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Upcycling Carbon-rich waste into advanced CO_2 capture adsorbents

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The upcycling of carbon-rich wastes into high-performance adsorbents is emerging as a key strategy at the intersection of waste valorization, circular economy, and carbon capture technologies. In recent years, biomass-derived carbons, biochars, and other waste-based carbon materials have attracted increasing attention as sustainable alternatives to conventional adsorbents, owing to their tunable porosity, low cost, and reduced environmental footprint. Advances in material engineering have demonstrated that the introduction of heteroatoms, particularly nitrogen, together with the development of tailored micro- and mesoporous structures, can significantly enhance CO_2 adsorption capacity and selectivity by strengthening the interactions between the carbon surface and CO_2 molecules.
In this work, agricultural residues are used as a representative case study to demonstrate a scalable route for the production of advanced CO_2 capture materials. Carbonized rice husk was combined with urea and subjected to an integrated mechanochemical and thermal treatment to obtain nitrogen-enriched porous carbons. The resulting adsorbent was benchmarked against a commercial carbon black functionalized under identical conditions, enabling a systematic assessment of the influence of precursor origin and structure on gas adsorption performance. The combined treatment markedly improved the CO_2 uptake of the biomass-derived material, reaching 7.95 mmol g^{-1} (35 wt%) at 30 bar and 25 °C, compared with 6.16 mmol g^{-1} (27 wt%) for the precursor. Moderate enhancements were observed for CH_4 adsorption in the same conditions, while H_2 storage capacities remained comparable under cryogenic conditions.
Beyond the specific rice husk case, these findings highlight the broader potential of converting diverse carbon-rich waste streams into functional adsorbents through solvent-free and energy-efficient processing routes. Mechanochemical activation coupled with thermal nitrogen doping offers a versatile platform for tuning surface chemistry and pore architecture, addressing key requirements for next-generation carbon capture materials. The approach contributes simultaneously to waste minimization and greenhouse gas mitigation, supporting the development of sustainable adsorbents for post-combustion capture, gas separation, and carbon management applications.

Keywords: *CO_2 capture, waste upcycling, nitrogen-doped carbon, biomass valorization, carbon adsorbents*

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