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Review

Engineered nano particles: Nature, behavior, and effect on the environment

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ABSTRACT

Increased application of engineered nano particles (ENPs) in production of various appliances and consumer items is increasing their presence in the natural environment. Although a wide variety of nano particles (NPs) are ubiquitously dispersed in ecosystems, risk assessment guidelines to describe their ageing, direct exposure, and long-term accumulation characteristics are poorly developed. In this review, we describe what is known about the life cycle of ENPs and their impact on natural systems and examine if there is a cohesive relationship between their transformation processes and bio-accessibility in various food chains. Different environmental stressors influence the fate of these particles in the environment. Composition of solid media, pore size, solution chemistry, mineral composition, presence of natural organic matter, and fluid velocity are some environmental stressors that influence the transformation, transport, and mobility of nano particles. Transformed nano particles can reduce cell viability, growth and morphology, enhance oxidative stress, and damage DNA in living organisms.

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1. Introduction

In terrestrial environments, ultra-fine or nano-particles (NPs) form either due to natural phenomena (e.g., volcanic eruptions, soot from forest fires, ocean spray particles, fine sand and dust, and biological matter (e.g., viruses)) or as products of anthropogenic processes, especially from combustion sources (e.g. welding, diesel engine exhaust, and coal fires) (Klaine et al., 2008). In the last decade, synthesized materials have become important in diverse fields, including medicine, industry, and environmental engineering. In general, chemically synthesized NPs within the size range of 1–100 nm are highly useful. Chemical approaches employed for the production of NPs are systematically developed and predetermined. Hence, NPs synthesized using these chemical approaches are referred to as engineered NPs (ENPs) (Quigg et al., 2013). Interestingly, the behaviors of ENPs differ noticeably from those of their bulk (non-NP) counterparts (Auffan et al., 2009).

Since the late 1990s, a great number of articles have been published to deal with the application of engineered nanoparticles in the areas of medicine, industry, and electronics (Grillo et al., 2015). For instance, the synthesis of magnetic nanoparticles was achieved through different pathways for the application toward biomedical imaging over the last decade (Laurent et al., 2008). Likewise, nanomaterials were also employed actively in various fields of environmental applications (sorbents, antibacterial agents, dye-degradation, and eco-friendly fertilizers) (Xu et al., 2013; Das et al., 2016; Sarmah and Pratihar, 2017). Hence, an exhaustive compilation of these reports will be helpful to identify the thrust areas for contemporary and future researchers.

In a broad sense, ENPs consist of a wide range of synthesized materials such as carbon nano-tubes (CNTs), carbon dots, epoxy resin-coated CNTs, polymer-coated Ag, super magnetic iron oxide nano-particles (SPION), mesoporous silica particle, catalytic metals, metal oxides, quantum dots, dendrimers, nanofilms, nanofibres, and composite nano-particles (refer to Table 1 for classification). The properties of ENPs are generally affected by their particle size; for example, nano-sized ZnO has a different rate of reaction, adsorption capacity, and redox state than bulk ZnO particles. Similarly, the transition temperature of ferromagnetic particles ($MnFe_2O_4$, $MgFe_2O_4$, etc) varies considerably according to size (Tang et al., 1991; Chen and Zhang, 1998). Therefore, great effort has been made to alter the physicochemical properties (shape, size, and surface charge) of ENPs to enhance their reactivity, strength, and electrical properties (Scheckel et al., 2010).

Use of ENPs is growing exponentially in the commercial sector. Currently, ENPs are widely used in manufacturing industries (e.g., pharmaceutical, electronics, cosmetics, diagnostic imaging, photothermal therapy, nucleic acid delivery, catalysis and material science, environmental remediation, and cleaner energy production) (Guerrero et al., 2012; Huo et al., 2012; Jafari et al., 2012; Kuo et al., 2012; Naahidi et al., 2013). A number of ENP-based products (such as implantable devices, antimicrobial commercial products, photo luminescent materials, and semi-conductors) are also available in the global market (Fischer and Chan, 2007; Law et al., 2008; Jafari and Chen, 2009; Scheckel et al., 2010; Bhatt and Tripathi, 2011; Padmavathy et al., 2012). Over a span of eight years (2000–2008), the global market value of ENPs increased from 125 million USD to 12.7 billion USD (in 2008) and is expected to reach about 30 billion USD by the end of 2020 (Wang et al., 2013). A global market survey in 2013 also revealed that the production of different types of ENPs will cross the margin of 350,000 tons in 2016.

The ever-escalating need for novel ENPs has had a large impact on their synthesis and utilization, which, in turn, has led to drastic increase in their release into the environment, causing pollution (Barua et al., 2013; Maurer-Jones et al., 2013). Keller et al. (2013) estimated that 9–37% of ENPs are emitted directly into the atmosphere, whereas the remaining 63–91% eventually end up in landfills. A few types of ENPs (TiO_2, Ag, ZnO, and CNT) are the most abundant in the environment, with the dominant fraction of (e.g., 80.6 (TiO_2), 81.8 (Ag), 87.3 (ZnO), and 97.7% (CNT)) deposited in soils and in landfills (Nowack et al., 2015). Because of their high rates of production and use, the likelihood of exposure to ENPs has increased substantially in recent years.

Because the chemical stability of ENPs tends to change with their aging, ageing could also influence their pattern of mobility or interactions with other materials (Liu and Lowry, 2006; Scheckel et al., 2009). Moreover, factors such as size, shape, and surface charge (or moieties) govern the transformation, agglomeration, dissolution, and mobility of ENPs in the environment (Klaine et al., 2008; Mueller and Nowack, 2008; Gottschalk et al., 2009). On a human time scale, these changes are deemed irreversible. Consequently, persistent transformations of the soil matrix occur and the soil becomes resistant to remediation and natural attenuation (Dror et al., 2015). These changes have various impacts on soil organisms.

Simulated modeling experiments based on ENT production volume have been performed, in addition to life cycle assessment to predict the environmental concentration of ENPs; however, the behavior of ENPs in both terrestrial and aquatic systems is complex and not yet well understood (Navarro et al., 2008; Perez et al., 2009; Bolyard et al., 2013). Gottschalk et al. (2013) predicted the emission concentration ranges of Ti, Ag, and Zn NPs as 10^{-8}~10, 10^{-8} -10^{-1}, and 10^{-3}~10^{0} mg kg^{-1}, respectively. However, these values are below their actual concentrations in most soil matrices. As simulation studies are generally performed using a non-destructive mode of analysis, their ability is limited to accurately quantify ENPs in the terrestrial environment.

Because of their minute sizes and correspondingly enhanced reactivity, ENPs can interact with organisms more efficiently than large particles. Hence, they pose potential environmental and human health hazards (Rosenfeldt et al., 2014). To respond to these concerns, a concerted effort is required to evaluate the potential risks of ENPs in the background of on-going research and development of nanotechnology applications (NSETS, 2006; Aiken et al., 2011). In this review, we provide a comprehensive review of the fate of different ENPs in major environmental compartments (soil, air, and water). Eco-toxicity issues associated with continuous exposure to ENPs are also addressed. This review also investigates the cohesion between factors affecting the transformation processes among different types of ENPs and their fates in the natural environment. We further describe how the distribution and dissolution patterns of ENPs in different matrices can influence their mobility and bioavailability along with their (eco-) toxicity.