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An Energy-efficient Metal-Organic-Framework/Polymer composite for CO₂ Capture

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Abstract

The continuous rise in atmospheric CO₂ levels represents a major threat to global environmental stability, intensifying the urgency for effective mitigation strategies. As global energy consumption grows, driven largely by reliance on fossil fuels, reducing CO₂ concentrations in the atmosphere remains one of the most viable approaches to minimizing long-term ecological impacts. Metal-organic frameworks (MOFs), composed of metal ions or clusters coordinated with organic linkers, have gained significant attention as highly tunable porous materials capable of addressing pressing challenges in energy and environmental sustainability¹. Their structural versatility, chemical stability, and selective adsorption properties position them at the forefront of next-generation solutions for several energy-intensive processes. MOFs have demonstrated substantial promise across a range of applications. In particular, their performance in CO₂ capture is notable. Compared to conventional sorbents, MOFs offer higher uptake capacities, greater selectivity, and lower regeneration energy requirements. Various CO₂ capture approaches, such as pre-combustion, post-combustion, oxy-fuel combustion, and direct air capture (DAC), operate under distinct thermodynamic and compositional conditions. Current state-of-the-art CO₂ capture techniques involve amine solvents, which are not ideal due to their corrosive nature and toxicity². Considering these conditions, adsorption-based methods, including pressure swing adsorption (PSA), vacuum swing adsorption (VSA), and temperature swing adsorption (TSA), are viable options for industrial deployment³.

Mg-MOF-74 is recognized for its exceptional CO₂ adsorption capacity among MOFs. However, its practical application is limited by poor water stability². Additionally, the conventional activation process, required to remove solvent molecules from the MOF pores, involves prolonged heating at temperatures up to 250 °C, making it both energy-intensive and time-consuming⁴. Integrating a CO₂-philic polymer into Mg-MOF-74 offers a promising strategy to overcome these limitations. Such incorporation may eliminate the need for high-temperature activation and simultaneously enhance moisture resistance, advancing the development of scalable, commercially viable adsorbents for industrial CO₂ capture applications.

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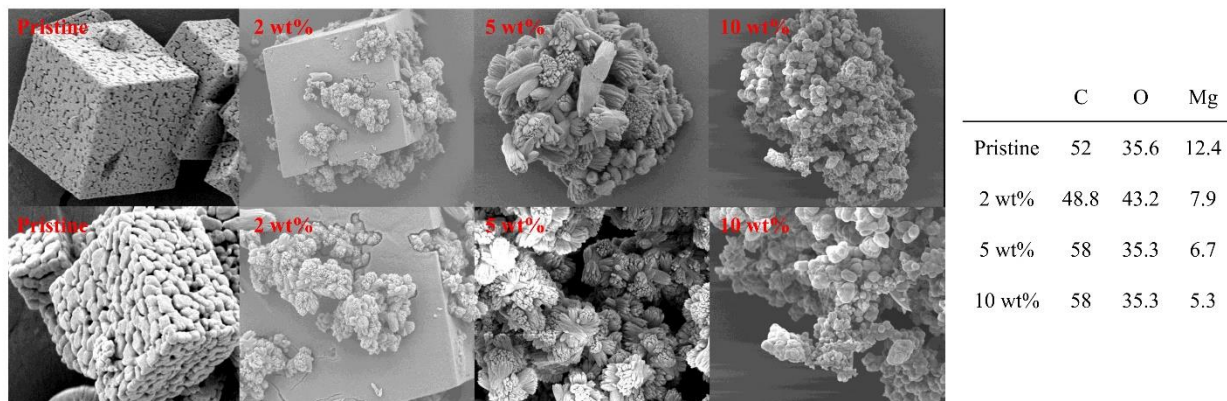


Figure 1. (left) SEM images showing the morphological evolution of Mg-MOF-74 upon incorporation of varying polymer loadings (2 wt%, 5 wt%, and 10 wt%). (right) Elemental composition (EDS analysis) of pristine and polymer-modified Mg-MOF-74 samples.

In this work, a novel polymer at various weight percents of 2, 5, and 10 was incorporated into the synthesized Mg-MOF-74 without activation, and their surface area, morphology, structure, and CO₂ adsorption behavior were assessed. Based on the provided SEM images and EDS data in Figure 1, the incorporation of the polymer at varying weight percentages notably alters the morphology of Mg-MOF-74. The pristine sample exhibits well-defined, smooth-surfaced cubic crystals typical of the unmodified MOF. Upon the addition of 2 wt% polymer, surface roughness increases with the appearance of aggregated clusters forming on the crystal surface, indicating initial polymer deposition. At 5 wt%, the morphology transforms significantly, with the original crystal structure largely obscured by dense and irregular polymer aggregates, suggesting deeper infiltration or surface coverage. With 10 wt% loading, the material appears as an amorphous cluster of agglomerated particles, with no visible traces of the original crystalline framework, indicating extensive morphological disruption due to excessive polymer incorporation. EDS analysis supports these morphological observations. As polymer loading increases, the magnesium content decreases steadily from 12.4 wt% in the pristine sample to 5.3 wt% at 10 wt%, reflecting partial coverage or replacement of the MOF surface by the polymer. Interestingly, the oxygen content increases significantly at 2 wt%, suggesting initial polymer interaction, before stabilizing, while carbon content increases most notably at 5 wt% and above, confirming polymer enrichment in the composite.

Interestingly, despite the apparent structural disruption, the CO₂ adsorption capacity improves significantly at 10 wt% polymer loading (Figure 2). This indicates that, while moderate polymer addition (2 and 5 wt%) may interfere with active sites or block pores, leading to a drop in performance compared to the pristine MOF, the higher 10 wt% loading introduces more favorable interactions or creates new binding environments that enhance CO₂ uptake. This finding highlights the non-linear relationship between polymer content and adsorption performance, underscoring the importance of tuning the loading level to optimize gas capture efficiency.

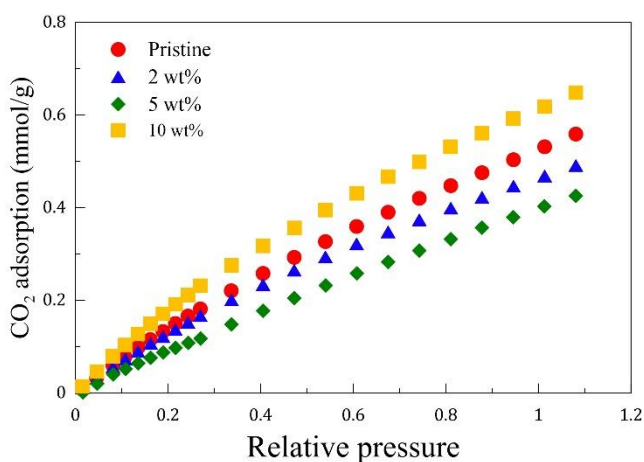


Figure 2. CO₂ adsorption capacity of pristine and polymer-incorporated Mg-MOF-74 samples measured at 298 K.

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