Porous carbon materials derived from spent coffee grounds with potential application in CO_2 capture

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Introduction

The continuous increase in atmospheric carbon dioxide (CO_2) concentration, mainly driven by fossil fuel combustion, represents one of the most critical challenges in climate change mitigation. Among the available carbon capture technologies, adsorption using porous solid materials has gained increasing attention due to its relatively low energy demand, operational flexibility, and suitability for cyclic regeneration. In this context, carbon-based adsorbents are particularly attractive owing to their thermal stability, tunable pore structure, and comparatively low production cost. In recent years, the valorization of biomass residues as precursors for porous carbon materials has emerged as a sustainable strategy aligned with circular-economy principles. Spent coffee grounds are an abundant agro-industrial residue with high carbon content and naturally occurring heteroatoms, making them a promising precursor for adsorbent development. This work focuses on the synthesis of porous carbon materials derived from spent coffee grounds via hydrothermal carbonization and pyrolysis, followed by physical activation with CO_2, to evaluate their potential for post-combustion CO_2 capture.

Materials and Methods

Spent coffee grounds were used as a carbon precursor and subjected to two independent thermal treatment routes: hydrothermal carbonization and pyrolysis. Different temperature and time conditions were applied to compare their effects on the material's chemical transformation. Both routes promoted the conversion of biomass into a progressively more aromatic carbon matrix.

A comparative analysis of the chemical evolution was performed using FT-IR to identify the most favorable conditions for each pathway. Subsequently, the selected materials were subjected to a physical activation test with carbon dioxide. Elemental analysis (CHNS/O) was also performed to evaluate the bulk chemical composition of the precursor and selected carbonized materials, providing complementary information on carbon enrichment and heteroatom evolution induced by the thermal treatments.

The evaluation of CO_2 adsorption was performed using volumetric adsorption measurements under controlled temperature and pressure conditions.

Results and Discussion

FT-IR spectra (Figure 1) reveal the progressive chemical transformation of spent coffee grounds after hydrothermal carbonization and pyrolysis, with a gradual removal of aliphatic and oxygenated functional groups. The attenuation of C–H stretching bands (2920–2850 cm^{-1}) and carbonyl signals, at around 1700 cm^{-1}, indicates the decomposition of lignocellulosic components and the condensation of the carbon framework.

For both thermal treatments, the persistence of the aromatic C=C band near 1590 cm^{-1} suggests the formation of a stable carbonaceous structure. This feature was particularly pronounced in the selected materials —pyrolysis at 500 °C for 3 h and hydrothermal carbonization at 220 °C for 16 h— which exhibited a suitable balance between the removal of labile functional groups and the preservation of aromatic domains.

Elemental analysis qualitatively supports these observations, showing an increase in carbon content and a relative decrease in oxygen and hydrogen after both hydrothermal carbonization and pyrolysis. This trend is consistent with the progressive aromatization and condensation of the carbon framework inferred from the FT-IR spectra.

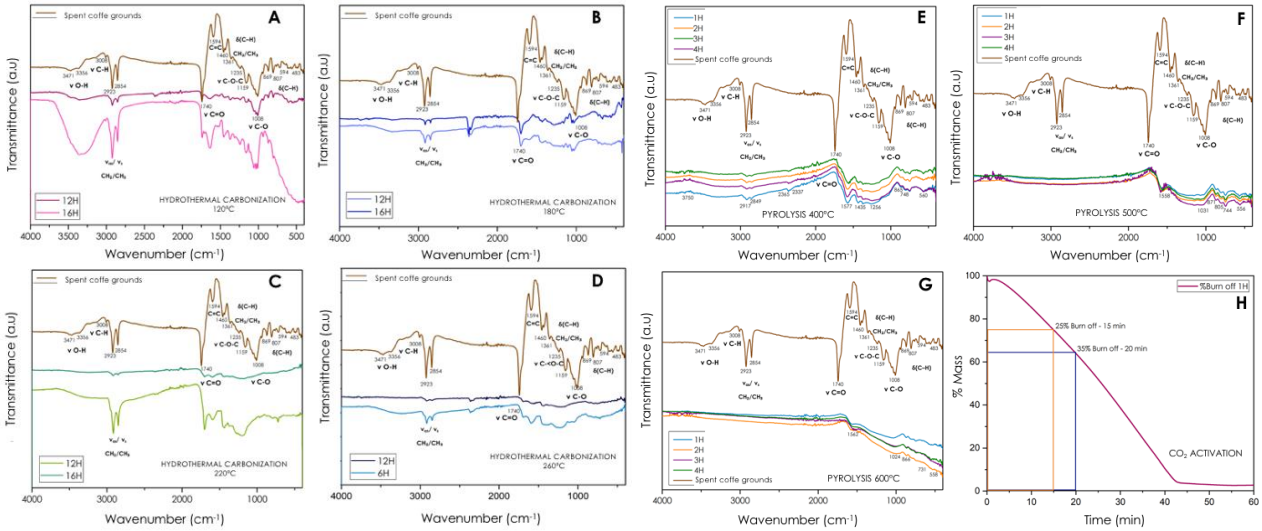

Figure 1. FT-IR spectra of spent coffee grounds and derived carbon materials after hydrothermal carbonization (A-D), pyrolysis (E-G), and CO_2 physical activation (H).

Physical activation with CO_2 was carried out on carbon pellets obtained by pyrolysis at 500 °C for 3 h, resulting in a controlled burn-off of 25–35 %, confirming the effective gasification of the carbon matrix. This activation level promotes porosity development while preserving the aromatic carbon framework, thereby avoiding excessive structural degradation.

Conclusions

Porous carbon materials derived from spent coffee grounds through hydrothermal carbonization and pyrolysis exhibit a progressive transformation toward stable aromatic structures. Optimal conditions within each synthesis route enable the application of CO_2 physical activation as a common step for comparative analysis. For carbon pellets obtained by pyrolysis at 500 °C for 3 h, CO_2 activation results in a controlled burn-off of 25–35 %, confirming effective gasification while preserving the aromatic framework and simplifying surface chemistry. These features support their suitability as adsorbents for post-combustion CO_2 capture. Ongoing adsorption studies, together with the pelletization and activation of hydrothermally carbonized materials, will further elucidate the structure–performance relationship of these systems.

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