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Research Progress on the Applications of Solid-Waste-Based Nanomaterials in Carbon Capture, Utilization, and Storage Technologies

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Abstract. With the continuous advancement of the "Dual Carbon" strategic goals, coupling solid waste resource utilization with carbon emission reduction has become a practical demand in the environmental field. This paper systematically reviews the types, preparation methods and functional properties of solid-waste-based nanomaterials, and summarizes their technical characteristics and current applications across the main stages of CCUS, including CO_2 capture, utilization and storage. Practical bottlenecks in preparing various solid-waste-based nanomaterials, improving their performance, and adapting them to actual operating conditions are analyzed. From the perspective of life-cycle assessment (LCA), the environmental benefits and burdens are discussed. The reviewed literature shows that improved material performance does not necessarily lead to lower overall environmental impacts, as activation and modification may require additional energy and chemicals. Future research directions are also proposed, providing a theoretical basis for developing low-cost solid-waste-based functional nanomaterials for CCUS with low environmental impacts, as well as for integrating solid-waste recycling with carbon emission reduction.

Keywords: solid-waste resource utilization, solid-waste-based nanomaterials, CCUS, CO_2 capture, life-cycle assessment

1. Introduction

Greenhouse gas emissions, particularly CO_2 emissions from fossil fuel consumption and industrial production, have intensified global climate pressures. Carbon capture, utilization and storage (CCUS) is a critical technology underpinning the "Dual Carbon" strategy for deep emission reduction [1]. Solid-state nano-adsorbents possess merits such as high specific surface area, tunable pore structures, facile surface modification and mild regeneration conditions, which can effectively overcome the drawbacks of traditional organic amine liquid-absorption processes [2]. Nevertheless, the synthesis of laboratory-produced nanomaterials relies on high-purity chemical feedstocks, featuring complicated synthesis procedures, high costs, substantial energy consumption and considerable carbon footprints. Their environmental benefits are therefore restricted, hindering large-scale industrial applications.

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Against this background, nano-functional materials fabricated via phase reconstruction using industrial and municipal solid wastes as precursors can be applied to CO_2 capture, resource utilization and mineralization storage. Such an approach can not only utilize solid waste and cut precursor costs, but also reduce the carbon footprint of CCUS, offering a new pathway for integrating solid-waste recycling and CO_2 mitigation [3]. This technology is still at the fundamental research stage and faces bottlenecks including microstructure regulation and stability under operating conditions. Moreover, systematic quantitative assessments of net emission reductions across the entire process remain limited. Hence, life-cycle assessment (LCA) is urgently required to assess environmental costs, evaluate the practical net-reduction potential of CCUS, and dissect core challenges, so as to support theoretical research and engineering implementation [4].

2. Main types and preparation methods of solid-waste-based nanomaterials

Solid-waste-based nanomaterials are produced using solid wastes as primary raw materials. Low-value solid wastes are converted into nanomaterials with targeted functions through element recombination and nanostructure construction, realizing the synergy between solid-waste valorization and carbon mitigation [5]. According to major compositions and structural features, they can be categorized into carbon-rich solid wastes, Si-Al-based industrial solid wastes, Ca-Mg-based alkaline solid wastes, transition-metal-containing solid wastes, layered clay-type solid wastes and multi-source composite solid wastes. Typical solid-waste feedstocks, dominant preparation approaches and as-prepared solid-waste-based nanomaterials are listed in Table 1 [6, 7].

Table 1. Classification and preparation characteristics of solid-waste-based nanomaterials

Category of solid waste	Typical solid-waste feedstocks	Major preparation methods	Resultant solid-waste-based nanomaterials
Carbon-rich solid waste	Agricultural and forestry straw, rice husk, wood chips, waste plastics, waste tires, gasification semi-coke, municipal sewage sludge	Carbonization-activation (pyrolysis combined with physical or chemical activation)	Hierarchically porous biochar, defective porous carbon, carbon nanodots and other solid-waste-derived carbon-based nanomaterials
Si-Al-based industrial solid waste	Fly ash, coal gangue, mineral processing tailings, red mud, waste kaolin residue	Acid/alkali activation-crystallization to destroy dense mineral structures and adjust Si/Al ratios	Nano-zeolites, mesoporous aluminosilicates, amorphous Si-Al oxide aggregates and other Si-Al-based nanoporous / molecular-sieve-like materials
Ca-Mg-based alkaline solid waste	Steel slag, carbide slag, magnesium slag, lime-kiln slag, phosphogypsum	Thermal decomposition, mechanical refinement or aqueous recrystallization to break native passivation shells	Nano-sized CaO/MgO, Ca-Mg-based layered hydroxides, nano-sized basic carbonates and other Ca-Mg-based nano-alkaline materials
Transition-metal-containing solid waste	Red mud, manganese slag, Ni-Co smelting slag, spent lithium-ion batteries, vanadium-titanium slag, electroplating sludge	Metal leaching-reprecipitation (wet extraction-precipitation-hydrothermal treatment-calcination)	Fe/Mn/Ni/Co oxides, spinels, metal-oxide heterojunctions and other transition-metal-based nano-oxides and heterostructured materials
Layered clay-type solid waste	Tailings, waste bentonite, composite Al-ash-steel-slag residues	Exfoliation-intercalation-co-precipitation to weaken interlayer forces and induce new-phase formation	Few-layer kaolinite/montmorillonite nanosheets, solid-waste-derived LDH and other layered silicate-clay-based nanosheet materials
Multi-source composite solid waste	Two or more compatible solid wastes or pre-synthesized nano-units	Compound mixing and in-situ growth of active phases	Coupled-structure materials such as carbon-alkaline phases, Si-Al supports-transition metals, layered materials-porous carbon

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It should be noted that not all solid wastes can be directly modified for utilization. Solid wastes with excessive heavy-metal contents, low fractions of effective components or large amounts of impurities that are difficult to remove generally require pre-sorting and impurity removal prior to subsequent structural modulation [5]. In general, most of the above conversion routes are still confined to laboratory-scale exploration, and significant challenges remain in achieving standardized and continuous industrial-scale production [7].

3. Applications of solid-waste-based nanomaterials in each CCUS sub-process

The CCUS chain mainly consists of CO_2 capture, utilization and storage. Each unit imposes differentiated requirements on functional media in terms of pore structure, surface active sites, acid-base properties and electron-transfer capacity. Synthesized from bulk solid wastes, retired battery residues and other metal-enriched solid wastes, solid-waste-based nanomaterials are not single-functional media. Owing to tunable compositions and potential low-carbon attributes, they show considerable potential in the above-mentioned sub-processes and have attracted increasing research attention.

3.1. Applications of solid-waste-based nanomaterials in CO_2 capture

Solid-waste-derived carbon-based nanomaterials, Si-Al-based nanoporous/molecular-sieve-like materials and layered composite nano-adsorbents can be fabricated from coal-based solid wastes, agricultural-forestry biomass wastes, waste plastics, red mud and other precursors. These materials enable selective enrichment and separation of CO_2 from flue-gas streams, supplying concentrated CO_2 streams for subsequent carbon storage or utilization [3].

Solid-amine-modified nano-aluminum-based adsorbents prepared using high-alumina fly ash as a Si-Al source achieve a CO_2 adsorption capacity of approximately 3.14 $mmol \cdot g^{-1}$ under simulated flue-gas conditions, with a capacity retention ratio above 95 % after 30 adsorption-desorption cycles, demonstrating favorable cyclic regeneration performance [8]. Nitrogen-doped nanoporous carbon derived from agricultural-forestry solid wastes combines abundant micropores with in-situ N-containing active sites, delivering an adsorption capacity of 2.8–3.4 $mmol \cdot g^{-1}$ at ambient temperature and pressure as well as a CO_2/N_2 selectivity of 19–23. It combines decent adsorption performance with the low-cost merit of biomass solid wastes [9]. Nevertheless, most existing tests adopt pure-component gases or dry simulated flue-gas systems, which cannot replicate real industrial flue-gas featuring high humidity, high dust loads and acidic impurities.

Overall, solid-waste-based nano-adsorbents possess tunable pore architectures and abundant surface active sites, showing considerable CO_2-capture potential. Current research is no longer limited to improving CO_2 adsorption capacity; instead, increasing attention is paid to adaptability to real flue-gas environments, long-term cyclic stability and regeneration energy consumption, together with comprehensive trade-offs among material performance, preparation costs and environmental benefits.

3.2. Applications of solid-waste-based nanomaterials in CO_2 utilization

Nanocatalytic materials modified from transition-metal-rich industrial solid wastes and retired energy-related solid wastes can activate inert CO_2 molecules driven by light or electricity, and selectively reduce CO_2 to high-value chemicals such as formic acid, methanol and ethylene. This offers a potential pathway to improve the economic feasibility of CCUS.

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In laboratory liquid-phase electrolysis or photocatalytic systems, metal components recovered from spent batteries and metallurgical slags exhibit catalytic reusability. Solid-waste-derived catalysts achieve Faradaic efficiencies of 60 %–85 % for formic-acid production; under optimized conditions, Faradaic efficiencies for high-carbon products such as ethylene reach 25 %–45 % [10]. Fe-Ni-based nano-alloy/Si-Al support composite electrocatalysts are fabricated from red mud via reduction-acid leaching-loading. The native Si-Al components in red mud exert a confinement effect that suppresses the agglomeration of metallic nano-particles, thus boosting CO_2 conversion toward C_2 products (ethylene, ethanol) with a maximum C_2-product selectivity of 41 % [11]. Moreover, Mn-Co oxide nanosheets synthesized from nickel-smelting slags possess abundant oxygen vacancies that lower the activation-energy barrier for CO_2, and deliver competitive CO-generation activity under visible-light irradiation for light-driven CO_2 photoreduction [12]. Most reported results have been obtained in small-volume three-electrode setups, far from continuous-flow industrial electrolyzers operated under high current densities. Common challenges include short lifetimes of photogenerated charge carriers and insufficient capability for targeted product regulation [10].

Benefiting from defect-derived active sites, heterojunction structures and support-confined effects, solid-waste-based nano-catalysts exhibit great promise for light- and electricity-driven directional CO_2 conversion. Research in this domain is currently dominated by lab-scale photocatalytic and electrocatalytic batch tests. Further validation is needed under continuous-flow conditions, high current densities and complex real-flue-gas conditions. Practical concerns including resource consumption during material preparation, metal-leaching risks in catalytic processes and energy input for product separation also deserve priority attention.

3.3. Applications of solid-waste-based nanomaterials in CO_2 storage

Industrial alkaline bulk solid wastes serve as core feedstocks for mineral carbonation. After reconstruction and modification, these wastes can be converted into Ca-Mg-based solid-waste-derived nano-alkaline oxides, hydroxides and composite functional materials. Active Ca-Mg species react with CO_2 to form thermodynamically stable solid carbonates, thereby enabling long-term mineral storage of CO_2 and showing potential for large-scale application.

Experimental results indicate that nano-modified Ca-Mg-based materials deliver effective carbon-sequestration capacities of 3–8 $mmol \cdot g^{-1}$. Compared with raw steel slag and carbide slag, nano-modification increases carbonation conversion ratios by 30 %–70 % [13]. Nano-sized $Ca(OH)_2$ aggregates are obtained from carbide slag through wet ball-milling and hydration activation. Primary grain sizes decrease to 50–200 nm, which sufficiently expose Ca-O active sites. Their carbonation conversion ratio under ambient temperature and pressure rises by over 58 % relative to raw slag, with a theoretical carbon-sequestration capacity of 118 kg-CO_2 per ton of slag [14]. Nano-sized CaO-MgO composite particles derived from electric-arc-furnace steel slag can remarkably mitigate passivation caused by carbonate-product shell encapsulation, sustaining reactions in gas-solid mineralization systems, and providing insights for on-site carbon sequestration using steel-industry solid wastes [13]. At present, relevant investigations are mostly batch-mode lab tests using pure or high-concentration CO_2; direct mineralization of low-concentration flue gas requires further investigation.

In summary, nano-modification can significantly enhance the CO_2-mineralization capacity, reaction efficiency and utilization ratio of active components for solid wastes. Nevertheless, nano-modification procedures such as grinding, thermal treatment and chemical activation increase process energy consumption and resource inputs. Therefore, carbon-sequestration performance should not be evaluated merely by carbon-sequestration capacity per unit material. Resource

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consumption and environmental loads throughout preparation and mineralization processes must be considered comprehensively. LCA is urgently required for systematic quantitative assessment of full-process energy consumption and environmental benefits.

4. Environmental-impact assessment of solid-waste-based nanomaterials for CCUS based on LCA

Life-cycle assessment (LCA) overcomes the limitations of simple macroscopic performance indicators including CO_2 adsorption capacity, catalytic efficiency and mineralization conversion ratio. Covering the whole workflow of solid-waste pretreatment, nanomaterial preparation, CCUS application and end-of-life disposal, LCA quantifies resource consumption and environmental loads within the system, and rationally weighs carbon-mitigation gains against full-chain environmental costs. Hence, it acts as a core tool for evaluating the genuine low-carbon value and sustainability potential of solid-waste-based nano-materials for CCUS. By substituting virgin raw materials with solid wastes, solid-waste-based nanomaterials reduce resource depletion and carbon emissions originating from conventional-raw-material exploitation and processing. They facilitate solid-waste utilization and reduce upstream emissions, and cut raw-material costs for CCUS. In subsequent CCUS operational stages, they accomplish CO_2 capture, utilization and storage, bringing potential full-chain environmental benefits.

In the CO_2-capture sub-process, solid-waste-based nano-adsorbents can replace traditional high-carbon adsorbents to achieve dual environmental gains of solid-waste disposal and CO_2 capture. In the light-/electro-catalytic CO_2-utilization sub-process, solid-waste-based nano-catalysts enable the recovery of valuable metals from waste, mitigating high-pollution emissions from primary metallurgy while realizing CO_2 utilization. In the CO_2-mineralization-storage sub-process, nano-activated solid-waste materials sufficiently expose active sites and accelerate carbonation reactions. Long-term stable CO_2 storage and co-disposal of hazardous solid wastes are achieved, granting certain emission-reduction or even negative-carbon potential. However, nano-modification, high-temperature activation, acid-base adjustment and other preparation steps for solid-waste-based materials consume substantial energy and chemicals, and generate pollutant loads that may trigger secondary pollution and ecological losses. Part of the low-carbon benefits brought by solid-waste recycling and carbon mitigation could thus be offset. The overall environmental performance heavily depends on the sustainability of preparation and operation systems [15].

According to existing LCA studies, solid-waste-based nanomaterials applied in CCUS show considerable potential for solid-waste valorization and carbon mitigation. Nevertheless, LCA outcomes are highly sensitive to system boundaries, functional units and practical working conditions. No unified paradigm has been established for environmental-load allocation rules, leading to poor comparability of sustainability-evaluation results among different processes [16]. Future efforts should focus on constructing standardized LCA frameworks and unifying evaluation specifications. Full-process greening can be realized via low-energy-consumption activation technologies, closed-loop recycling of chemical agents and renewable-energy integration to strictly control secondary-pollutant discharges, so as to promote industrial-scale, low-carbon and sustainable deployment of solid-waste-based nanomaterials.

5. Conclusions

Owing to favorable nanostructural features and multi-functional merits, solid-waste-based nanomaterials can well adapt to the full CCUS workflow of CO_2 capture, resource utilization and

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mineralization storage. They facilitate the joint realization of solid-waste treatment and carbon-emission reduction targets, with great application prospects and circular-economy values. From the LCA perspective, although replacing virgin feedstocks with solid wastes can cut raw-material consumption and upstream carbon emissions, environmental burdens originating from nano-material synthesis, modification-activation and practical-condition operation still exist in the form of energy consumption, reagent usage and pollutant emissions. Accordingly, macroscopic performance indicators such as CO_2 adsorption capacity, catalytic efficiency and mineralization conversion ratio alone cannot objectively judge the comprehensive environmental friendliness and real low-carbon value of solid-waste-based nanomaterials. A comprehensive life-cycle assessment of environmental benefits and burdens is therefore essential. Currently, experimental data on long-term stability under complex real-world working conditions remain scarce, standardized LCA frameworks tailored for solid-waste-based nano-materials for CCUS are incomplete, and unified norms for evaluation boundaries and allocation rules are absent. Future research directions include developing low-energy-consumption green preparation technologies to mitigate environmental burdens during material fabrication; investigating material stability and deactivation mechanisms under realistic complex conditions and long-cycle operation to fill gaps in working-condition datasets; refining LCA paradigms and unifying evaluation criteria, so as to realize synergistic optimization of material performance, environmental benefits and economic costs.

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