

Functionalized bio-based materials for water treatment: Advances in cellulose, lignin, melanin, and hybrid systems

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Abstract

Access to safe drinking water remains a global challenge due to increasing contamination by heavy metals, organic pollutants, dyes, pharmaceuticals, oils, and pathogenic microorganisms. In this context, sustainable and low-impact materials for water purification are gaining increasing attention. This review focuses on bio-based materials, specifically cellulose, lignin, and melanin, as well as their functionalized derivatives and hybrid systems, for water purification applications. These materials are integrated within a common framework, allowing direct comparison of their structure–property–performance relationships and highlighting potential complementary functionalities. Emphasis is placed on adsorption–filtration processes, membrane technologies, and electrospun fibrous systems. Nanocellulose-based materials, including cellulose nanocrystals, nanofibers, and bacterial cellulose, are discussed in terms of extraction methods, surface functionalization, adsorption behavior, and performance toward a wide range of contaminants. Lignin-based systems, such as sorbents, hydrogels, foams, aerogels, and hybrid membranes, are examined with attention to the effects of chemical modification on adsorption capacity, selectivity, and reusability. Emerging melanin and melanin-like materials, particularly polydopamine-based systems, are also considered, highlighting their ability to bind metal ions and organic pollutants and their integration into multifunctional composites and membranes. Across all material classes, the role of surface chemistry, porosity, and structural organization in determining adsorption performance is discussed, together with adsorption models, regeneration behavior, practical constraints, and the current level of technological maturity of the different material systems. After an overview of biodegradability and sustainability aspects, the review critically examines key limitations, including long-term stability, regeneration efficiency, validation under realistic wastewater conditions, and scalability, which currently hinder large-scale implementation. These aspects are discussed to outline future research directions toward the development of effective and sustainable water purification technologies based on renewable bio-based materials