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Introduction

Agro-industrial activities generate substantial amounts of biowaste, including agricultural residues, food processing by-products, and organic waste streams. Traditionally, such waste materials have been considered as environmental liabilities, o en leading to pollution and resource depletion [1]. However, in the context of advancing sustainability goals, there is growing recognition of the untapped potential inherent in these biowastes. By harnessing innovative technologies and adopting a circular economy approach, these biowastes can be transformed into valuable resources, thereby promoting environmental stewardship and economic prosperity [2,3]. One promising avenue for the valorization of agro-industrial biowaste is the synthesis of nanomaterials for wastewater treatment applications. Nanotechnology o ers unique opportunities for enhancing the e ciency and e cacy of wastewater treatment processes due to the high surface area-to-volume ratio and distinctive physicochemical properties of nanoscale materials. Moreover, by utilizing agro-industrial biowaste as precursor materials, it is possible to develop eco-friendly nanomaterials that minimize the environmental footprint associated with conventional synthesis methods. the global focus on sustainability has prompted a reevaluation of traditional waste management practices, particularly in the agro-industrial sector [4,5]. With agricultural activities and food processing industries generating substantial quantities of biowaste, there is growing recognition of the need to transition towards more environmentally responsible and economically viable approaches. One promising avenue in this endeavor is the valorization of agro-industrial biowaste for the synthesis of eco-friendly nanomaterials, speci cally tailored for wastewater treatment applications [6,7]. e utilization of agro-industrial biowaste presents a dual opportunity: it addresses the challenge of waste management while simultaneously providing a sustainable source of raw materials for the synthesis of value-added products. By repurposing these waste streams, we can mitigate environmental pollution, reduce reliance on virgin resources, and contribute to the circular economy model, which emphasizes the optimization of resource use and the minimization of waste generation [8,9]. Central to this approach is the integration of green chemistry principles, which advocate for the design of chemical processes that minimize environmental impact and maximize resource e ciency. Green chemistry o ers a framework for the development of eco-friendly synthesis routes that utilize benign

***Corresponding author:** Zhiren Wang, Department of Mechanical Engineering, Northwestern Polytechnical University, China, E-mail: zhirenwang@gmail.co.edu

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Circular economy integration

In addition to green chemistry principles, the circular economy concept plays a crucial role in maximizing the sustainability benefits of agro-industrial biowaste valorization. At its core, the circular economy seeks to optimize resource utilization, minimize waste generation, and promote closed-loop material cycles. By transitioning from a linear "take-make-dispose" model to a circular "reduce-reuse-recycle" paradigm, the circular economy offers a holistic approach to sustainable development. In the context of nanomaterial synthesis from agro-industrial biowaste, the circular economy framework emphasizes the importance of closing the material loop and minimizing resource inputs. This can be achieved through strategies such as cascading utilization, where biowaste is sequentially valorized into multiple high-value products, or symbiotic industrial ecosystems, where waste streams from one process serve as feedstocks for another. By integrating circular economy principles into nanomaterial synthesis pathways, researchers can minimize waste generation, reduce environmental impact, and enhance resource efficiency throughout the product lifecycle.

Case studies and applications

Numerous case studies demonstrate the feasibility and effectiveness of harnessing agro-industrial biowaste for the synthesis of eco-friendly nanomaterials in wastewater treatment applications. For example, researchers have successfully synthesized nanoparticles from agricultural residues such as corn stalks, coconut shells, and peanut shells for the removal of heavy metals, organic pollutants, and emerging contaminants from wastewater streams. These nanoparticles exhibit excellent adsorption capacities, catalytic activities, and antimicrobial properties, making them promising candidates for sustainable