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Review

Silver and titanium dioxide nanoparticle toxicity in plants: A review of current research

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ABSTRACT

Nanoparticles (NPs) have become widely used in recent years for many manufacturing and medical processes. Recent literature suggests that many metallic nanomaterials including those of silver (Ag) and titanium dioxide (TiO_2) cause significant toxic effects in animal cell culture and animal models, however, toxicity studies using plant species are limited. This review examines current progress in the understanding of the effect of silver and titanium dioxide nanoparticles on plant species. There are many facets to this ongoing environmental problem. This review addresses the effects of NPs on oxidative stress-related gene expression, genotoxicity, seed germination, and root elongation. It is largely accepted that NP exposure results in the cellular generation of reactive oxygen species (ROS), leading to both positive and negative effects on plant growth. However, factors such as NP size, shape, surface coating and concentration vary greatly among studies resulting in conflicting reports of the effect at times. In addition, plant species tend to differ in their reaction to NP exposure, with some showing positive effects of NP augmentation while many others showing detrimental effects. Seed germination studies have shown to be less effective in gauging phytotoxicity, while root elongation studies have shown more promise. Given the large increase in nanomaterial applications in consumer products, agriculture and energy sectors, it is critical to understand their role in the environment and their effects on plant life. A closer look at nanomaterial-driven ecotoxicity is needed. Ecosystem-level studies are required to indicate how these nanomaterials transfer at the critical trophic levels affecting human health and biota.

Contents

1. Introduction

Nanoparticles (NPs) are widely used in a variety of processes

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that include manufacturing, medical, and diagnostic applications (Baetke et al., 2015; Hu et al., 2015; Biffi et al., 2015; Tong et al., 2014). This review offers a summary of current studies using Ag and TiO_2NPs and their effects on gene expression, reactive oxygen species generation, and growth in plants and ecosystems. Although NPs are generally characterized as less than 100 nm (nm), some studies utilizing NPs larger than 100 nm are also included in this review. It should also be noted that NPs tend to agglomerate, and so while primary particle size may be less than 100 nm, effects of agglomerates greater than 100 nm have been taken into consideration as well. These agglomerates are loose constructions of primary particles held together by adhesion that may be changed in various conditions and should not be confused with aggregation, in which primary particles begin to form a defined crystalline structure and the total surface area is less than the sum of the surface areas of the primary particles (Walter, 2013). Agglomerates depend on surface chemistry of nanoparticles, concentration, and composition of medium to form loose structures (Clement et al., 2013).

Increased reactive oxygen species (ROS) are a hallmark of toxicity for both Ag and TiO_2NPs, but the increased activity has been shown to cause positive growth effects in some species of plants, particularly in the case of AgNPs. Seed germination and root elongation studies seem to show similar results, showing a large range of effects on plant growth depending on species and growth environment (hydroponic versus soil). Research on AgNP effects in plants is robust, whereas few reports of TiO_2NPs interactions with plant species are available. Ecotoxicity aspects of these nanomaterials has attracted attention in recent years (Aslani et al., 2014; Chichiricco and Poma, 2015; Srivastava et al., 2015; Du et al., 2016), but mechanisms of NP toxicity are still largely unknown due to varying experimental setups and NP characteristics (size, shape, coating). Therefore, a more standardized approach to understanding Ag and TiO_2NP toxicity is critical. This review aims to examine current literature and identify differences in approaches to NP studies, and how those differences may affect experimental outcomes. In addition, the information presented here will also focus on the toxicity limits for those species examined. An in-depth analysis of Ag and Ti nanomaterial interactions with taxa is lacking.

2. Silver nanoparticles – an introduction

Silver nanoparticles (AgNPs) have found multiple uses in industry and therapeutics. These include diagnostic, antibacterial, conductive, and optical applications. Diagnostic applications include biosensors and assays in which AgNPs may be used as biological tags for qualitative detection, while conductive applications use AgNPs to enhance thermal and electrical conductivity (Oldenburg, 2016). AgNPs in optical applications allow for enhanced spectroscopy, for example, in metal enhanced fluorescence (MEF) and surface-enhanced Raman scattering (SERS) (Oldenburg, 2016). Vance et al. (2015) from “The Project on Emerging Nanotechnologies” recently reported that silver is the most commonly used nanomaterial in consumer products, accounting for 435 entries (24%) in its database of approximately 1814 NP-containing goods. This list is not comprehensive, and it is likely that more new products have been manufactured using AgNPs since its publication.

The pharmaceutical industry seems to be one of the largest users of AgNPs, where these nanomaterials are used as antimicrobial and anti-fungal preparations. Silver has been used historically for burns, wounds, and bacterial infections, and the use of AgNPs in these treatments is more important now than ever due to growing antibiotic resistance in bacteria (Rai et al., 2009). Manufacturers are incorporating AgNPs into their consumer products as anti-bacterial protection, coating household appliances such as washing machines, refrigerators, and air conditioner, and purifiers with AgNP material. AgNP use has also been shown to be effective in enhancing efficacy of anti-fungal drugs and acting directly as an anti-fungal agent in plants (Singh et al., 2013; Xu et al., 2013). In addition, AgNPs have been shown to enhance efficacy of cancer treatments by increasing effectiveness of drug delivery and producing anti-tumorigenic effects, which shows great potential in cancer therapeutics. (Franco-Molina et al., 2010; Locatelli et al., 2014). Studies focusing on the therapeutic applications of AgNPs in the gastrointestinal tract have shown that gastric cells can be sensitized to radiation through the use of AgNPs (Huang et al., 2011), and they may also prove to be useful in drug delivery systems that bypass drug release in the stomach and instead release in the intestine (Hezaveh and Muhamad, II, 2012).

The above applications increase the chance of environmental exposure of these nanoparticles due to manufacturing wastes disposal and accidents as well as NP product consumer waste. Due to this close contact, it is necessary to monitor and observe the effects of AgNPs on plants and ecosystems. It has been shown that bacteria, algae, aquatic organisms, plants, and humans are exposed to AgNPs and the dissolved silver causes toxicity (Ma et al., 2010; Fabrega et al., 2011; Xu et al., 2011). Since plants are the basis of the food chain, AgNPs infiltrating ecosystems is a concern and has implications in agriculture, food safety, and human health (Ma et al., 2010). In response to this, recent technologies have been developed in order to track presence of AgNPs. SERS technology has been particularly useful as a fast, simple, and sensitive technique to monitor AgNPs in samples. Fig. 1 (Anjum et al., 2013) illustrates the uptake of AgNPs by plants and their release into the food chain in soil-based plant systems. The National Institute for Occupational Safety and Health (NIOSH) has issued recently a draft Current Intelligence Bulletin (CIB) entitled Health Effects of Occupational Exposure to Silver Nanomaterials (NIOSH, 2016). Given how little information has been set forth by agencies, in charge of reviewing potentially hazardous effects of chemicals, a warranted examination of AgNPs is necessary. Much of the research has only been pursued in recent years, and details are yet lacking. This recent increased focus on reviewing toxicity of AgNPs in the environment has covered many aspects such as uptake mechanisms, effects on plant growth, translocation mechanisms through plant species, and effects of ion release (Aslani et al., 2014; Chichiricco and Poma, 2015). Literature indicates how presence of coating can alter toxicity in plant species (uncoated versus polyvinyl pyrrolidone-coated AgNPs), but lack of detailed investigations fails to explain the role of citrate-coated AgNPs as well as particle size differences in studies examined (Garner et al., 2015). Justifiably, a closer look at AgNPs and their effects on plants and the environment should be pursued in order to understand the real world-effects on ecosystems.

2.1. *Cellular oxidative stress, cytotoxicity & antioxidative responses (gene expression and enzyme activity)*

The model organism *Arabidopsis thaliana* has been used in many studies investigating the effects and toxicity of AgNPs on plants. Gene expression study on *A. thaliana* has shown up-regulation of 286 genes and down-regulation of 81 genes after AgNP treatment, and overlap in differentially expressed genes when compared to plants treated with only Ag^+ (Kaveh et al., 2013). This suggests some effects originate from Ag^+ released by the AgNPs specifically. Seedlings in this study were exposed to AgNPs (up to 20 mg l^{-1}; 20 nm) or $AgNO_3$ for 10 days, after which leaves and roots were harvested and gene expression was examined via microarray analysis. It was shown that differentially expressed up-regulated genes were found mainly to be related to response to metals and