Editorial

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Water pollution and contamination are critical global challenges that require immediate, practical solutions. Industrial wastes contain a variety of highly toxic inorganic and organic pollutants, including dyes and heavy metals, which adversely affect the environment and human health. Among different types of water pollution, synthetic dyes are considered one of the most hazardous classes of wastewater pollutants. Numerous studies have demonstrated that many dyes exhibit carcinogenic, mutagenic, and teratogenic properties. Every year, large quantities of different dyes, such as methylene blue, methyl orange, rhodamine B, and Congo Red, are produced and widely used in various industries, such as pharmaceuticals, textiles, paper, cosmetics, plastics, leather, agriculture, photoelectrochemical cells, and food processing [1].

Methylene blue and Rhodamine B are classified as cationic dyes and are more toxic than anionic dyes, such as methyl orange and Congo red [2, 3]. Various methods have been developed for dye removal from natural ecosystems, including chemical methods (oxidation, neutralization, ion exchange, and recovery), physical methods (adsorption, filtration, sedimentation, and reverse osmosis), and biological methods (using bacteria, fungi, and actinomycetes). However, conventional physical and chemical methods are often limited by high costs and the generation of secondary pollutants, such as toxic sludge. In addition, biological approaches are associated with low efficiency and long processing time for dye degradation, and inability to degrade highly stable synthetic dyes. Photocatalysis, as an efficient alternative, uses metal-based nanoparticles under ultraviolet or visible light to drive the total oxidation and decomposition of organic contaminants. This advanced oxidation process has been proposed as a cost-effective, eco-friendly, and efficient method to completely decompose organic chemicals into CO_2 and H_2O or transform them into safer molecules [1, 4].

In recent years, nanotechnology has played a central role in advancing wastewater treatment strategies. In particular, green nanoparticles have gained considerable attention due to their cost-effective, environmentally friendly, and sustainable nature. Green synthesis utilizes biological resources (plant extracts, bacteria, fungi, and algae) as reducing and stabilizing agents. Among these, plant-mediated synthesis is especially attractive because of its simplicity, scalability, and rich phytochemicals, including flavonoids, alkaloids, phenolics, and terpenoids,

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which facilitate nanoparticle formation and stabilization [5]. In addition, green-synthesized nanoparticles often show improved physicochemical stability. Natural organic matter present in environmental systems can adsorb onto nanoparticle surfaces, reducing agglomeration, improving dispersion, and increasing catalytic efficacy while potentially lowering toxicity. The green synthesis method is safer, more economical, and environmentally benign compared to physical and chemical synthesis methods, which often involve expensive reagents, high energy consumption, and toxic solvents. Notably, green-produced nanoparticles are generally less toxic and more biocompatible and are suitable for environmental applications [6].

In recent years, green synthesis of plant-based nanoparticles, such as silver (Ag) [7], gold (Au) [8], selenium (Se) [9-11], copper oxide [12, 13], zinc oxide (ZnO) [11], titanium dioxide (TiO_2) [14], zero-valent iron [15], and cobalt oxide [16] or rare-earth oxides [17] have been investigated for different applications, and they proved potential antimicrobial, anticancer, and photocatalytic activities. The ability of green nanoparticles to efficiently degrade a wide range of dyes, including methylene blue, rhodamine B, and methyl orange, highlights their potential as powerful tools for advanced wastewater treatment. More importantly, their synthesis from renewable biological resources offers a pathway toward the development of sustainable remediation technologies.

Photocatalysis using metal oxide semiconductors, particularly ZnO and TiO_2 nanoparticles, has attracted considerable attention for wastewater treatment. However, several limitations hinder their practical applications, including limited visible light absorption, rapid electron-hole recombination, and reduced efficiency in turbid wastewater. To overcome these challenges, researchers have developed modified systems containing doped semiconductors, heterojunction structures, and composite materials. These modifications significantly enhance photocatalytic efficiency by improving charge separation and extending light absorption into the visible region. Similarly, reduction-based catalytic systems employ nanoparticles, such as Au, Se, and Ag, which rely on external reducing agents, such as sodium borohydride.

Future research should focus on agro-industrial residues-fruit peels and agricultural by-products- as reducing agents instead of utilizing fresh plant extracts. This approach not only reduces the cost of nanocatalyst production but also aligns with circular economy principles by converting environmental waste into high-value functional materials. Despite substantial progress, several critical challenges remain. Most studies are limited to laboratory-scale experiments using model dye solutions, which do not adequately represent the complexity of real industrial wastewater containing mixed contaminants, salts, and organic matter. Additionally, nanoparticle recovery, long-term environmental fate, scalability of green synthesis methods, and potential ecotoxicological effects require further investigation. Addressing these challenges will require a shift toward real-world applications, comprehensive lifecycle assessments, and process integration. Interdisciplinary collaboration among materials scientists, environmental engineers, toxicologists, and policymakers will be essential to accelerate the translation of laboratory findings into practical solutions.

In conclusion, green-synthesized nanoparticles represent a promising yet underexploited solution to the persistent problem of dye pollution in wastewater. Their high catalytic capabilities, combined with environmentally friendly synthesis methods, align strongly with the goals of sustainable development. However, realizing their full potential requires a shift from laboratory-scale validation to real-world implementation. By addressing challenges related to scalability, standardization, and safety, green nanotechnology can evolve from a promising concept into a practical, impactful solution to global water pollution.

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