DOI: http://doi.org/10.21698/simi.2025.ab04

ASSESSING CATALYTIC ENHANCEMENT IN DYE REMOVAL ON METAL-ION–IMPREGNATED ACTIVATED CARBONS VIA ADSORPTION WITH HYDROGEN PEROXIDE ACTIVATION

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Keywords*: activated carbon, catalytic oxidation, dye removal, Fe/Mn impregnation, hydrogen peroxide*

Introduction

The continuous release of dyes from textile, pharmaceutical, and food industries into aquatic systems has raised serious environmental concerns. Dyes are typically non-biodegradable, stable against light and oxidation, and toxic to aquatic and human life. Conventional treatment technologies, such as coagulation, flocculation, and biological degradation, are often inefficient for dye removal. In this context, adsorption and catalytic oxidation have attracted increasing attention as complementary or hybrid processes. Activated carbons obtained from renewable biomass sources represent sustainable sorbents with tunable pore structure and surface chemistry. Their performance can be further improved by impregnation with transition metals, providing active sites for heterogeneous catalysis. Such multifunctional sorbent–catalysts can simultaneously remove contaminants through adsorption and activate oxidants such as hydrogen peroxide (H_2O_2), mimicking Fenton-like processes. This dual functionality reduces external oxidant demand, enhances process efficiency, and broadens the applicability to different dye classes.

Materials and methods

Bio-carbons were synthesized from lignocellulosic agricultural residues via carbonization and subsequent impregnation with Fe, Mn, Cu, Co, and Ni salts. The obtained composites (ACCN–Me) were characterized for their stability by immersion in water, boiling conditions, and acidic medium (HCl 0.1N). The quantification of metal release under different conditions allowed the definition of safe operational pH ranges, indicating stability in neutral media and significant leaching in acidic environments.

Catalytic activity was evaluated using the volumetric method of H_2O_2 decomposition, monitoring oxygen evolution. Reference materials included commercial activated carbon Centaur, catalytic carbon Quantum DMI-65, and MnO_2. Batch adsorption experiments were conducted using model dyes Congo Red (CR), Methylene Blue (MB), Rhodamine G (RdmG), and Murexide (Mrxd), at concentrations between 0.02 and 1 mmol/L. Experiments were performed with and without H_2O_2 (0.02–0.1 M) under constant agitation, using 90–125 µm fractions of composites. Dye concentrations were measured spectrophotometrically at their maximum absorbance wavelengths (498 nm for CR, 665 nm for MB, 526 nm for RdmG, and 523 nm for Mrxd).

Results and conclusions

Stability tests revealed negligible leaching of metals under neutral and boiling water, confirming the robustness of the composites in real aquatic environments. However, in acidic medium significant release was observed: Mn (66.8 mg/L), Cu (35.1 mg/L), Ni (17.4 mg/L), and Co (6.8 mg/L), highlighting the need for neutral operational conditions but also opening regeneration pathways under controlled acidic treatment. Catalytic activity assays demonstrated that MnO_2 exhibited the highest H_2O_2 decomposition rate among references, while Centaur and Quantum DMI-65 showed moderate activity. Among the synthesized composites, the catalytic activity decreased in the order: ACCN-Mn > ACCN-Cu > ACCN-Co > ACCN-Ni, with ACCN-Mn almost doubling the activity of Centaur. Fe-impregnated carbons also displayed remarkable activity, comparable to Mn-based materials.

Adsorption experiments showed that Fe–carbons removed up to 95–96% of Congo Red within 30 minutes without peroxide. In the case of MB and Mrxd, adsorption alone removed 65–75%, while coupling with H_2O_2 increased removal efficiencies to 80–85%. For RdmG, adsorption capacity increased with H_2O_2 concentration, reaching 86.6% removal at 0.1 M peroxide. This synergistic effect confirms that the adsorption–H_2O_2 mode reduces equilibrium dye concentrations more efficiently than adsorption alone.

Comparative studies with commercial references confirmed that Fe- and Mn-modified carbons outperformed Centaur carbon in both adsorption and catalytic activity, and approached the performance of MnO_2, but with significantly lower oxidant requirements. These findings demonstrate the potential of bio-derived carbons as cost-effective alternatives for wastewater treatment.

Fe- and Mn-impregnated bio-carbons derived from agricultural residues exhibited high efficiency in dye removal through integrated adsorption–catalysis processes. Their key advantages include: (i) rapid uptake of dyes such as Congo Red (up to 96% removal in 30 min), (ii) synergistic enhancement with hydrogen peroxide leading to up to 85% removal of other dyes, (iii) stability under neutral aqueous conditions, and (iv) lower oxidant demand compared to commercial catalytic carbons. These findings confirm that the sorbent–catalysts can be employed in batch and fixed-bed configurations, combining operational stability with the possibility of controlled regeneration. These multifunctional sorbent–catalysts bridge adsorption and advanced oxidation, providing sustainable solutions for wastewater decolorization and pollutant control.

Acknowledgment

This research was funded by the subprogram "ECOAQUA" (code 010603) of the Institute of Chemistry of Moldova State University and supported by the Horizon Europe MSCA Staff Exchange project CLEANWATER (No. 101131382).