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Review article

Nanoparticle-plant interaction: Implications in energy, environment, and agriculture

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ABSTRACT

In the recent techno-scientific revolution, nanotechnology has gained popularity at a rapid pace in different sectors and disciplines, specifically environmental, sensing, bioenergy, and agricultural systems. Controlled, easy, economical, and safe synthesis of nanomaterials is desired for the development of new-age nanotechnology. In general, nanomaterial synthesis techniques, such as chemical synthesis, are not completely safe or environmentally friendly due to harmful chemicals used or to toxic by-products produced. Moreover, a few nanomaterials are present as by-product during washing process, which may accumulate in water, air, and soil system to pose serious threats to plants, animals, and microbes. In contrast, using plants for nanomaterial (especially nanoparticle) synthesis has proven to be environmentally safe and economical. The role of plants as a source of nanoparticles is also likely to expand the number of options for sustainable green renewable energy, especially in biorefineries. Despite several advantages of nanotechnology, the nano-revolution has aroused concerns in terms of the fate of nanoparticles in the environment because of the potential health impacts caused by nanotoxicity upon their release. In the present panoramic review, we discuss the possibility that a multitudinous array of nanoparticles may find applications convergent with human welfare based on the synthesis of diverse nanoparticles from plants and their extracts. The significance of plant–nanoparticle interactions has been elucidated further for nanoparticle synthesis, applications of nanoparticles, and the disadvantages of using plants for synthesizing nanoparticles. Finally, we discuss future prospects of plant–nanoparticle interactions in relation to the environment, energy, and agriculture with implications in nanotechnology.

1. Introduction

Nanotechnology is the manipulation of nanoscale matter; its expansion could exert broad effects ranging from genes to ecosystems. In the last decade, a large variety of nanomaterials (NMs) have been developed and used under the umbrella of nanotechnology in multifaceted sectors (Lien et al., 2017). The basis of nanotechnology was laid by Nobel laureate Richard P. Feynman through his popular lecture "*There's Plenty of Room at the Bottom*" (Feynman, 1960). In 1974, Norio Taniguchi coined the term *nanotechnology* (Taniguchi, 1974). Since then, it has emerged as a cutting-edge technology, acting as a convergent science that attracts a plethora of disciplines (environmental science, energy, plant science, agriculture, materials physics, and nanomedicine) and sectors closely linked with human welfare. The synthesis protocols for diverse nanoparticles (NPs) were established and advanced to the molecular level (Gugliotti et al., 2004). The use of NPs imparted tremendous efficiency compared to bulk particles/particulate matter (PM) because of their large specific surface area, diverse functionalities, easy functionalization, the presence of active sites on the surface, extraordinary electrical and optical properties, extremely high stability, and high adsorption capacity (Boparai et al., 2011; Zhao et al., 2014; Choi et al., 2015; Jiang et al., 2015; Kumar et al., 2015; Y.-G.

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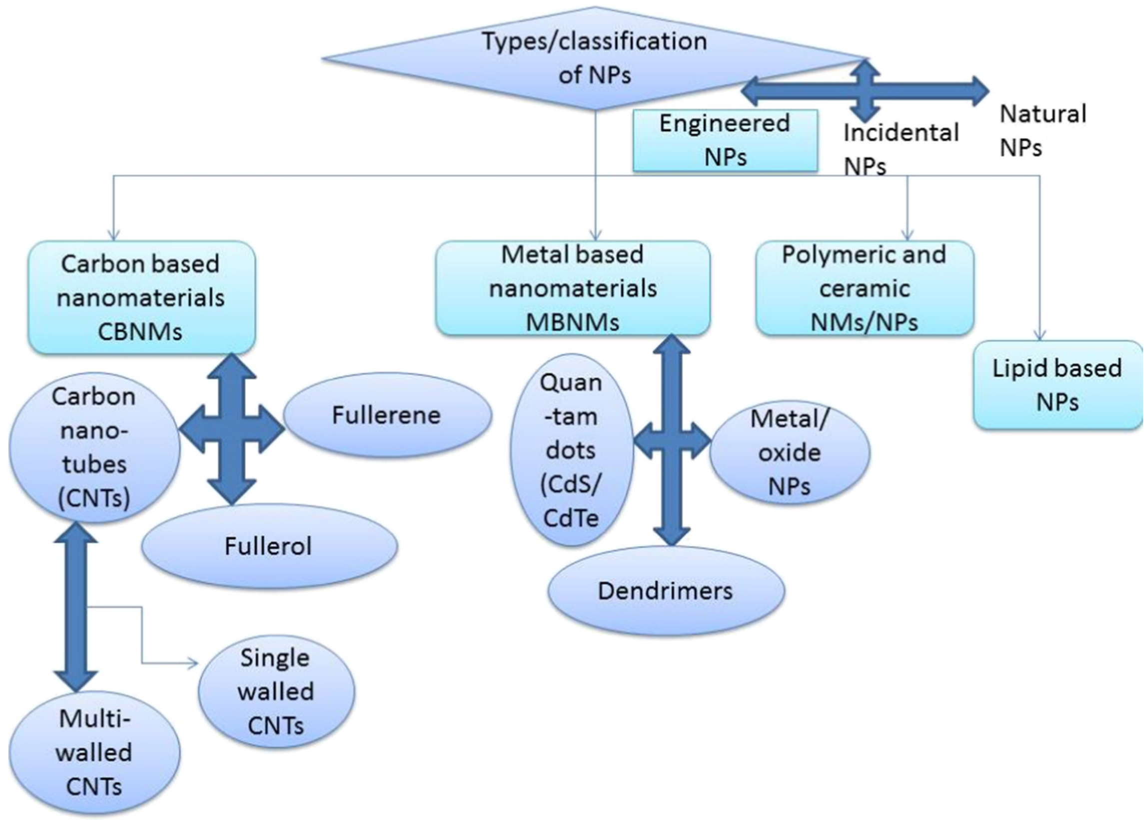

Fig. 1. Diverse types of nanoscale NPs/NMs (C-based; metal-based; polymeric/ceramic; lipid-based; etc.).

Wang et al., 2015; Gowda et al., 2016; Kumar et al., 2016; Xiao et al., 2016; Kumar et al., 2017a, b). In the health sector, engineered NPs are finding applications in various disciplines, such as drug delivery, disease diagnosis, tissue engineering, and biosensors, thus opening new avenues in nanomedicine. However, the release of NPs/NMs into the environment can also threaten human health (Seaton et al., 2009; Quadros and Marr, 2010; Hayashi et al., 2012; Rim et al., 2013; Fadeel et al., 2017).

Fast-developing nanotechnology has also exerted several harmful effects on the food web through the entry of NPs/NMs (Rizwan et al., 2017). The toxic and harmful effects of NMs can be spread to water, air, and soil systems. Being at the interface of water, air, and soil, plants can serve as an effective means to explain the emerging disciplines of nanotechnology, such as phytosynthesis of NPs, phytoremediation, bioenergy generation, agricultural crops, and environmental sectors. Hence, this review primarily focuses on the role of NP interactions with plants from the perspectives of the phytosynthesis of NPs, environmental remediation/phytoremediation, and bioenergy production. Plants can be considered an environmentally friendly sustainable tool, as green chemistry plays a significant role in the phytosynthesis/biosynthesis of NPs. Their interaction with NPs may result in a paradigm shift in diverse sectors, particularly bioenergy, environment, and agriculture. Because of the non-toxic nature, phyto/biosynthesized NPs can be safely used in biomedical sectors (e.g., disease diagnostics, magnetic resonance imaging, computed tomography, prosthetics, drug delivery, and drug development) for human welfare. Nevertheless, the significance of the proposed theme has not been sufficiently addressed. Existing literature that covers nanoscale materials has focused on specific issues, such as the use of certain biosystems for NP synthesis, scattered information on applications or impacts of NPs on the environment, energy, and agriculture sectors. Our review is hence organized to adequately describe the benefits and limitations of nanoscale materials in a sustainable way such that they may be judiciously applied to the environment, energy generation, agriculture, and human health.

To date, there is a strong demand to develop an integrated approach to resolve problems associated with nanotoxicity. This review provides detailed information on plants as hyperaccumulators growing on marginal/degraded land and aquatic/wetland (including nuisance/invasive plants having phytoremediation potential) for NP synthesis, NP-based bioenergy generation, and environmental remediation. We also attempt to establish a relationship between phytoremediation and bioenergy production. These approaches will help reduce the pressure on agricultural systems and hence address the challenge of food security. Furthermore, the challenges associated with the maximum exploration of plant-NPs interaction for energy, environment, and agriculture applications are discussed. This review will thus help readers gain a better knowledge on the significance of plant–NP interactions in relation to energy, environment, and agriculture.

2. Classification, green synthesis, and applications of NPs

2.1. Types of NPs

On the basis of size ranges of NMs in different dimensions, NMs can be classified as 0- (0D), 1- (1D), 2- (2D), and 3-dimensional (3D) (Yu et al., 2015). The spherical shaped particles with a diameter in the range of 1–100 nm are termed as 0D NMs e.g., NPs, fullerenes, and quantum dots. Note that a list of NMs (such as nanotubes, nanofibers, nanoribbons, nanowires, and nanobelts) is categorized as 1D NMs with two dimensions in nano range (i.e., 1–100 nm). Likewise, the NMs with one dimension confined in nanorange (and two dimensions are larger than 100 nm) are termed as 2D NMs, e.g., graphene, MoS_2, and other nanosheets/nanolayers. On the other hand, the NMs with all the three dimensions larger than 100 nm but exhibited nanosized effect (e.g., in terms of nanosized pores) are known as 3D NMs. The porous