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Editorial

Nanoscale Solutions: The Transformative Applications of Functionalized Nanomaterials in Environmental Remediation

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Environmental pollution has become a pervasive and pressing issue in the modern world, mainly arising from human activities that release harmful substances into the air, water, and soil [1]. As industrialization, urbanization, and the increasing use of fossil fuels have accelerated, organic pollutants (e.g., pesticides, herbicides, chlorinated hydrocarbons (CHCs), and polycyclic aromatic hydrocarbons (PAC)), inorganic contaminants (e.g., metals ions from Cd, Cu, Pb, Zn, Hg, V, Tl, and U), metalloids (e.g., As and Sb), micro- and nanoparticulate matter, greenhouse gases, and toxic volatile organic compounds (VOCs: formaldehyde, carbon tetrachloride, trichloroethylene, toluene, etc.) have reached unprecedented levels [2–6]. Their persistence in the environment has become a global concern. Novel and sustainable approaches for remediation are urgently needed [7].

In fact, this contamination poses a threat to ecosystems, biodiversity, and human health, making environmental pollution a global issue that demands immediate attention [8,9]. The consequences of environmental pollution are far-reaching, as they impact air quality, water resources, and the overall balance of ecosystems. From smog-choked urban areas to contaminated water bodies, the visible and invisible effects of pollution underscore the need for comprehensive solutions [2,10]. Addressing environmental pollution requires a concerted effort via sustainable practices and technological innovations to mitigate the damage already done and prevent further degradation of our shared environment, considering soil and water consumption or the presence of toxic microorganisms [11–13].

In the modern era, however, environmental remediation faces new and intricate challenges. Rapid technological advancements, emerging pollutants, and the global nature of environmental issues demand innovative solutions. Climate change adds an additional layer of complexity, altering the dynamics of ecosystems and requiring adaptive remediation strategies [14]. For instance, it is well known that organic pollutants have a high impact on aquatic life, atmosphere, and human health. Due to their persistent chemical characteristics, the hazardous effects increase with adverse effects on the quality of the ecosystem, especially considering that their fate cannot be exactly predicted [15].

Addressing these modern challenges requires a multifaceted approach integrating traditional remediation methods with cutting-edge technologies and a deep understanding of the interplay between human activities and the environment [16].

In this framework, the use of nanomaterials in environmental remediation (which is called *nanoremediation*) has emerged as a groundbreaking and innovative approach with an almost 80% drastic reduction in operational costs and a significant reduction in time frame for treating contaminated sites compared to conventional remediation methods [16–18]. Sustainable and timely remediation can be obtained with nanostructured materials that combine surface functionalization with the use of a variety of systems, i.e., bio-based nanosorbents, inorganic porous materials, nanodots, nanospheres, nanocomposites, and magnetic or photoactivable nanoparticles [19–21]. For instance, metal nanoparticles can be used for their surface interaction with pollutants and catalytic reduction of organic molecules [22].

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Nanomaterials, which are characterized by their size in the range of nanometers (10^{-9} m), peculiar properties, and unique functionalities, offer a powerful toolset for targeted and efficient remediation processes. Their application in environmental cleanup ranges from removing pollutants in water (both industrial and domestic), mine tailing, and soil to air sensing and purification [23–25]. This cutting-edge technology not only enhances the efficacy of remediation efforts but also minimizes the environmental impact of traditional cleanup methods [26]. Indeed, according to their nature, nanomaterials can act as excellent adsorbers, catalysts, and sensors for different pollutants. Due to their high surface-to-volume ratio, it is possible to (1) improve the adsorption capacities of sorbent materials; (2) enhance the mobility in solution, ensuring that a whole volume can be quickly scanned; (3) take advantage over the high surface reactivity (mainly due to the high density of low-coordinated atoms at the surface, which are known as *dangling bonds*) to further functionalize nanomaterials and enlarge the physico-chemical mechanisms to degrade or scavenge pollutants; and (4) synthesize them in different sizes and morphologies (ranging from spheres to more anisotropic shapes), given that they are versatile materials, tuning their properties according to the final purpose.

According to the nanomaterial type, different mechanisms can be used to remove pollutants from different sources, often combining synergistic properties. Metal and metal oxide nanoparticles (gold, silver, copper, silica, iron oxides, titanium oxides, zinc oxide, manganese oxide, etc.) and their bimetallic combination [22,27,28] or metal–organic frameworks and zeolites [29,30] showed the ability to adsorb several pollutants. Noble metal nanoparticles, especially gold (AuNPs) and silver nanoparticles (AgNPs) are used for the adsorption and catalytic degradation of antibiotics owing to their high surface reactivity and superior reaction kinetics [31]. However, the small size of metal nanoparticles often complicates the recovery and tends to agglomerate due to Ostwald ripening, which minimizes their high surface energy [32]. This leads to a reduction in both sorption capacity and catalytic activity (due to the loss of active sites in the catalyst). To prevent agglomeration, stabilization of nanoparticles with surface capping/functionalizing agents, i.e., charged or hydrophobic molecules, polymers, and dendrimers, have been attempted [32–35]. Besides their adsorption abilities, silver nanoparticles (AgNPs) are known for their antibacterial effects against a broad spectrum of microorganisms (e.g., viruses, bacteria, and fungi) and are, therefore, widely used for water disinfection [36]. Magnetic nanoadsorbents (e.g., magnetite-Fe_3O_4, maghemite-Fe_2O_3, and nickel–ferrite) are particularly attractive as they can be easily retained and separated from treated wastes, although issues related to toxicity still exist [37,38]. Titanium dioxide nanoparticles (TiO_2NPs) have been extensively used for the oxidative and reductive transformation of organic and inorganic contaminants in air and water (e.g., phenolic compounds, metal ethylene diamine tetra acetate complexes, airborne microbes, odorous chemicals, etc.) via photocatalytic degradation (a chemical degradation pathway based on redox reactions of electron/hole pairs upon irradiation) [39]. However, due to their 3.2 eV bandgap, radiation in the UV range (320–400 nm, 5% of solar irradiation) must be used to induce charge separation within the particle. Therefore, it is necessary to enhance the performance of TiO_2 nanoparticles (using photons from the near visible to visible region), manipulating the particle size, doping TiO_2 with foreign atoms, or modifying with noble metals [40,41].

Nanofiltration by membranes represents another useful approach for contaminants removal, especially in the case of water treatment, without releasing harmful by-products. Nowadays, cellulose acetate and polyamides are the most used as filtration membranes, although other polymers (e.g., polyvinyl alcohol (PVA) and sulfonated polysulfone (sPS)) can also be used for membrane synthesis [42]. Recently, hybrid organic/inorganic nanocomposite materials in the presence of inorganic nanomaterials (e.g., some metal and metal oxides) as polymer fillers (5–10%) are attracting increasing attention due to the synergistic combination of the counterparts [42,43]. The main limitation of the nanofiltration approach is membrane fouling. Scaling or the formation of precipitates takes place when the concentration of ionic salts exceeds their solubility in water. Thus, alternative methods to prevent membrane fouling are needed to improve the lifetime of membranes [42].

Carbon-based nanomaterials possess superior physical properties compared to their bulk counterparts, such as higher pore volume and pore diameter and increased surface area, which make them useful for commercial use as nanoadsorbents having increased capacity, affinity, as well as selectivity [44]. Among them, carbon nanotubes and graphene oxide (GO) showed effective acid polar gas species adsorption capacity (H_2S, NO_x, SO_2, etc.) and ultrafine dust removal [45–47]. However, the separation efficiency is greatly affected by surface functionalization, which can enhance the capture efficiency of ca. 99% in metal–organic framework and carbon nanotube (CNT)-modified filters [45].

In summary, the scientific literature has documented many instances of environmental remediation strategies using nanomaterials (metal, bimetallic, metal oxide, polymers, carbon-based, and related composites) (Figure 1). However, challenges still exist regarding the stability of nanomaterials in different environmental conditions (pH, ionic strength, granulometry, and viscosity), selectivity (the presence of co-contaminants), and reusability (recovery and regeneration), thereby enhancing their sustainability. To cope with these limitations, functionalization or combination of the materials appears to be one possible solution. In addition, sophisticated characterization methods should be used to understand the structure-function relationship of functionalizing agents in the nanomaterial-stabilizer interface in more detail. Importantly, in vitro and in vivo toxicity studies should be carried out, as risk evaluation of pharmacological and bioremediation activities is required in laboratory and clinical settings. By rising to these challenges, it will be possible to advance the application of nanomaterials to fight environmental pollution.

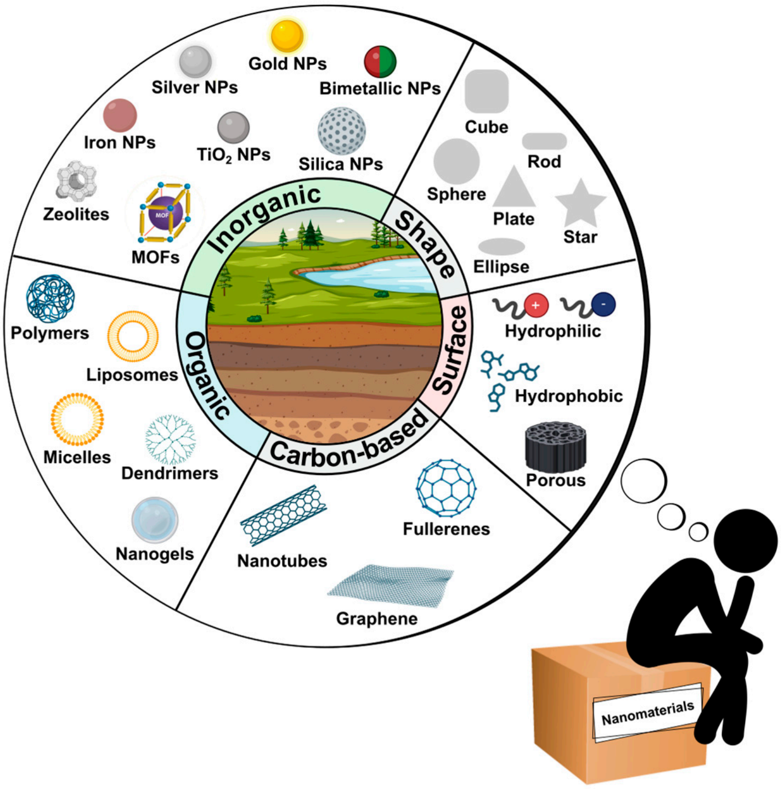

Figure 1. Representative nanomaterials categories and their properties as efficient tools for environmental remediation purposes. Nanomaterials icons created in BioRender.com.

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