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Review

Environmental impacts of nanomaterials

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ABSTRACT

Nanotechnology is currently one of the highest priority research fields in many countries due to its immense potentiality and economic impact. Nanotechnology involves the research, development, production, and processing of structures and materials on a nanometer scale in various fields of science, technology, health care, industries, and agriculture. As such, it has contributed to the gradual restructuring of many associated technologies. However, due to the uncertainties and irregularities in shape, size, and chemical compositions, the presence of certain nanomaterials may exert adverse impacts on the environment as well as human health. Concerns have thus been raised about the destiny, transport, and transformation of nanoparticles released into the environment. A critical evaluation of the current states of knowledge regarding the exposure and effects of nanomaterials on the environment and human health is discussed in this review. Recognition on the potential advantages and unintended dangers of nanomaterials to the environment and human health is critically important to pursue their development in the future.

1. Introduction

Nanomaterials (NMs) contain at least one structural dimension at the nanoscale (one nanometer is a billionth of a meter or 10^{-9} of a meter) and have attracted intense research interest due to their application potential in various fields of science and technology (OECD, 2014). Note that the characteristic structures of NMs should fall between single atoms and bulk materials. Consequently, NMs generally exhibit unique and significantly improved but sometimes unpredictable physical, chemical, and biological properties different from their bulk materials (nano.DE-Report, 2013). Today's scientists are able to produce diverse materials at the nanoscale such as nanoclays, nanofibers, carbon nanotubes, and graphene with lighter, stronger, and more expanded control on light spectrum as well as more prominent chemical reactivity (Khan et al., 2017).

Despite such progress in NMs technology, information regarding the possible effects of NMs on the human health is yet insufficient. As NMs may not be detectable after discharge into the environment, they can cause various types of environmental problems if remediation plan is not secured. Therefore, additional study is required to systematically explain the structure-function relationships of NMs with respect to their fundamental chemistry (e.g., functionality and toxicity). Moreover, full hazard appraisals should be performed on NMs that present a genuine exposure danger during manufacture or use. Hence, green nanoscience has been proposed to lessen conceivable environmental and human health hazards from the creation and utilization of NMs and to advance supplanting existing items with new nano-products that are more ecologically benevolent (Iavicoli et al., 2014). For applications of nanotechnology in various fields, a number of concerns remain including uncertain ecological impacts, environmental soundness, fouling properties, low detection limits, high expenses, regeneration, and environmental deposition. In this review, we outline the adverse effects of NMs on the human health as well as environment. Such efforts may be helpful for proper expansion of applications and research interest toward further development of nanotechnology.

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2. Types and properties of NMs

Structures with a dimension of 1–100 nm are considered NMs (Guisbiers et al., 2012). Because of the big surface area-to-volume ratio and probable occurrence of quantum effects, NMs behave quite differently than their bulk counterparts (Ding et al., 2016). According to the European Commission, a NM is defined as a "natural, incidental, or manufactured material containing particles, in an unbound state or as an aggregate or as an agglomerate and where, for 50% or more of the particles in the number size distribution, one or more external dimensions is in the size range 1–100 nm" (European Commission, 2016). Although there are already numerous kinds of NMs, it is expected that a variety of new forms will appear in the future. However, based on their construction, NMs are currently classified as (i) carbon-based, (ii) metal-based, (iii) dendrimers, and (iv) composites (Saleh, 2016).

Carbon-based NMs have gained extra attention in the scientific and engineering community because of their unique and exceptional physical, chemical, optical, mechanical, and thermal properties (Cha et al., 2013). Carbon-based NMs commonly take the shape of nano-particles, hollow spheres, ellipsoids, sheets, or tubes. Carbon nanotubes (cylindrical shape) are usually synthesized by arc discharge or chemical vapor deposition of graphite (Saleh, 2016). Carbon nanotubes are considered the most robust and stiffest materials as far as rigidity and flexible modulus are concerned (Kim et al., 2017). The chain of unbroken covalent carbon-carbon bonds makes them exceptionally strong materials (Kim et al., 2017). Graphene is a one atom-thick carbon layer arranged in a two-dimensional hexagonal lattice with excellent heat and electric conductivity along with optical transparency in the infrared and visible range (Edwards and Coleman, 2013). Moreover, because of graphene's robust yet highly flexible property with the capacity of binding other elements (e.g., gases and metals), it is a highly attractive option for various applications (Kulkarni, 2015). Various structures of carbon-based NMs are shown in Fig. 1.

Metal-based NMs include quantum dots, nanogold, nanosilver, and nanometallic oxides (e.g., titanium dioxide, zinc oxide, and iron oxide) (Tourinho et al., 2012). Quantum dots are fluorescent semiconductors ranging from 2 to 10 nm (Libralato et al., 2017). Quantum dots are characterized by a broad absorption spectrum and intense narrow emission spectra in direct relation to their size (Libralato et al., 2017). Dendrimers are man-sized symmetric molecules with mono-dispersed structure consisting of tree-like branches built across a molecule or a linear polymer core (Abbasi et al., 2014). The surface of a dendrimer has many chain ends and may experience changes in size, shape, and adaptability to another element (Mendes et al., 2017). Furthermore, three-dimensional dendrimers contain inside cavities into which different particles can be set for different applications in both biological and materials sciences (Mendes et al., 2017). The properties of composite NMs can be designed according to their application or requirement and are dependent on the choice of matrix, curing phase, shape, and orientation (Sahay et al., 2014).

Nanomaterials can also be classified based on their dimensionality: (i) zero-dimension (0D), (ii) one-dimension (1D), (iii) two-dimensions (2D), and (iv) three-dimensions (3D) NMs (Fig. 2) (Tiwari et al., 2012). The majority of nano-particles are 0D NMs, which include NMs with all dimensions within the range of 1–100 nm.1D NMs are needle or rod like-shaped with a length from 100 nm to 10 μm and include nanotubes, nanorods, and nanowires (Tiwari and Kim, 2011). 2D NMs display plate-like shapes including nanocoatings, nanofilms, and nanolayers (Tiwari and Kim, 2011). 0D, 1D, and 2D NMs can be used on a substrate or they can be distributed in fluid or solid matrixes.3D NMs can have three arbitrary dimensions and possess multilayer nano-crystalline structure (Tiwari et al., 2012). These NMs may consist of bulk powders, nanowire bundles, multi-nanolayers, dispersions of nanoparticles, and nanotubes.

3. Fate and behavior of nanoparticles in the environment

The destiny of NMs in the environment is controlled by the combined effects of their physicochemical properties, and their interactions with other pollutants (Maiti et al., 2016). Nanomaterials found in the environment can come either from various natural activities (e.g., volcanic activities, forest fires, soil erosion, weathering, clay minerals, and dust storms) or from intentional/unintentional anthropogenic activities (e.g., burning fossil fuels, mining/demolition, automobile traffic, and NMs production and waste stream) (Fig. 3) (Smita et al., 2012). After NMs are discharged into the environment, they accumulate in different environmental matrices, for example, air, water, soil, and sediments (Iavicoli et al., 2014). In this section, we discuss the fate of

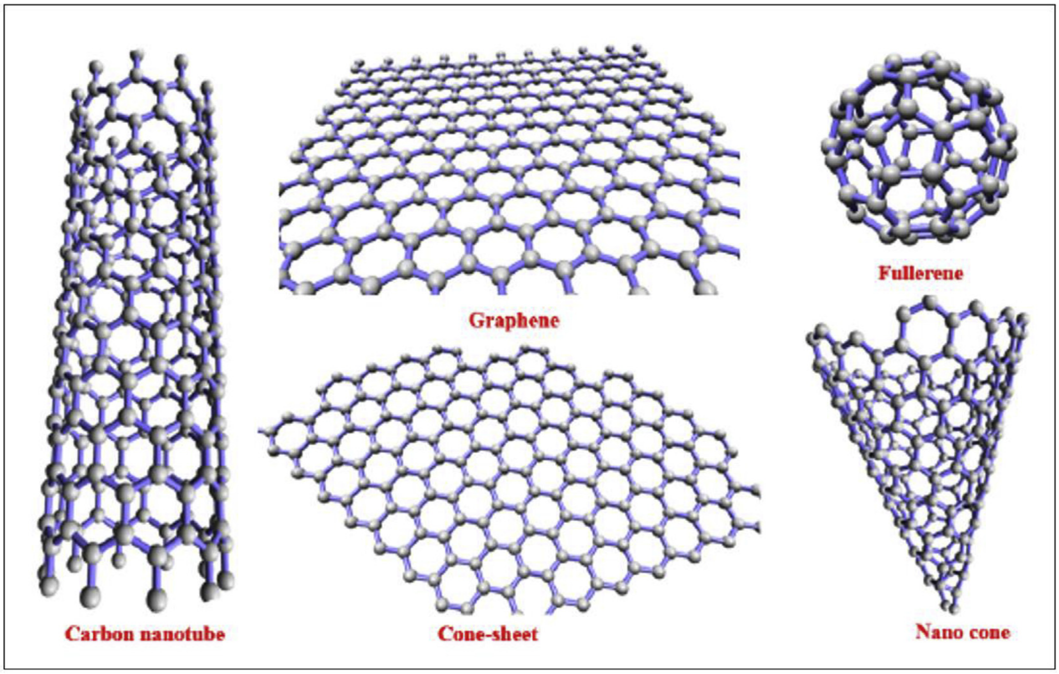

Fig. 1. Various structures of carbon-based nanomaterials (Saleh, 2016).