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Original Paper

The Development of Natural Adsorbents in the Context of Carbon Peaking and Carbon Neutrality

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Abstract

Under the goals of carbon peaking and carbon neutrality, developing green and low-carbon technologies for pollutant control is of crucial importance. Natural adsorbents, with their advantages of wide availability, renewability, environmental friendliness, and low cost, demonstrate significant potential in the context of the dual carbon targets. This paper systematically examines the demand for adsorption technologies driven by the dual carbon strategy, analyzes the core advantages of natural adsorbents (such as biochar, clay minerals, and natural polymers), and focuses on elaborating the design strategies for natural adsorbents oriented toward efficient carbon capture and synergistic pollutant removal (including raw material selection and pretreatment, pore structure regulation, surface functional group modification, and composite preparation and modification). Additionally, it reviews the progress of their applications in fields such as atmospheric CO_2 capture, removal of heavy metals/organic substances from water bodies, and soil remediation. Finally, in response to the challenges in the large-scale application of natural adsorbents, future development directions are proposed.

Keywords

Natural adsorbents, Carbon peaking and carbon neutrality, Carbon capture, Pollutant removal, sustainable development

1. Introduction

Global warming has emerged as the foremost environmental challenge across the globe, placing nations worldwide under immense pressure to curtail greenhouse gas (GHG) emissions (Feng, Yang, Xie, Dong, Ding, 2017). With the acceleration of industrialization and urbanization, the sharp increase in greenhouse gas emissions has intertwined with environmental pollution issues, posing a serious threat to ecological security and human health. China has made the solemn commitment to "achieve carbon peak by 2030 and carbon neutrality by 2060" (referred to as the "dual carbon" goals) (Zhan, Wang, Wang, Zhang, & Li, 2024), which puts forward an urgent requirement for the green and low-carbon transformation of economic and social development. As an efficient and easy-to-operate separation technology, adsorption plays a key role in fields such as carbon capture, utilization and storage (CCUS)(Ilango, Nguyen, Alzeer., Winnefeld, & Kinnunen, 2025; Zhang, Wang, Blunt, Anthony, Park, Hughes, & Yan, 2020), wastewater and waste gas purification (Devi, Kumar, Kumar, Bulla, Jatrana, Rani, & Singh, 2023), and soil remediation, The highest adsorption capacity of ~2600 mg g^{-1} for contaminants was attained using biomass-derived activated carbon with > 99% removal efficiency and a high surface area of ~3700 m^2 g^{-1}. (Devi, Kumar, Kumar, Bulla, Jatrana, Rani, & Singh, 2023). However, the preparation of traditional adsorbents (such as activated carbon, molecular sieves, and synthetic resins) is often energy-intensive, involves fossil raw materials, or generates secondary pollution, which conflicts to some extent with the concept of dual carbon. Therefore, the development of new adsorbents with sustainable sources, low-carbon preparation processes, excellent adsorption performance, and environmental friendliness has become a research hotspot. Natural adsorbents, with their unique "green genes", are emerging as an important direction for the innovation of adsorption technology in the context of dual carbon goals.

2. Core Requirements for Adsorbents under the Dual-Carbon Strategy

2.1 "Emission Reduction" Requirements

"Emission Reduction" Imperatives fundamentally reconfigure the environmental footprint assessment framework for adsorbents, necessitating a paradigm shift from energy-intensive conventional synthesis. During raw material acquisition, regionally abundant biomass residues or low-grade minerals should be prioritized to dramatically reduce transport-related emissions through shortened supply chains. Processing and activation stages require systematic energy structure optimization: phasing out pyrolysis/calcination systems driven by fossil fuels, while integrating near-zero-carbon alternatives such as solar drying, biomass-powered heating, and green-electricity-assisted activation. Particular attention must be paid to energy hotspots in activation—for instance, the electrical intensity of mechanical milling or regeneration energy for chemical activators—where technological innovation and equipment upgrades can achieve cross-process energy efficiency breakthroughs.

More profoundly, emission reduction mandates a strategic transition from petroleum-derived precursors (e.g., phenolic resins) and coal-based energy dependence toward establishing renewable feedstock networks centered on biomass cycles (crop residues, algae) and mineral resources (bentonite, attapulgite). This transformation not only reduces cradle-to-grave carbon intensity but also catalyzes deep integration of adsorbent manufacturing with circular economy principles.

2.2 "Carbon Sink Enhancement" Requirements

Creating high-performance adsorbents for CO_2 capture from industrial point sources and ambient air requires integrated optimization across three domains: adsorption efficiency, cost-effectiveness, and energy management. In the cement sector, process emissions originate inherently from limestone thermal decomposition, positioning carbon capture, utilization and storage as the critical decarbonization pathway. Optimal materials must concurrently exhibit: high-density selective binding sites such as amine functionalities or alkali metal centers; structural resilience under harsh flue gas conditions; and compatibility with low-energy regeneration techniques to minimize operational burdens.

For direct air capture applications, materials demand enhanced affinity toward trace-level CO_2 molecules to overcome diffusion limitations. Strategic functionalization of natural minerals or hierarchical pore engineering of biochars can establish adaptable adsorption systems tailored to diverse emission profiles. Ultimately, these innovations will accelerate the transformation of emission-intensive industries from passive end-of-pipe control toward proactive carbon resource cycling.

Over recent years, several innovative initiatives have been advanced: chemical absorption—currently the most mature post-combustion CO_2 capture technology—was successfully trialed at a cement plant in Brevik, Norway, and later operationalized at a facility in Texas between 2013 and 2016 (Querejeta, Gil, Rubiera, & Pevida, 2023).

Preparing biochar via pyrolysis of agricultural and forestry wastes. Its stable carbon structure enables long-term carbon storage in soil or materials, achieving negative carbon emissions. Given that biomass conversion to biochar enhances crop yields, higher yields can potentially reduce the agricultural land required for crop production and hence, can decrease carbon emissions from avoided land-use change, it holds the potential to reduce carbon emissions. Simulations from relevant models indicate that a 1% increase in U.S. yields of corn, soybeans, and wheat beyond the trending level would lead to a reduction in net global total emissions by 25-87 Tg of CO_2 equivalent (Dumortier, Dokoohaki, Elobeid, Hayes, Laird, & Miguez, 2020).

2.3 "Synergistic Governance" Requirement

While removing pollutants (e.g., heavy metals, organic pollutants), adsorbents themselves should possess low-carbon characteristics throughout their life cycle to avoid creating new environmental burdens, thereby achieving synergistic effects between pollution control and carbon emission reduction.

2.4 "Circular Economy" Requirement

Adsorbents should be easy to regenerate and reuse. After deactivation, they should be safely disposed of or resourcefully utilized (e.g., as soil conditioners or building material additives) to form a closed loop, reducing resource consumption and waste generation (Obodo & Aigbe, 2023).

3. Advantages of Natural Adsorbents

Natural adsorbents refer to natural substances derived directly from nature or requiring only simple physical/mild chemical treatment, which have the ability to adsorb specific substances from gas or liquid media.

3.1 Core Advantages (Aligning with the Dual-Carbon Goals)

3.1.1 Renewability and Abundance of Raw Materials

They are mainly sourced from agricultural and forestry wastes (straw, fruit shells, wood chips), natural minerals (bentonite, attapulgite, zeolite), marine biomass (chitosan, alginate), etc., with huge reserves and sustainable supply.

3.1.2 Environmental Friendliness

They have good biocompatibility (Obodo, & Aigbe, 2023), and their degradation products are usually non-toxic or low-toxic, reducing the risk of secondary pollution.

3.1.3 Low Energy Consumption and Cost in Preparation

Processing (such as drying, crushing, partial carbonization) is relatively mild, with significantly lower energy consumption compared to high-temperature activation or polymerization processes of synthetic adsorbents, and low cost (Gupta, Carrott, Carrott, & Suhas,2009).

3.1.4 Carbon Sequestration Potential (Especially Biochar)

Biochar is a stable carbon pool, and its production and application processes have negative carbon effects.

3.1.5 Natural Surface Activity

Many natural materials (such as biochar, clay minerals) themselves have abundant pore structures and oxygen-containing functional groups (-OH, -COOH), providing a good basis for adsorption.

3.2 Main Types

Natural adsorbents primarily encompass four major categories based on material origin. Biochar and its derivatives, formed through oxygen-limited pyrolysis (300-700°C) of agricultural and forestry wastes, constitute carbon-rich solids characterized by well-developed porosity, high specific surface area, and abundant surface functional groups, representing one of the most extensively studied categories. Clay minerals, including bentonite (montmorillonite-dominant), attapulgite, kaolin, and zeolite, exhibit layered structures, strong cation exchange capacity, and substantial specific surface areas. Natural polymer materials—such as cellulose (from wood/cotton/straw), chitosan (derived from crustacean shells), starch, and alginate—possess rich active groups (e.g., hydroxyl, amino, carboxyl). Additional types like natural zeolites, diatomite, and peat further diversify this adsorbent family, offering complementary properties for environmental applications.

4. Dual-Carbon Oriented Design Strategies for Natural Adsorbents

To enhance the performance and efficiency of natural adsorbents in specific applications (especially carbon capture), targeted design is required.

4.1 Raw Material Selection and Pretreatment

Raw material selection and pretreatment protocols must prioritize locally abundant, underutilized biomass streams—such as crop residues (e.g., rice husks, wheat straw), forestry byproducts (e.g., sawdust, bark), or low-value mineral deposits (e.g., unrefined clays, volcanic tuff)—to simultaneously minimize transport-related carbon emissions and advance circular bioeconomy principles through waste valorization.Concurrently, multistage pretreatment optimization is critical for energy conservation. Mechanical comminution controlling particle size distribution (typically 0.1-2 mm) to enhance subsequent reaction kinetics. Renewable-energy-integrated drying employing solar thermal systems(Naveenkumar, Ravichandran, Harish, Ruskin, Pozhingiyarasan,& Kolanjinathan, 2023) or biomass-powered dehydrators(Parmigiani, Zani, Invernizzi, Mazzù, Villam & Lezzi, 2010). Mild chemical conditioning via dilute acid (e.g., 0.5M H_2SO_4 or alkali (e.g., 2% NaOH) washing, which selectively removes lignin/hemicellulose barriers while introducing oxygen-containing functional groups, the hemicellulose components were hydrolyzed and solublized within ~5 min of pretreatment, beyond that cellulose begins to degrade, thereby boosting precursor reactivity without intensive energy input (Foston, & Ragauskas, 2010).

4.2 Pore Structure Regulation

Pore structure regulation targets enhanced specific surface area and optimized pore size distribution tailored to specific adsorbates, as exemplified by CO_2 capture requiring micropore development due to its kinetic diameter (Sevilla, Parra, & Fuertes, 2013). This is achieved through three primary approaches: physical activation employs mild pyrolysis under gaseous agents like CO_2 or steam to etch porous networks; chemical activation utilizes reagents including KOH, H_3PO_4, or $ZnCl_2$ for efficient pore creation at reduced temperatures—though environmental impacts necessitate consideration of recyclability(Zavaleta, Terrones, Guerrero, Azabache, Espinoza, & Ipanaqué, 2025) and greener alternatives such as K_2CO_3 or $FeCl_3$; while template-directed methods leverage natural or biodegradable scaffolds to guide precise pore architectures(Rahimzad, & Khoshbouy, 2024; Li, Zhang, Wu, 2020).

4.3 Surface Chemical Property Modification

Surface chemical modification engineers functional groups to enhance adsorbent-adsorbate interactions. For CO_2 capture, dual strategies are employed: nitrogen functionalization via co-pyrolysis (e.g., urea/chitosan) or NH_3 treatment introduces basic moieties ($–NH_2$, pyridinic/pyrrolic N) to strengthen acid-base interactions, while alkali/alkaline earth metal loading ($K^+/Na^+/Ca^{2+}/Mg^{2+}$) promotes chemisorption through carbonate formation or augments physisorption. For pollutant removal, anionic groups (carboxyl/sulfonic) are grafted to enhance cation adsorption via electrostatic/chelation mechanisms (e.g., heavy metals), whereas hydrophobic moieties incorporation improves organic contaminant uptake through hydrophobic/π-π interactions.

Surface chemical modifications aimed at enhancing CO_2 adsorption may concurrently establish synergistic or antagonistic relationships with pollutant removal capabilities(Van Daele, Balalta, Hoekx, Jacops, Daems, Altantzis, & Breugelmans, 2024; Liu, Wang, Wei, Liu, Wang, Wu, & Lu, 2023), governed fundamentally by molecular-scale spatial and energetic competition. Synergistic effects typically arise from bifunctional site engineering: nitrogen doping creates basic groups (e.g., amines) whose lone-pair electrons concurrently chelate heavy metal ions during CO_2 capture; alkali metal loading generates ion-exchange sites during carbonation that concomitantly sequester cationic contaminants. Such electronic structure modulation enables coordinated gas-liquid pollutant control(Ge, He, Zhao, Duan, Gu, Zhang, & Geng, 2017; Wang, Han, Gao, & Zheng, 2018).

Conversely, modification-induced adsorption preference shifts often trigger conflicts: microporous optimization enhances CO_2 selectivity but excludes macromolecular organics via steric hindrance; alkaline surface enhancement for CO_2 chemisorption provokes electrostatic repulsion toward cationic heavy metals in acidic environments due to charge reversal; hydrophobic functionalization improves VOC adsorption while establishing interfacial water diffusion barriers that impede hydrophilic pollutant mass transfer.

Resolving these conflicts necessitates multidimensional decoupling principles: spatial partitioning through heterojunction construction isolates CO_2-selective micropores from macromolecular pollutant domains; stimuli-responsive moieties dynamically regulate surface charge and wettability; electron density gradient design balances affinity for multicomponent pollutants(Özcan, Altun, Davarcı, Çalık, Sadak, &Zorlu, 2025). Ultimately, molecular-scale compatibility between carbon capture and contaminant remediation is achieved.

4.4 Composite and Hybrid Preparation

Composite and hybridization strategies enhance the multi-pollutant control capacity of natural adsorbents through synergistic multi-component interfacial systems. Biochar decorated with nano-iron oxides establishes electron-transfer pathways, where valence state cycling of iron species drives hexavalent chromium reduction to less toxic trivalent chromium while activating radical chain reactions to degrade antibiotic contaminants (Jang, & Kim, 2022). Chitosan/bentonite composite hydrogels leverage bentonite's interlayer confinement to capture cationic pollutants, synergizing with chitosan's directional chelation sites through spatial-charge cooperativity (Dassanayake, Perera, Jayawardena, & Emmanuel, 2023); their three-dimensional networks concurrently optimize contaminant mass transfer. Amine-functionalized biochar composites construct molecular recognition sites on carbon scaffolds (Shafawi, Mohd Amer, Aghamiri., Lahijani, Mohammadi, & Mohamed, 2025), where amine-CO_2 specific proton transfer enhances dilute-phase capture selectivity, while hydrophobic microdomains suppress competitive water adsorption. The enhanced efficacy fundamentally stems from interfacial electron coupling, optimized mass transfer channels, and complementary functional sites, achieving molecular-scale adsorption-catalysis-transformation synergy (Qin, Zhao, Sui, Wang, Chen, Zhang, & Leung, 2024; Ling, Ng, & Ong, 2022).

4.5 Structural Engineering

Structural engineering focuses on the deliberate design of adsorbent macroscale morphologies and spatial configurations to systematically address core engineering challenges in reactor compatibility, fluid dynamic behavior, and mass transfer optimization. For fixed-bed reactor applications, mechanically robust pellets or monolithic structures withstand sustained compressive stresses within packed columns. Their uniform geometric profiles substantially mitigate fluid channeling effects, ensuring homogeneous flow distribution across reactor cross-sections. Engineered hierarchical pore networks enhance fluid permeability, maintaining system pressure drop within energy-efficient operational thresholds (Ilis, Demir, Mobedi, & Saha, 2019).

Fluidized-bed systems necessitate low-density fibrous or microspherical materials for optimal performance. The high specific surface area of such architectures provides abundant contaminant contact interfaces, while their unique fluidization characteristics promote intense gas-solid mixing. Concurrently, tailored surface morphology reduces material attrition induced by particle collisions.

For direct air capture (DAC) scenarios involving trace-level concentration, membrane or aerogel configurations combining ultra-high surface area with minimal flow resistance demonstrate distinct advantages: hierarchically structured pore systems enable molecular-scale capture in microporous domains while macroporous channels serve as rapid diffusion pathways, reducing overall pressure drop by orders of magnitude compared to conventional packed beds. Aerogel's three-dimensional nanoscale frameworks achieve structural integrity at extreme porosity through reinforcement strategies, whereas electrospun fiber membranes allow surface functionalization for targeted gas recognition.

Fundamentally, macroscopic structural engineering orchestrates three interdependent parameters—pore connectivity, fluid path tortuosity, and characteristic dimensions—to establish optimal balances among competing objectives: minimizing hydraulic resistance, maximizing effective mass transfer rates, and preserving mechanical durability. This design paradigm embodies the synergistic integration of Darcy's flow principles and Fickian diffusion theory, systematically reducing fluid transport energy consumption while preserving adsorption kinetic efficiency. Innovative configurations—including bioinspired ceramic monoliths, aligned carbon nanofiber assemblies, and gradient-density aerogel modules—collectively demonstrate the transformative potential of structural optimization in overcoming traditional adsorption engineering limitations9 (Rezaei, & Webley, 2009).

5. Application Fields and Progress

5.1 Atmospheric CO_2 Capture

Biochar exhibits inherent advantages for CO_2 capture owing to its polar hydrophilic surface chemistry, hierarchical porosity, and high specific surface area. Current research prioritizes engineered biochar production through structural modifications that enhance surface properties and sorption capacity. Nitrogen-functionalized variants (e.g., amine-grafted biochar) or alkali metal-loaded derivatives demonstrate superior CO_2 adsorption capacities and selectivity compared to unmodified counterparts.

However, these advanced materials confront persistent challenges in cyclic stability and energy-intensive capture of dilute CO_2 streams—particularly problematic in direct air capture applications. Conversely, natural zeolites and clay minerals offer cost-effective physisorption pathways but exhibit fundamentally limited capacity and selectivity relative to both surface-modified biochars and synthetic molecular sieves.(Dissanayake, You, Igalavithana, Xia, Bhatnagar, Gupta, & Ok, 2020).

5.2 Water Pollution Control

For heavy metal removal (e.g., Pb^{2+}, Cd^{2+}, Cu^{2+}), biochar (utilizing oxygen-containing functional groups/mineral components), organo-modified clay minerals (e.g., bentonite), and chitosan (via amino/hydroxyl group chelation) demonstrate high efficacy, with ongoing design efforts focused on enhancing capacity, selectivity, and interference resistance. Organic pollutant adsorption employs biochar (through pore filling/hydrophobic interactions) and modified minerals to capture dyes, pesticides, antibiotics, and phenolic compounds—yet faces challenges in removing trace refractory organics like per- and polyfluoroalkyl substances (PFAS). Nutrient management leverages Mg/Ca-modified biochar for phosphorus adsorption and potential recovery as slow-release fertilizers.

5.3 Soil Remediation and Carbon Sequestration

Biochar delivers synergistic benefits in contaminated soil management: Its distinctive pore architecture and surface chemistry immobilize mobile heavy metals and sequester organic pollutants through ion exchange, coordination complexation, and hydrophobic interactions, substantially mitigating ecological risks. Concurrently, it enhances soil physical structure by improving aggregate stability and water retention capacity, creating microenvironments conducive to nutrient slow-release. The core value lies in the carbon sequestration essence of highly aromatic carbon matrices resisting biotic/abiotic degradation (Ye, Chen, Gao, Wang, Hu, Dong, & Xiong, 2022), transforming agroforestry waste into century-scale carbon reservoirs that achieve the tripartite objectives of contamination containment, soil enhancement, and net-negative emissions. Design necessitates systematic balancing of environmental persistence, functional integrity of microbial consortia, and long-term ecotoxicological safety.

5.4 Cross-Domain Applications

Natural adsorbent technologies are profoundly integrating into diverse environmental remediation scenarios: For energy gas purification, molecular sieves selectively remove carbon dioxide via size-sieving effects while metal-modified materials achieve efficient desulfurization through surface catalytic conversion. Indoor air purification leverages directional capture capabilities of functionalized materials—such as coordinatively unsaturated sites targeting formaldehyde, lipophilic microdomains adsorbing volatile organic compounds, and photosensitive components enabling synchronous adsorption-degradation. Emerging frontiers explore synergistic effects between capacitive energy storage and carbon sequestration in electrode materials, alongside the emergency response potential of bio-based gels for ecological disasters, collectively demonstrating technological versatility and innovative vitality.

6. Challenges and Future Perspectives

Amidst growing urgency to achieve carbon neutrality, natural adsorbents emerge as pivotal yet imperfect solutions for sustainable separation technologies. Their implementation confronts persistent structural challenges where organic components undergo progressive chemo-mechanical degradation during cyclic operations, fundamentally undermining long-term stability and necessitating frequent regeneration—a process that itself accelerates material fatigue through repetitive swelling-desiccation stress or oxidative damage. Mitigating these limitations demands integrated approaches combining gentle regeneration techniques (e.g., low-temperature steam stripping or electrochemical methods) with covalent stabilization strategies to reinforce molecular architectures against degradation pathways (Verougstraete, Martin-Calvo, Van der Perre, Baron, Finsy, & Denayer, 2020; Zhou, Meng, Gao, Zhao, Zhao, & Ma, 2021).

Concurrently, molecular recognition capabilities remain critically constrained in environmentally relevant multicomponent systems, where competing species—such as sulfur oxides and nitrogen oxides in flue gas, or alkaline earth metals in hard wastewater—create adsorption site competition that severely diminishes target-selective capture efficiency. This manifests operationally as inadequate CO_2/N_2 separation ratios in post-combustion streams and suboptimal heavy metal recovery in hypersaline effluents. Transcending these barriers requires foundational advances in interfacial science, particularly atomistic-level understanding of binding thermodynamics to engineer precision recognition sites through biomimetic or templated functionalization (Rezaei, & Webley, 2012).

Scalability hurdles further compound industrial translation challenges, spanning inconsistent biomass feedstock properties that impair batch reproducibility, energy-intensive thermal processing requiring alternative activation pathways, and intrinsic form factor compromises where macroscopic structuring (e.g., pelletization, monolithic formation) must reconcile conflicting demands of rapid adsorption kinetics, mechanical resilience, and hydraulic permeability. Critically, the environmental promise of these materials hinges on rigorous life cycle validation quantifying net carbon benefits across extraction, synthesis, deployment, and end-of-phase management—particularly whether sequestration offsets chemical modification emissions when benchmarked against conventional alternatives.

Forward-looking innovation must therefore embrace multifunctional integration, developing stimuli-responsive systems with pH/photo-triggered capture-release cycles, catalytic hybrids enabling simultaneous contaminant degradation, and closed-loop architectures facilitating concomitant capture-conversion processes—collectively transitioning beyond passive filtration toward adaptive environmental remediation ecosystems aligned with circular economy principles.

Conclusion

Within the framework of global dual-carbon objectives, natural adsorbents have evolved into foundational enablers of sustainable adsorption technologies, underpinned by their inherent advantages: renewable resource derivation from biomass/mineral reserves, environmental benignity manifested through non-toxic degradation pathways, energy-efficient synthesis protocols substantially reducing adsorbent production energy requirements, and quantifiable carbon sequestration potential via stable carbon matrix formation.

Performance-optimized engineering approaches—systematically integrating life-cycle-assessed raw material selection, hierarchically structured pore architecture, molecularly tailored surface functionalization, multiphase composite hybridization, and application-specific macroscopic configurations—collectively elevate fundamental adsorption parameters (equilibrium capacity, kinetic rate constants, thermodynamic selectivity). This enables deployment across carbon capture applications (e.g., post-combustion CO_2 concentration, direct air capture) and multimedia remediation systems encompassing aquatic (heavy metal/organic contaminant removal), atmospheric (volatile organic compound adsorption), and terrestrial (hydrocarbon/pesticide immobilization) domains.

Persistent challenges regarding cyclic degradation resistance under adsorption-desorption stress, molecular recognition fidelity in multicomponent matrices, and scalable manufacturability necessitate convergent advancements in materials science, environmental engineering, and chemical process technology. Concurrent minimization of cradle-to-gate carbon footprints—through renewable energy integration, low-temperature processing, and closed-loop regeneration—will establish natural adsorbents as critical technological pillars for synchronizing carbon neutrality targets with comprehensive environmental governance, ultimately catalyzing ecosystems predicated on regenerative human-nature symbiosis.

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