Removal of Emerging Contaminants from Wastewater by Biomass Waste Derived Adsorbents: Towards Sustainable Water Remediation

Abstract

Organic dyes and heavy metals are the major pollutants for contamination of water. This study explores biochar-based adsorbents for efficient removal of these contaminants due to their versatility, regeneration ability, and cost-effectiveness. Herein, the efficient adsorbent, sawdust-derived biochar doped with $ZnCl_2$ (Z@SB) for removal of organic dyes, namely malachite green (MG) and methyl orange (MO), was explored via batch adsorption study. The specific surface area from BET analysis improved 5.66 times after chemical modification, which enhanced performance, with % removal of MG and MO increasing by 2.8 and 3.5 times, respectively. The Langmuir isotherm analysis revealed the maximum adsorption capacity (Q_{max}) of MG and MO dyes were 318.47 and 225.73 mg/g, respectively. Moreover, green coconut shells (Cocos nucifera) were converted into efficient bio-adsorbents ($H@GCS_T$/$H@GCS_P$) for Pb(II) removal through torrefaction/pyrolysis and acid activation. Surface morphology showed highly porous structures, with BET surface areas of 1009.21 and 1523.84 m²/g for $H@GCS_T$ and $H@GCS_P$, respectively. Acid activation enhanced percentage removal of Pb (II) by 2.45 times for $H@GCS_T$ and 2.10 times for $H@GCS_P$. The Langmuir isotherm model best described the adsorption process, with maximum adsorption capacities of 201.19 and 132.71 mg/g for $H@GCS_T$ and $H@GCS_P$, respectively. The adsorption kinetics followed the pseudo-second-order mode. Furthermore, the synthesis of Ap@BC, a carbonized material produced from biochar derived from waste biomass and activated with $(NH_4)_2S_2O_8$. Sodium alginate was utilized to prepare adsorbent beads from this material, which were investigated for their remarkable potential as an efficient adsorbent for methylene blue dye (MB), employing both batch and fixed-bed column systems. Various characterization techniques, including TGA, FTIR, Raman spectroscopy, and SEM, provided valuable insights into the surface properties of Ap@BC, significantly enhancing its dye-binding capabilities. Kinetic analyses revealed that MB removal adheres to the Pseudo-second-order kinetic model, indicative of a chemisorption mechanism. The monolayer adsorption capacity of 52.6 mg/g, as determined by the Langmuir isotherm model. The fixed-bed column experiment showed that the efficiency of the column enhanced significantly with increased bed depth and reduced flow rates, emphasizing the operational advantages of Ap@BC in real-world applications. The robust fit of the kinetic data with Thomas and Yoon Nelson models highlights its feasibility for large-scale deployment. Additionally, study introduces an unsteady-state dynamic model to describe dye ion adsorption kinetics onto sodium alginate/$(NH_4)_2S_2O_8$-activated pyrolyzed biochar composite beads (RH@BpH/GC@BpH) in a fixed-bed system. The model estimates axial dispersion coefficients of 7×10^{-2} m²/s for RH@BpH and 5×10^{-2} m²/s for GC@BpH. Adsorption mechanisms, including n-π interactions, hydrogen bonding, and electrostatic interactions, highlight the effectiveness of adsorbents in addressing dye pollution. A detailed LCA revealed the environmental impact of producing 1 kg of Z@SB for decolorization, with low GWP (1.58 kgCO2-Eq), FDP, HTP, and other indicators. Similarly, the LCA for 1 kg of $H@GCS_T$/$H@GCS_P$ adsorbents for lead removal showed HTPinf of 4.10/4.37 kg1,4-DCB-Eq and METPinf of 0.10/0.11 kg1,4-DCB-Eq, alongside positive results in other parameters. Commercial activated carbon costs 42.88 USD/kg, while biochar adsorbents are about three times more cost-effective. Their superior regeneration and reusability make them highly promising for real-field wastewater treatment applications.

Keywords: *Wastewater treatment, Dye Removal, Heavy Metal de-contamination, Activated biochar, Adsorption, Batch study, Fixed bed column study, Sustainability, Life cycle assessment (LCA).*