functional groups but creating a stable network in which binding sites remain accessible during repeated adsorption and regeneration.

Zeolites and Silica-Based Nanostructures

Zeolites are crystalline aluminosilicates with well-defined pore

systems and exchangeable cations. Their adsorption selectivity arises from pore dimensions, electrostatic fields, and the interactions between CO_2 and framework-associated cations. They can offer rapid adsorption and useful selectivity for dry gas streams. Their major limitation is sensitivity to water. Because water can bind strongly to polar zeolite surfaces, moisture may significantly reduce CO_2 uptake under humid conditions [9]. Drying the feed gas can improve performance but introduces an additional energy and equipment requirement.

Mesoporous silica provides a chemically versatile support for amine functionalization. Silica surfaces can be modified using grafting or impregnation methods to introduce primary, secondary, or tertiary amines. The mesoporous structure can facilitate amine dispersion and mass transport, while the surface chemistry can be tailored for particular operating conditions. Amine-functionalized silica is particularly relevant to DAC because chemical binding can help compensate for the low atmospheric CO_2 concentration. Nevertheless, the performance depends strongly on amine loading, pore accessibility, humidity, regeneration temperature, and long-term chemical stability [10].

Activated Carbon Biochar and other Carbonaceous Materials

Activated carbon contains a distribution of micro- and mesopores that can be generated by physical or chemical activation. Its low cost, availability, and compatibility with several industrial processes make it an important benchmark for evaluating advanced adsorbents. CO2 uptake depends on pore-size distribution, surface oxygen groups, nitrogen-containing functionalities, and the interaction between the adsorbent and gas molecules. Narrow micropores may provide strong adsorption potentials at low pressure, whereas larger pores can improve transport. Biochar extends this approach by converting biomass residues into porous carbon materials. Feedstocks may include agricultural residues, forestry by-products, and selected organic wastes [11].

Pyrolysis and subsequent activation can generate adsorption sites while offering a route for valorizing otherwise underused biomass. However, the sustainability of biochar depends on feedstock sourcing, process heat, activation chemicals, washing requirements, yield, and the fate of the material after use. Chemical activation can produce highly porous adsorbents but may require corrosive reagents and substantial wastewater treatment. Biomass-derived materials also vary in composition, making reproducibility and quality control important challenges. Carbon nanotubes and graphene-based materials offer high electrical conductivity and adjustable surface chemistry [12]. Functionalized forms may improve adsorption or serve as components in mixed-matrix membranes and electrochemical capture systems. Nevertheless, their cost, dispersion behaviour, possible toxicity, and end-of-life management must be considered before large-scale deployment.

Polymeric Membranes and Mixed-Matrix Nanocomposites

Membrane separation relies on differences in gas permeability and selectivity. In solution–diffusion membranes, permeability. CO_2-selective polymers may provide favourable solubility for CO_2 relative to nitrogen or methane. However, the trade-off between permeability and selectivity, plasticization, aging, and mechanical stability can restrict performance. Adding MOFs, zeolites, silica, or other nanofillers may improve transport or selectivity, but only when the polymer–filler interface is well controlled [13]. Interfacial voids can create nonselective pathways, while excessive filler loading can increase brittleness or complicate fabrication. Consequently, the performance of a mixed-matrix membrane must be evaluated using actual mixed-gas feeds, realistic pressures, humidity, and long-duration operation rather than ideal single-gas measurements.

Metal Oxides and Hybrid Nanocomposites

Metal oxides can contribute to carbon capture through surface adsorption, chemical carbonation, and support functions. Basic oxides such as calcium oxide and magnesium oxide are especially relevant to high-temperature CO2 capture, where carbonate formation and decomposition can be exploited in cyclic processes. The reverse reaction requires heating and is accompanied by changes in solid volume and microstructure. Repeated carbonation and calcination can lead to sintering, pore closure, and declining conversion [14]. Nanostructuring may improve initial reactivity by shortening diffusion distances and increasing accessible surface area, but it does not eliminate long-term sintering or the energy requirements of calcination.

Hybrid nanocomposites combine the advantages of multiple material classes. Examples include amine-functionalized MOFs, silica-polymer composites, carbon-metal oxide hybrids, and MOF-containing membranes. The objective is to combine strong CO_2 affinity with accessible porosity, mechanical strength, and improved transport. A successful hybrid must provide a genuine synergistic benefit rather than simply combining two expensive components. Its performance should therefore be compared with the individual components using matched experimental conditions and complete process-level metrics.

Mechanistic Pathways Governing Capture Performance

Pore Confinement and Molecular Discrimination

The pore structure of a nanomaterial determines how effectively gas molecules access and occupies adsorption sites. In microporous materials, confinement increases the influence of pore-wall interactions, particularly when the pore dimensions are comparable to the dimensions of the adsorbed molecule. The resulting adsorption potential can enhance uptake at relatively low pressures. Molecular discrimination is not determined by molecular size alone. CO_2 possesses a quadrupole moment and interacts strongly with polar sites, while its kinetic diameter is close to that of several competing gas molecules [15].

Effective separation therefore depends on a combination of pore aperture, adsorption enthalpy, diffusion rate, and gas composition. An optimal pore structure must balance adsorption affinity with transport. Extremely narrow pores may generate strong interactions but impede diffusion, particularly after functionalization. Conversely, excessively large pores may reduce confinement effects and weaken low-pressure adsorption. Hierarchical porosity can address this trade-off by combining narrow adsorption pores with larger transport channels.

Role of Surface Functionalization

Surface functionalization introduces chemical groups that interact selectively with CO2. Primary and secondary amines can support carbamate formation, while other nitrogen-containing groups and polar functionalities may alter adsorption energetics. In porous frameworks, functionalization can be achieved through linker design, post-synthetic modification, grafting, or impregnation. The relationship between functional-group density and working capacity is generally nonlinear. Increasing the concentration of active sites may initially enhance adsorption, but excessive modification can obstruct pores, decrease surface area, and hinder diffusion. Functionalization may also alter framework flexibility or reduce mechanical stability [16].

A rational design strategy should therefore optimize the number of accessible sites rather than the total concentration of chemically introduced groups. Spectroscopic characterization, elemental analysis, pore-size measurements, adsorption calorimetry, and kinetic studies can help distinguish accessible active sites from those that are chemically present but functionally unavailable.

Comparative Performance of Major Material Classes

Reported adsorption capacities are frequently measured under different temperatures, pressures, gas compositions, and pretreatment conditions. Some studies report gravimetric uptake in mmol g-1, while others use mg g-1 or mass percentage. These metrics cannot be compared reliably without conversion and confirmation that the experimental conditions are equivalent. Pure-gas measurements can also exaggerate performance relative to mixed-gas experiments [17].

Furthermore, equilibrium uptake may be reported without measuring regeneration energy, breakthrough capacity, or long-term cycling. These inconsistencies limit the value of simple rankings. A defensible comparison should distinguish equilibrium capacity, working capacity, CO_2/N_2 or CO_2/CH_4 selectivity, adsorption rate, regeneration requirements, cyclic stability, and material cost as Table 1. DAC materials require additional consideration of very low inlet CO_2 concentration, air-contacting energy, humidity, and the energy needed to deliver concentrated CO_2.

Table 1: Comparative Characteristics of Nanostructured Materials for CO_2 Capture

Material class	Principal capture mechanism	Main advantages	Major limitations	Most relevant applications
MOFs	Pore filling, physisorption, open metal sites and functionalized binding	Tunable pore chemistry and high design flexibility	Moisture sensitivity in some frameworks; synthesis and shaping costs	Flue gas, gas purification, selected DAC systems
COFs	Pore confinement and functional-group interactions	Adjustable organic chemistry and low framework density	Cost, crystallinity, hydrolytic stability and mechanical strength	Selective adsorption and hybrid systems
Zeolites	Electrostatic adsorption and molecular sieving	Established processing, defined pores and strong adsorption	Water competition and regeneration requirements	Dry flue gas and gas separation
Mesoporous silica with amines	Chemisorption and reversible amine-CO_2 interactions	High functionalization flexibility and useful transport pathways	Amine degradation, pore blockage and regeneration energy	Dilute CO_2 streams and DAC
Activated carbon	Physisorption and micropore filling	Relatively low cost and established production routes	Variable selectivity and limited affinity in some low-pressure applications	Industrial gas treatment and adsorption beds
Biochar	Micropore filling and surface interactions	Potential use of biomass residues and waste-derived feedstocks	Feedstock variability, activation impacts and inconsistent performance	Low-cost capture and waste valorization
Carbon nanotubes and graphene composites	Surface adsorption, functionalization and conductive transport	Adjustable surface chemistry and multifunctional integration	Cost, dispersion, safety and end-of-life concerns	Hybrid adsorbents, membranes and electrochemical systems
Polymeric mixed-matrix membranes	Solution-diffusion with selective nanofillers	Continuous operation and compact process design	Permeability–selectivity trade-offs and interfacial defects	CO_2/N_2 and $CO_2/CH4$ separation
Metal oxide sorbents	Surface adsorption and reversible carbonation	Potential for high-temperature capture	Sintering and demanding regeneration conditions	High-temperature industrial processes

Industrial Flue-Gas Capture

Post-combustion capture presents a difficult separation problem because CO2 is diluted by nitrogen and may coexist with oxygen, water vapour, sulphur oxides, and nitrogen oxides. Nanostructured adsorbents can improve capture by increasing the density of accessible sites, strengthening CO_2-specific interactions, and reducing diffusion resistance. Amine-functionalized silica and selected porous frameworks are promising candidates because chemical binding can provide stronger affinity than purely physical adsorption at low partial pressures. Zeolites and carbon-based materials may be attractive where moisture can be controlled and the regeneration process is favourable [18].

However, industrial deployment requires tolerance to impurities and repeated thermal or pressure cycling. Flue-gas pretreatment may be necessary to reduce contaminant exposure, while the sorbent itself must resist degradation during prolonged operation. Material selection should therefore be integrated with gas cleaning, heat recovery, contactor design, and CO_2 compression.

Biogas Upgrading and Natural Gas Purification

Biogas typically contains methane and CO_2, with water vapour and trace impurities that vary according to feedstock and production conditions. Removing CO_2 increases methane concentration and can improve the suitability of the gas for subsequent use. Natural gas processing may similarly require CO_2 removal to meet pipeline or process specifications. For these applications, CO_2/CH_4 selectivity is a central consideration. MOFs, zeolites, activated carbon, and polymeric membranes can be assessed according to

their adsorption or permeation behaviour under the actual pressure and composition of the feed. Adsorption-based systems may be attractive where cyclic regeneration and gas recovery are manageable. Membranes may be favourable for continuous operation and modular equipment. Hybrid configurations can combine the strengths of both approaches, although additional equipment and process complexity must be justified by improved recovery or lower energy use [19].

Nanostructured materials utilize physical adsorption, chemical binding, and spatial confinement to selectively capture carbon dioxide. While high surface area micropores facilitate rapid physisorption via van der Waals interactions, surface-functionalized basic groups like amines form reversible chemical bonds with CO_2 molecules as Figure 1. Precision pore tuning further allows molecular sieving to separate CO_2 from larger gas streams such as N_2 and CH_4, creating an energy-efficient path for carbon mitigation.

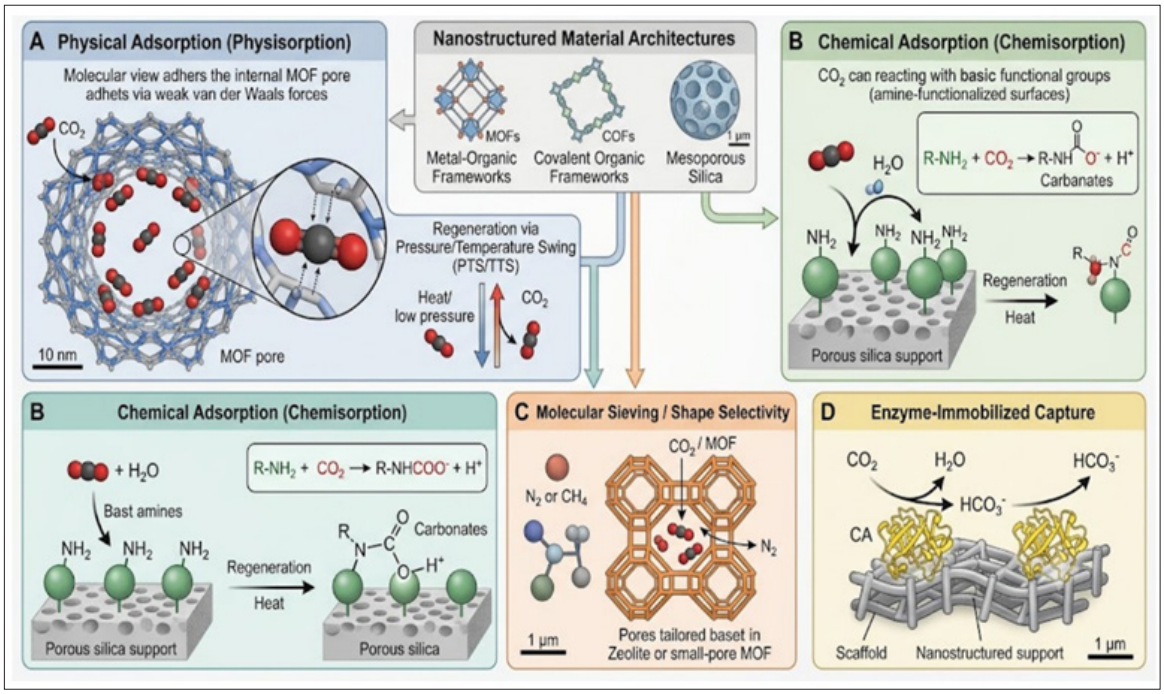


Figure 1: Mechanisms of CO2 Capture by Nanostructured Materials

Greenhouse Gas Mitigation Beyond CO2 Capture

Methane Separation and Recovery

Methane is a potent greenhouse gas, and its release from fossil-fuel production, waste management, agriculture, and other sources contributes to climate change. Nanostructured membranes and porous adsorbents can support methane recovery, CO_2 removal from biogas, and separation of methane-containing gas mixtures. The mitigation benefit depends on the actual reduction in methane emissions. Separating methane from a gas stream is not equivalent to preventing methane leakage, and the climate benefit can be reduced if methane escapes during collection, processing, or subsequent use [20]. Accordingly, methane capture systems should be evaluated using mass balances that account for recovery, leakage, energy consumption, and the fate of the recovered gas.

Nitrous Oxide and other Greenhouse Gases

N_2O emissions originate from agricultural soils, industrial processes, and combustion-related sources. Selected catalytic materials and nanostructured metal oxides can contribute to N_2O decomposition or catalytic abatement. These applications are distinct from conventional CO_2 adsorption because they may require catalytic conversion rather than reversible storage. The role of nanostructured materials is to increase active-site accessibility, tune redox properties, or improve catalyst dispersion [21].

However, performance must be evaluated in the presence of water, oxygen, and competing species that can inhibit catalytic activity. It is important not to generalize CO2 capture results to N_2O removal. Each greenhouse gas requires its own mechanistic assessment, reaction conditions, emission accounting, and performance metrics.

CO_2 Utilization and Catalytic Conversion

Captured CO_2 can serve as a feedstock for selected chemicals, fuels, mineral products, and other materials. MOFs, metal-based nanocatalysts, and hybrid photocatalytic or electrocatalytic systems have been explored for CO_2 conversion into products such as carbon monoxide, formate, methane, and selected multicarbon compounds. CO_2 conversion is not automatically carbon-negative [22]. The climate benefit depends on the source of energy and hydrogen, process efficiency, product lifetime, and whether the product replaces a more emissions-intensive alternative. Fuels produced from CO_2 generally release the carbon again during combustion, whereas durable mineral products may retain carbon for much longer periods.

An integrated capture–conversion system should therefore be assessed using a complete carbon and energy balance rather than the conversion efficiency alone. Recent literature on MOF-based capture and conversion highlights both the potential for multifunctional materials and the challenges of translating laboratory performance into practical processes [23]. This figure 2 illustrates the crucial nexus between innovative materials science and scalable climate change mitigation strategies. By leveraging the advanced CO_2 capture mechanisms detailed previously (Figure 2), nanomaterials can be directly integrated into various points within the anthropogenic carbon cycle, from large-scale point source separation to distributed direct air capture systems.

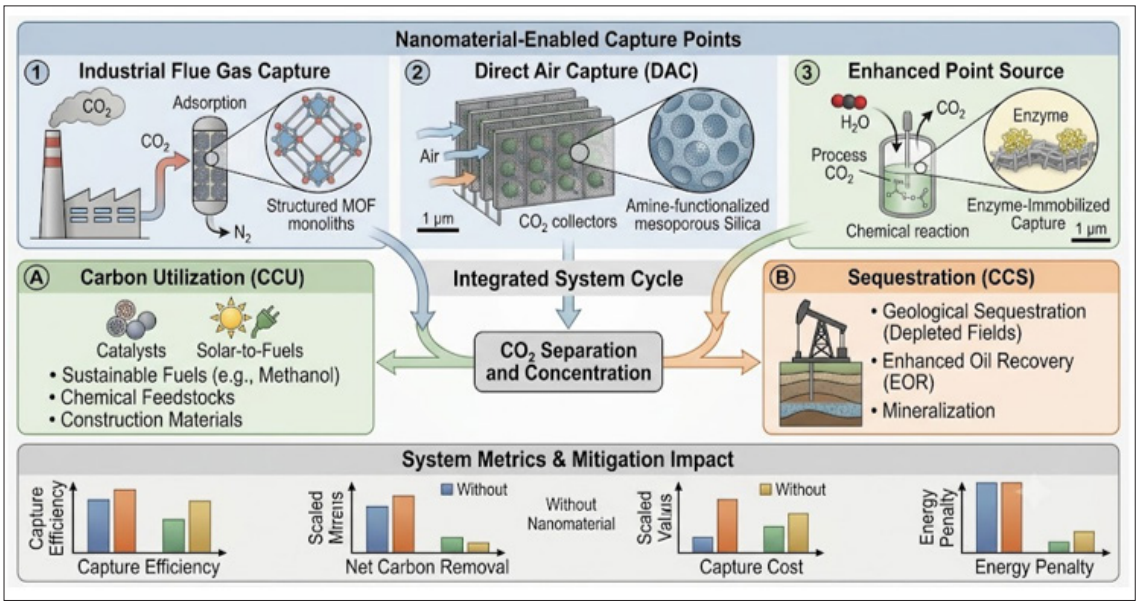


Figure 2: Integration of Nanomaterial-Enabled Capture with Greenhouse Gas Mitigation

Nevertheless, recyclability must be demonstrated experimentally. A material that can theoretically be recycled may not be economically or environmentally recoverable if the process requires large amounts of energy, aggressive chemicals, or complex separation steps [24]. The optimal design should consider recyclability from the beginning, including how the material can be separated from binders, supports, contaminants, and reactor components as table 2.

Table 2: Sustainability Assessment Framework for Nanostructured Co2 Capture Materials

Sustainability dimension	Key indicators	Common concern	Preferred evaluation approach
Raw materials	Precursor consumption, critical-metal dependence, feedstock origin	Scarce or high-impact precursors	Material inventory and supply-chain assessment
Manufacturing	Energy use, solvent demand, synthesis yield	High-temperature processing and solvent-intensive synthesis	Cradle-to-gate LCA
Capture operation	Working capacity, selectivity, pressure drop	Poor performance in realistic gas mixtures	Mixed-gas breakthrough and process modelling
Regeneration	Heat, electricity, vacuum and compression demand	High energy consumption and indirect emissions	Full energy balance
Durability	Capacity retention, attrition, chemical stability	Frequent material replacement	Long-duration cyclic testing
Safety	Dust generation, leaching, degradation products	Occupational exposure and environmental release	Hazard assessment and release testing
Circularity	Recovery yield, reuse, material replacement rate	Difficult separation or low-value waste	Recovery trials and end-of-life modelling
Climate benefit	Net emissions avoided or CO2 removed	Capture emissions offsetting gross benefit	Consistent life-cycle carbon accounting

Emerging Strategies and Future Research Directions

Machine learning and molecular simulation can accelerate the screening of porous materials by predicting adsorption isotherms, selectivity, pore accessibility, and structure–property relationships. These approaches may reduce the number of experimental candidates that require synthesis and testing. However, predictions depend on the quality of the training data and the assumptions used in the simulations [25].

Models trained on pure-gas equilibrium data may not reliably predict performance under humid, multicomponent conditions. Future datasets should include working capacity, kinetics, regeneration requirements, stability, and material-manufacturing information. A useful development pathway combines computational screening with experimental validation, process modelling, and life-cycle assessment. This approach can identify candidates that are not merely excellent adsorbents but are also practical to manufacture and operate. Electrochemical capture approaches can alter the affinity of a material for CO_2 through changes in electrical potential or redox state. Such systems may enable regeneration without conventional bulk heating, depending on the chemistry and device architecture [26].

Potential advantages include modular operation and compatibility with intermittent renewable electricity. Challenges include electrode stability, electrolyte management, parasitic reactions, current efficiency, mass transfer, and the durability of redox-active materials. The correct benchmark is the energy required per unit of CO2 recovered at the required purity, including all auxiliary loads. Avoiding a thermal regeneration step does not necessarily

guarantee lower overall energy consumption. A standardized reporting framework would enable more meaningful comparison between material classes and improve the reliability of process-level predictions.

This figure 3 outlines a comprehensive, life-cycle-oriented approach to designing the next generation of CO_2 sorbents, moving beyond simple capacity metrics. It integrates three critical pillars: the use of renewable, green synthetic precursors; process-intensified, scalable manufacturing techniques; and a focus on material circularity, ensuring end-of-life recycling or valorization. By prioritizing these sustainability criteria from the atomic level up, this development paradigm aims to minimize the overall environmental footprint and energy penalty of carbon capture technologies [27].

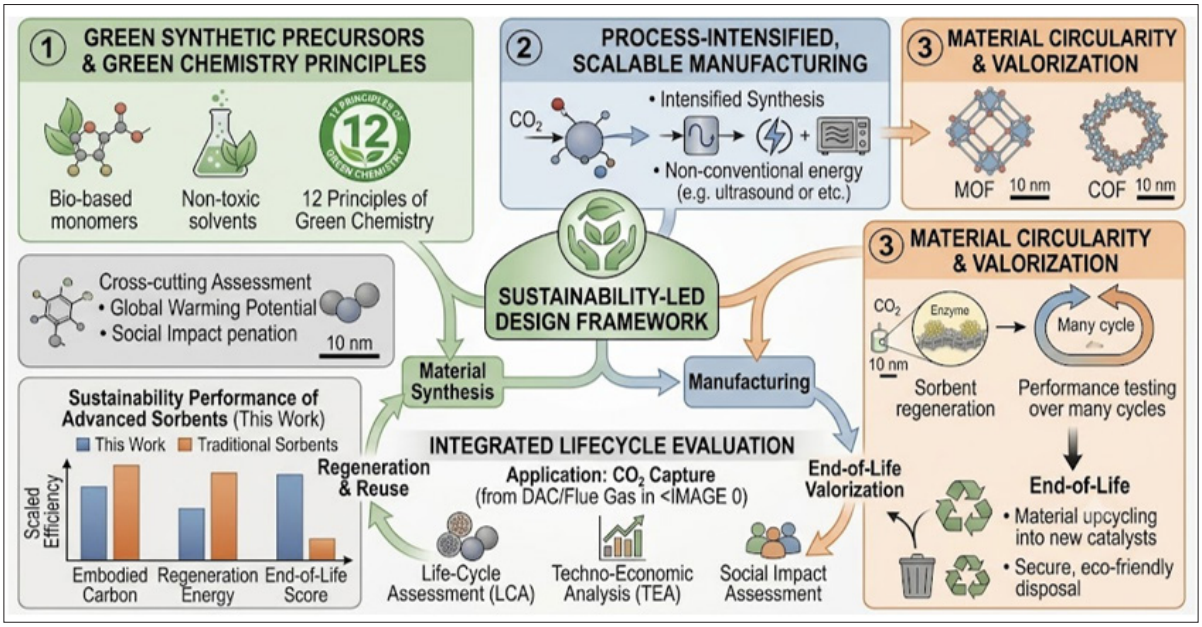


Figure 3: Sustainability-Led Development of Nanostructured Capture Materials

Conclusions

Nanostructured materials including MOFs, COFs, zeolites, carbon sorbents, amine-functionalized silicas, and nanocomposites provide a versatile platform for CO_2 capture through engineered porosity and surface chemistry. However, material selection involves inherent trade-offs: strong chemical binding enhances uptake but increases regeneration energy, while high porosity can compromise mechanical strength. Consequently, laboratory adsorption capacity must be linked directly to process-level performance, considering working capacity, diffusion, humidity tolerance, and cyclic durability.

Evaluating net environmental benefits requires incorporating life-cycle assessment and techno-economic analysis early in material design to account for synthetic impacts, replacement rates, and operational energy demands. Priority directions include computational screening, humidity-tolerant sorbents, low-energy regeneration, and scalable, structured sorbent architectures. Ultimately, the commercial viability of nanostructured capture technologies depends on total emissions avoided, resource efficiency, cost-effectiveness, and long-term durability across the full operational life cycle.

References

1. Soo XYD, Lee JJC, Wu WY, Tao L, Wang C, et al. (2024) Advancements in CO_2 capture by absorption and adsorption: A comprehensive review, Journal of CO_2 Utilization 102727.
2. Panda D, Kulkarni V, Singh SK (2023) Evaluation of amine-based solid adsorbents for direct air capture: A critical review, Reaction Chemistry & Engineering 8: 10-40.
3. Duan X, Song G, Lu G, Wang Y, Sun J, et al. (2023) Chemisorption and regeneration of amine-based CO_2 sorbents in direct air capture, Materials Today Sustainability 100453.
4. Simari C (2025) Nanomaterials for direct air capture of CO_2: Current state of the art, challenges and future perspectives, Molecules 30: 3048.
5. Madhu K, Pauliuk S, Dhathri S, Creutzig F (2021) Understanding environmental trade-offs and resource demand of direct air capture technologies through comparative life-cycle assessment, Nature Energy 6: 1035-1044.
6. Kong F, Chen W (2024) Carbon dioxide capture and conversion using metal–organic framework (MOF) materials: A comprehensive review, Nanomaterials 14: 1340.
7. Xie F, Wang N, Chen H, Li M, Li Y, et al. (2025) Advances in amine-functionalized metal organic frameworks for carbon capture, Journal of Materials Chemistry A 13: 41653-41685.
8. Hui Q, Fu J, Xu H, Wang C, Ding Q, et al. (2025) Metal–organic frameworks for CO2 capture: Challenges and efforts from laboratory research to industrial applications. Industrial & Engineering Chemistry Research 64: 9457-9483.
9. Ma H, Fu H, Tong Y, Umar A, Hung YM, et al. (2025) Advances in CO2 capture and separation materials: Emerging trends, challenges, and prospects for sustainable applications. Carbon Capture Science & Technology 15: 100441.
10. Nikkhah S, Zendehboudi S, Rezaei N, Saady NMC (2026) A comprehensive review of metal–organic frameworks (MOFs) applications as sorbents and membranes for carbon capture through direct air capture (DAC) technology. Fuel 416: 137999.
11. Velagala SKR, Sabri Y, Parthasarathy R, Sreedhar I (2026) A bird's eye view of recent advances in direct air capture of CO2 using MOFs. Fuel 405: 136525.
12. Zagho MM, Hassan MK, Khraisheh M, Al-Maadeed MAA, Nazarenko S (2021) A review on recent advances in CO2 separation using zeolite and zeolite-like materials as adsorbents and fillers in mixed matrix membranes (MMMs).

Chemical Engineering Journal Advances 6: 100091.

13. Lin L, Meng Y, Ju T, Han S, Meng F, et al. (2023) Characteristics, application and modeling of solid amine adsorbents for CO2 capture: A review. Journal of Environmental Management 325: 116438.
14. Saenz Cavazos PA, Hunter-Sellars E, Iacomi P, McIntyre SR, Danaci D, et al. (2023) Evaluating solid sorbents for CO2 capture: linking material properties and process efficiency via adsorption performance. Frontiers in Energy Research 11: 1167043.
15. Chen G, Liu G, Pan Y, Liu G, Gu X, et al. (2023) Zeolites and metal–organic frameworks for gas separation: the possibility of translating adsorbents into membranes. Chemical Society Reviews 52: 4586-4602.
16. Katare A, Kumar S, Kundu S, Sharma S, Kundu LM, et al. (2023) Mixed matrix membranes for carbon capture and sequestration: Challenges and scope, ACS Omega 8: 17511-17522.
17. Khan AU, Othman MHD, Younas M, Seema H, Khan Z (2025) Nanomaterials as Key Drivers for Enhanced CO_2 Separation in Mixed Matrix Membranes. Journal of Membrane Science and Research 11: e728387.
18. Cheng Y (2026) Advanced Porous Materials in Mixed Matrix Membranes for CO2 Capture. Small 22: e75067.
19. Wang Y, Ma Z, Zhang X, Li J, Zhou Y, et al. (2022) Mixed-matrix membranes consisting of Pebax and novel nitrogen-doped porous carbons for CO2 separation. Journal of Membrane Science 644: 120182.
20. Nabais AR, Ahmed S, Younis M, Zhou JX, Pereira JR, et al. (2022) Mixed matrix membranes based on ionic liquids and porous organic polymers for selective CO2 separation. Journal of Membrane Science 660: 120841.
21. Madhu K, Pauliuk S, Dhathri S, Creutzig F (2021) Understanding environmental trade-offs and resource demand of direct air capture technologies through comparative life-cycle assessment', Nature Energy 6: 1035-1044.
22. Soo XYD, Lee JJC, Wu WY, Tao L, Wang C, et al. (2024) Advancements in CO_2 capture by absorption and adsorption: A comprehensive review, Journal of CO_2 Utilization 102727.
23. Simari C (2025) Nanomaterials for direct air capture of CO_2: Current state of the art, challenges and future perspectives, Molecules 30: 3048.
24. Kong F, Chen W (2024) Carbon dioxide capture and conversion using metal–organic framework (MOF) materials: A comprehensive review, Nanomaterials 14: 1340.
25. Xie F, Wang N, Chen H, Li M, Li Y, et al. (2025) Advances in amine-functionalized metal organic frameworks for carbon capture, Journal of Materials Chemistry A 13: 41653-41685.
26. Boddeda B, Putta BES (2025) Nanofabrication: Advances, Applications, and Future Prospects in Emerging Technologies. Biosciences Biotechnology Research Asia 22: 1294.
27. Bhaskar S, Reddy N, Ramamurthy SS (2025) Future perspectives and research directions: technological advances and novel applications of nanostructures. Nano-Engineering at Functional Interfaces for Multi-Disciplinary Applications 581-600.

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