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Transformation and bioavailability of metal oxide nanoparticles in aquatic and terrestrial environments. A review☆

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ABSTRACT

Metal oxide nanoparticles (MeO-NPs) are among the most consumed NPs and also have wide applications in various areas which increased their release into the environmental system. Aquatic (water and sediments) and terrestrial compartments are predicted to be the destination of the released MeO-NPs. In these compartments, the particles are subjected to various dynamic processes such as physical, chemical and biological processes, and undergo transformations which drive them away from their pristine state. These transformation pathways can have strong implications for the fate, transport, persistence, bioavailability and toxic-effects of the NPs. In this critical review, we provide the state-of-the-knowledge on the transformation processes and bioavailability of MeO-NPs in the environment, which is the topic of interest to researchers. We also recommend future research directions in the area which will support future risk assessments by enhancing our knowledge of the transformation and bioavailability of MeO-NPs.

1. Introduction

Nanomaterials (NMs) are nano-objects having a size range of 1–100 nm, at least in one dimension (Batley et al., 2013; Kumar et al., 2012), and a novel physical and chemical properties which may vary according to their size, distribution, morphology and phase. NMs comprise a variety of materials classified as carbonaceous, metal oxides, semiconductors, polymers, clays, emulsions, and metals (Batley et al., 2013) which can be engineered from a combination of identical or different elements. They have attracted wide applications in various areas of science and technology due to their unique properties, limited size and high surface area/sites, respect to their bulk counterparts.

Metal oxide nanoparticles (MeO-NPs) are metallic oxides having a size within a nanoscale range, which include both deliberately synthesized and naturally occurring particles resulting from natural and anthropogenic processes. Hitherto, numerous MeO-NPs which are attractive nominees from the scientific and technological perspective, due to their variety of crystal structure and the nature of the metal-oxygen bonding (varies from nearly ionic to covalent or metallic) (Niederberger and Pinna, 2009) have been engineered and well documented. MeO-NPs also exhibit a fascinating electronic and magnetic properties, and are among the most utilized engineered NPs (Hendren et al., 2011; Piccinno et al., 2012) in different areas such as commercial products (e.g. fuel cells, plastics, consumer products) (Devener and Anderson, 2006; Lagaron and Lopez-Rubio, 2011; Lee et al., 2010; Mu and Sprando, 2010), environmental application (e.g. environmental analysis, sensing, remediation, amendments) (Amde et al., 2016, 2015; Bai and Zhou, 2014; Corr, 2013; Gan et al., 2016; Ghasemi et al., 2017; Ju-Nam and Lead, 2016; Lee et al., 2016; Mahdavi et al., 2014; Mirzaei et al., 2016; Parga et al., 2012; Park et al., 2016; Rahman et al., 2017; Singhal et al., 2017; Trujillo-Reyes et al., 2014; Vuong et al., 2016), sustainable chemistry (e.g. catalysis) (Almukhlifi and Burns, 2016; Gawande et al., 2016; Montini et al., 2016; Navalon et al., 2016; Peng et al., 2016), and health (e.g. antimicrobial, cancer treatment) (Al-Ajmi et al., 2016; Ansari et al., 2015; Applerot et al., 2009; Chauhan et al., 2015; Padmavathy and Vijayaraghavan, 2008; Saba and Amini, 2017; Salata, 2004; Tuli et al., 2015; Yang et al., 2016). For a quick overview, the

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properties, recent preparations techniques, applications, and coatings of selected MeO-NPs have been compiled and tabulated as provided in the supporting information (Table SI1).

Consumption of MeO-NPs in these activities, in large and/or small amounts, open the door for their intentional and unintentional (Fig. 1) release to the environment (Batley et al., 2013; Holden et al., 2016; Kaegi et al., 2008; Keller et al., 2013; Kiser et al., 2012, 2009; Tolaymat et al., 2017) with unidentified consequences, and their possible presence in the environmental systems have been reported (da Silva et al., 2011; Gottschalk et al., 2009; Mueller and Nowack, 2008; Sun et al., 2016), even though limited information exists, currently, on their released quantity (Bauerlein et al., 2017; Ju-Nam and Lead, 2016). There might be also the possibility to become a threat to drinking water supplies in the future due to the fact that consumption quantities of engineered NPs are expected to increase significantly (Troester et al., 2016) and, consequently, increases the quantity of nano-wastes (Bystrzejewska-Piotrowska et al., 2009).

In the environment, MeO-NPs are subjected to various chemical and/or physical processes (Auvinen et al., 2017; Garner et al., 2017) that will drive them away from their pristine state toward different products having distinct physicochemical properties (Wang et al., 2013a). Sources, introduction routes, and the major transfer and transformations that MeO-NPs experience in the environment is represented in Fig. 1.

On the other hand, bioavailability and deleterious effects of MeO-NPs towards aquatic and terrestrial organisms have been reported in recent (Chen et al., 2012b; Ma et al., 2013a; Miao et al., 2015; Mouneyrac et al., 2014; Poynton et al., 2011; Skjolding et al., 2016; Zhao et al., 2012b). Even though their toxicity mechanisms are not exactly known, it might be attributed to the formation of reactive oxygen species (ROS) and various hazardous entities of the particles due to the transformation processes which shall also affect their fate, transport, bioavailability and toxicity in the environmental systems. It should be also noted that the transformation pathways (e.g. adsorption) may also decrease the toxic-effects and persistence of MeO-NPs in the environment.

Therefore, a formative review, based on recent studies, on the transformations and their effects on the fate and bioavailability of MeO-NPs in the environment is highly important from the environmental point of view. Although there are some review papers (Cornelis et al., 2014; Cross et al., 2015; Dwivedi et al., 2015; Dwivedi and Ma, 2014; Klaine et al., 2008; Lowry et al., 2012; Peijnenburg et al., 2015; Tourinho et al., 2012) addressing fate of NMs in the environment before this one, most of these papers are general, and condensed all engineered NMs together, while some others have discussed few topics on limited environmental systems. Also, none of these papers has discussed the aforementioned behaviors related to MeO-NPs, separately, and no critical review has been done on MeO-NPs alone to the best of our knowledge. Moreover, MeO-NPs have unique properties such as high specific surface area, superparamagnetic property, relatively dissolvable

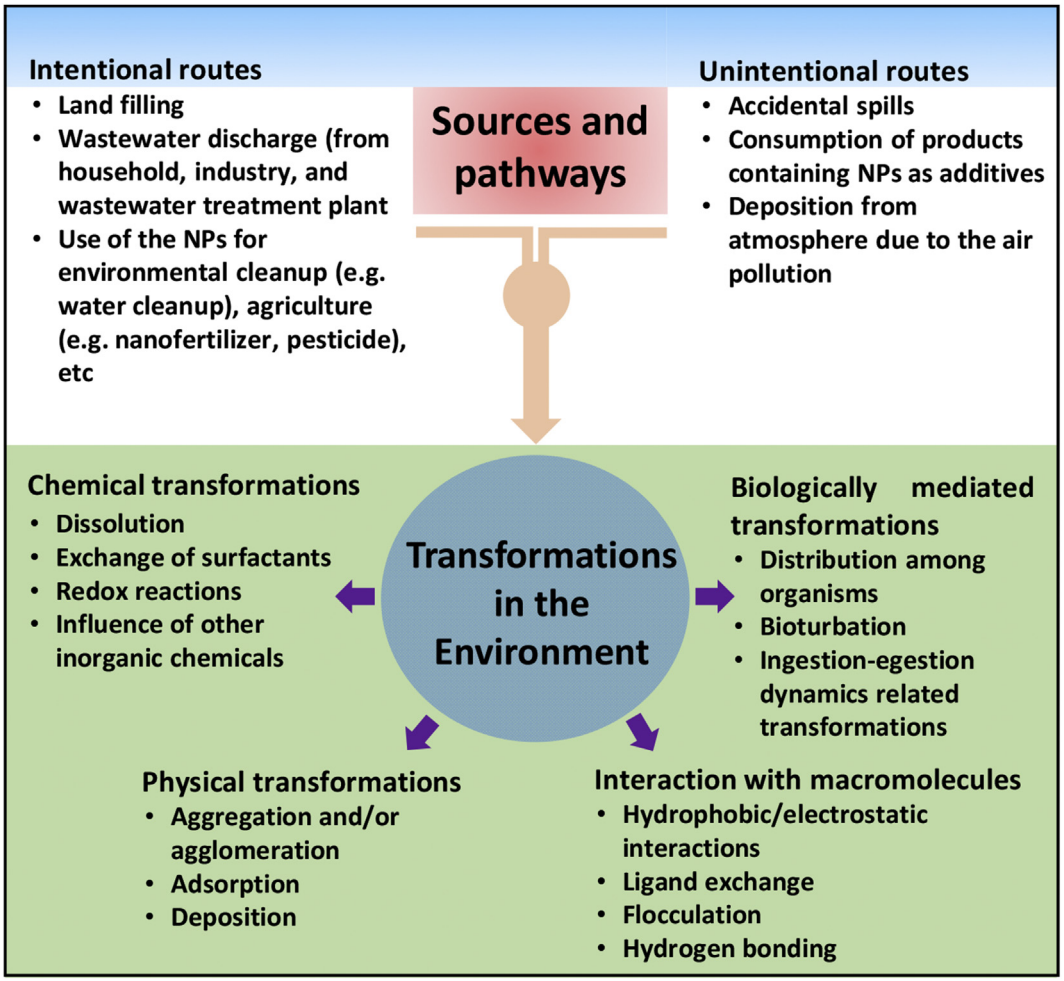

Fig. 1. Sources, introduction routes, and summary of the transformations that MeO-NPs experience in the environment.