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Mini- Review

Toxicological Concerns of Nanomaterials: Human Health and Environmental Impacts

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Introduction

Nanomaterials have been increasingly applied across multiple scientific and industrial domains due to their unique physiochemical properties. However, their potential adverse effects on human health and the environment have become a critical concern [1-12]. The toxicological impact of nanomaterials is influenced by multiple factors, including their type, morphology, size, surface chemistry, electrical, magnetic, and optical properties, as well as their crystalline structure, aggregation, concentration, dispersion state, and synthesis methods [1-3]. Certain nanomaterials, such as carbon nanotubes (CNTs), have been observed to exhibit higher toxicity compared to other nanoparticles like carbon black, silver, alumina (Al_2O_3), iron oxide (Fe_2O_3), silicon nitride (Si_3N_4), and zirconia (ZrO_2). Moreover, the toxicity of CNTs varies according to their type, diameter, and surface functionalities. Similarly, silver nanoparticles display greater toxic potential relative to iron oxide, alumina, zirconia, and asbestos [4]. In addition, higher concentrations of nanomaterials generally lead to increased toxicity [5], and the presence of impurities or incomplete synthesis can further exacerbate these effects [6]. This mini-review aims to summarize the current knowledge on the health and environmental impacts of nanomaterials and to highlight future research directions for their safe and sustainable application.

Impacts on Human Health

The toxicity of nanomaterials represents a significant challenge for professionals involved in their development, including scientists, chemists, and engineers. Documented toxic effects encompass genotoxicity, cytotoxicity, dermal toxicity, carcinogenicity, pulmonary toxicity, cardiovascular toxicity, hepatic toxicity, immunotoxicity, and haemolytic toxicity [7, 8]. Beyond these, nanomaterials may also affect the central nervous system, causing malfunctions in multiple organ systems and potentially leading to neurotoxicity and immunotoxicity [6]. This broad spectrum of adverse health outcomes underscores the need for careful handling and comprehensive risk assessment in research and industrial applications.

Environmental Impacts

Nanomaterials are also associated with detrimental effects on environmental systems. For instance, iron nanoparticles can accumulate in organisms, inducing apoptosis, reactive oxygen species generation, and oxidative stress [9]. In sediment and soil, nanoparticles may be absorbed by particles and undergo biotic and abiotic degradation, ultimately being released into water bodies [10-11]. Experimental studies using nano-cerium oxide (n-CeO_2) demonstrated that low concentrations reduced organism life span by 12%, while higher concentrations caused an 18% reduction [12]. Furthermore, nanoparticles can translocate from plant roots to leaves and edible parts, posing potential toxicity risks along the food chain. Nanomaterials also impact atmospheric and marine environments; their release can contribute to dust cloud formation, and marine organisms, including unicellular species, are susceptible to toxicity. Specifically, nano-ZnO and nano-TiO_2 can disrupt bacterial cell membranes, causing adverse effects on marine bacteria [6].

Despite these concerns, the United States Environmental Protection Agency (USEPA) notes that assessing nanomaterial toxicity is challenging due to their unique chemical properties, high reactivity, and low dispersion in liquids. Environmental samples may experience changes in nanomaterial properties between collection and analysis, complicating the identification of their origin [6]. Nevertheless, these challenges are generally less critical once nanomaterials are incorporated into retrofitting systems after manufacturing.

Conclusions and Future Research Directions

In summary, nanomaterials exhibit significant toxic potential for both human health and the environment. Their adverse effects are influenced by multiple factors, including type, size, concentration, surface characteristics, and synthesis method. Detecting and characterizing these toxicities remains challenging due to the high reactivity and complex behavior of nanomaterials in biological and environmental systems.

Looking forward, future research should continue to advance recent investigations on the use of carbon- and silicon-based nanomaterials to improve the mechanical, thermal, and microstructural characteristics of epoxy and cement-based adhesives in fiber-reinforced polymer (FRP)-retrofitted systems [13-15]. Initial studies on nanomaterial-enhanced epoxy adhesives (NMEAs) in near-surface mounted (NSM)-FRP retrofitting applications have demonstrated notable improvements in structural performance [16], while subsequent reviews have emphasized the essential role of bonding agents in controlling bond behavior [17]. Further work has explored the effectiveness of different bonding agents for repairing heat-damaged concrete and optimizing FRP retrofitting strategies across various conditions [18-23]. Together, these findings lay a foundation for interdisciplinary progress, integrating nanomaterial design, structural engineering, and environmental safety, and guiding the development of sustainable, high-performance retrofitting solutions.

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Conflict of interest

No conflict of interest.

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