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Review

Physiological and biochemical response of plants to engineered NMs: Implications on future design☆

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ABSTRACT

Engineered nanomaterials (ENMs) form the basis of a great number of commodities that are used in several areas including energy, coatings, electronics, medicine, chemicals and catalysts, among others. In addition, these materials are being explored for agricultural purposes. For this reason, the amount of ENMs present as nanowaste has significantly increased in the last few years, and it is expected that ENMs levels in the environment will increase even more in the future. Because plants form the basis of the food chain, they may also function as a point-of-entry of ENMs for other living systems. Understanding the interactions of ENMs with the plant system and their role in their potential accumulation in the food chain will provide knowledge that may serve as a decision-making framework for the future design of ENMs. The purpose of this paper was to provide an overview of the current knowledge on the transport and uptake of selected ENMs, including Carbon Based Nanomaterials (CBNMs) in plants, and the implication on plant exposure in terms of the effects at the macro, micro, and molecular level. We also discuss the interaction of ENMs with soil microorganisms. With this information, we suggest some directions on future design and areas where research needs to be strengthened. We also discuss the need for finding models that can predict the behavior of ENMs based on their chemical and thermodynamic nature, in that few efforts have been made within this context.

Contents

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1. Introduction

According to the European Union Commission Delegated Regulation, Engineered Nanomaterials (ENMs) are intentionally produced materials containing at least 50% of the particles with at least one external dimension of 100 nm (EU, 2013). Applications of these materials are constantly growing and, for the year of 2016 alone, a production of 44 267 tons has been forecasted (Future Markets, 2016). With such huge amounts of ENMs, a growing concern in the scientific community comprises the potential risk for environmental and human health.

Currently, ENMs are mainly used in energy, coatings, electronics, medicine, chemicals, and as catalysts (Biswas and Wu, 2005). However, in the past few years, the potential application of nanotechnology in agriculture to improve crop productivity has been recognized. Recent reviews and papers dealing with this subject can be found in the literature (Thul et al., 2015; Mukhopadhay, 2014; Dasgupta et al., 2015; Parisi et al., 2015). Examples of potential applications of ENMs for agricultural purposes include the following: (a) nutrient management (Mukhopadhay, 2014); (b) genetic improvement (Torney et al., 2007); (c) plant disease treatment (Park et al., 2006); and (d) plant growth promotion (Arora et al., 2012), among others. Because plants form the basis of the food chain, they may also function as a point-of-entry of ENMs for other living systems. Thus, risks and safety issues should be addressed before some of the applications are approved for commercial purposes. This includes understanding the whole process of absorption, uptake, bioconcentration, potential biotransformation and the negative effects of ENMS in plants.

The purpose of this paper was to provide an overview of the current knowledge on the transport and uptake of selected ENMs, including Carbon Based Nanomaterials (CBNMs) in plants, and the implication on plant exposure in terms of the effects at the macro, micro, and molecular level. We also discuss the interaction of ENMs with soil microorganisms. With this information, we suggest some directions on future design and areas where research needs to be strengthened. For the purpose of this paper, we will use the term ENMs and ENPs/NPs indistinctly.

2. Plants and ENMs: routes of exposure and interaction

The process in which the plant system comes in contact with ENMs can be explained with a basic model: starting at the emission source, ENMs are transported through different media and eventually interact with the plant rhizosphere (soil, water) and/or with the plant phyllosphere (air).

Dietz and Herth (2011) have provided a valuable model that explains the different pathways for NPs uptake, translocation, and association. The model considers NPs interaction with roots (root tips, cortex, lateral roots, woundings), and shoots (cuticle, epidermis, bark, stomata, stigma, etc.). In addition, these authors consider differences in the rates of NPs transport. The size and surface properties of ENMs will influence these pathways. In addition, evidence indicates that biotransformation may occur in these processes. For example, Peng et al. (2015) demonstrated that CuO NPs chemically interacted with plant parts and biomolecules in rice to produce different Cu species. Thus, in lateral roots, the majority of Cu was present as CuO NPs, while in young leaves CuO NPs, Cu-cysteine Cu-citrate, and Cu_2O were present at nearly the same proportion (around 20%). However, these transformations will depend on the type of ENM. Differences in ENMs type may affect uptake and the translocation mechanism, and consequently, plant phytotoxicity (Aslani et al., 2014).

After passing the root barrier and if no chemical interaction occurs, the xylem diameter determines the maxima allowed size of the particle that can be transported. In that xylem diameter also determines the speed of water transport, this could also be an essential parameter involved in the kinetics and fate of ENMs transport in plant systems (Ma et al., 2010). By tracing luminescent $NaYbEr_4$:Yb,Er NanoCrystals (NCrs), Hischemöller et al. (2009) suggested that axial transport occurs, which allows the entry of the NPs solution into the velamen radicum after a few seconds of exposure. After a while, NPs were detected in the apoplast followed by exodermis, parenchym, the vascular cylinder and xylem. More luminescent studies tracking NCrs confirmed translocation to the stems and leaves after a few days.

Other mechanisms have been proposed considering the exodermis tissues from primary roots, which contain cutin and/or suberin. These biopolymers are hydrophobic and avoid the entrance of water or aqueous solutes from the soil into the central cylinder. However, lateral roots lack exodermis tissue, thus allowing the entrance of NPs in aqueous solution and into the central cylinder and the xylem (Schreiber, 2010; Dietz and Herth, 2011). It is likely that hydrophobic NPs might interact with root hydrophobic biopolymers. However, to our knowledge, no data has been published on this matter. Several other complex mechanisms are involved in metallic NPs accumulation processes including metal biotransformation. However, as shown in this section, size and hydrophobicity appear to determine to a great extent ENMs entry and transport in plants. Due to the variety of ENMs and plants, the need remains to perform research on how processes of absorption, translocation and accumulation occur under different complex scenarios, including the interaction of ENMs with metabolites and other molecules. From the point of view of these authors, the need prevails of finding models that can predict the ENMs behavior based on their chemical and thermodynamic nature, in that few efforts have been made within this context. Also, the kinetics of NPs uptake by plants needs to be addressed.

3. Physiological response of plants to ENPs

Dietz and Herth (2011) describe the interaction of ENMs with