

Development of Plasma-Modified Biochar from Slow Pyrolysis for Phosphate Removal.

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ABSTRACT

Phosphate-induced eutrophication necessitates the development of efficient and selective removal technologies. Although zirconium-based adsorbents exhibit strong affinity toward phosphate through inner-sphere complexation, their performance is often limited by restricted accessibility of active sites. In this study, hydrogel beads based on alginate and coffee husk biochar through slow pyrolysis were developed and functionalized with zirconium, then modified using Low-Pressure Cold Plasma (LPCP) to increase surface reactivity and adsorption efficiency. The results demonstrate that moderate plasma treatment (10 W) significantly improves adsorption capacity while maintaining structural integrity. Equilibrium studies reveal a maximum adsorption capacity of 71.36 mg g⁻¹, surpassing many previously reported zirconium-based adsorbents. Optimal performance is achieved under mildly acidic to near-neutral conditions, and competitive ion studies demonstrate high selectivity toward phosphate. Furthermore, the plasma-optimized material maintains excellent performance over multiple reuse cycles, indicating enhanced structural stability. The integration of biomass-derived biochar, zirconium coordination chemistry, and plasma-based surface engineering offers a sustainable strategy for developing high-performance adsorbents for advanced phosphate removal.

Key words: *Slow Pyrolysis, Low-pressure cold plasma (LPCP); Phosphate removal; Adsorption; Biochar; Hydrogel beads; Zirconium*