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The effects of metallic engineered nanoparticles upon plant systems: An analytic examination of scientific evidence

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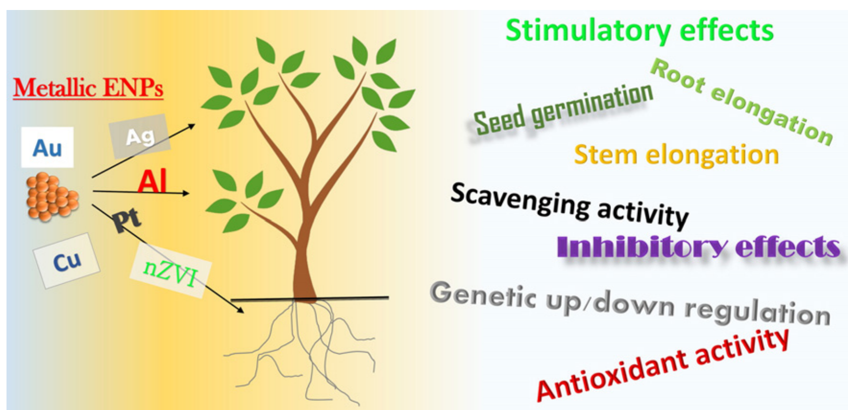
HIGHLIGHTS

- Metallic ENPs have stimulatory and inhibitory effects on plants.
- nZVI and Cu ENPs have potential use as micronutrients for plants.
- Metallic ENPs may have a vital role in sustainable production agriculture.

GRAPHICAL ABSTRACT



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ABSTRACT

Recent evidence for the effects of metallic engineered nanoparticles (ENPs) on plants and plant systems was examined together with its implications for other constituents of the Society-Environment-Economy (SEE) system. In this study, we were particularly interested to determine whether or not metallic ENPs have both stimulatory and inhibitory effects upon plant performance. An emphasis was made to analyze the scientific evidence on investigations examining both types of effects in the same studies. Analysis of evidence demonstrated that metallic ENPs have both stimulatory and inhibitory effects mostly in well-controlled environments and soilless media. Nano zero-valent iron (nZVI) and Cu ENPs have potential for use as micronutrients for plant systems, keeping in mind the proper formulation at the right dose for each type of ENP. The concentration levels for the stimulatory effects of Cu ENPs are lower than for those for nZVI. Newer findings showed that extremely smaller concentrations of Au ENPs (smaller than those for nZVI and Cu ENPs) induce positive effects for plant growth, which is attributed to effects on secondary metabolites. Ag ENPs have demonstrated their usage as antimicrobial/pesticidal agents for plant protection; however, precautions should be taken to avoid higher concentrations not only for plant systems, but also, other constituents in the SEE. Further research is warranted to investigate the stimulatory

Abbreviations: ENPs, engineered nanoparticles; SEE, Society-Environment-Economy; nZVI, nano zero-valent iron; EDTA-Fe, ethylenediaminetetraacetate-iron solution; ROS, reactive oxygen species.

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Stimulatory effects
Inhibitory effects

and inhibitory effects of metallic ENPs in soil media in order to broaden the horizon of sustainable agriculture production in terms of higher and safer yields so as to meet the food requirements of human population.

1. Introduction

In today's world, one is confronted with global challenges having their roots in human actions such as over-population, resource depletion, and human and ecologic health. Therefore, emerging technologies have been continually called upon as an avenue to present opportunities to tackle these global challenges. By virtue of their occurrence in economic systems, there is always a need to keep the constituents of the larger SEE System in consideration so as to augment the benefits and reduce the risks for all, the founding principle for the planet's sustainability (Tolaymat et al., 2015a; Tolaymat et al., 2015b).

Metallic nanomaterials have been introduced as emerging technologies to respond to some of the aforementioned challenges. For example, iron and copper ENPs have been utilized as plant micronutrients. Compared with the macronutrients (N, P, K), only trace levels of micronutrients are required for the healthy growth of crops and other plants. In this respect, micronutrients are often added to the macronutrients at low rates (e.g., 5 mg/l) as soluble salts for crop uptake (Liu and Lal, 2015). Furthermore, due to their success as antifungal and antibacterial agents, Ag ENPs have been introduced in applications to control phytopathogens and to extend the vase life of some flowers (Nair et al., 2010). Metallic ENPs have also been used as nanopesticides to increase the dispersion and wettability of agricultural formulations, and unwanted pesticide movement (Khot et al., 2012).

With the above in mind, while some metallic ENPs may have positive effects upon plant systems, it is also possible that this class of ENPs have negative implications for plant systems (Anjum et al., 2015; Arruda et al., 2015; Ma et al., 2015; Ma et al., 2010; Miralles et al., 2012; Van Aken, 2015). For example, barriers to growth for plant systems may occur if the concentration level exceeds the threshold for which the nanomaterial is needed as a micronutrient (Dimkpa, 2014). Metallic ENPs may also impact soil microbial structure or function, influencing nutrient turnover in soil over longer time scales. In addition, metallic ENPs may directly or indirectly alter the formation of symbiotic associations with root fungi and bacteria, influencing nutrient availability and uptake, and plant growth (Dimkpa, 2014). Specific applications for some metallic nanomaterials may also prove to be detrimental to plant systems. nZVI, for example, is emerging as an option for the treatment of contaminated soil and groundwater targeting chlorinated organic contaminants and inorganic anions or metals (Bennett et al., 2010; Gomes et al., 2014; Kocur et al., 2014; Mueller et al., 2012). It is possible that specific ENPs at concentration levels in the harmful or toxic range find their way to plant systems, hence, impacting plant performance and growth.

With the founding principle for planet Earth's sustainability in mind, the main goal of this study is to examine the evidence in the published literature for the positive and negative effects of metallic ENPs, if any, upon plant systems and to provide insights for these implications in the broader context of the SEE system. An emphasis was made to analyze investigations examining both effects in the same studies. The following specific aims are designed to achieve the study objective: (1) to document the evidence for the effects of metallic ENPs on plants and plant systems; (2) to analyze the evidence in terms of exposure, subject population, study outcomes, study design, and main results; and, (3) to provide insights on the evidence and uncertainties for the constituents of the SEE system. With the above in mind, we were particularly interested to determine whether or not metallic nanoparticles have stimulatory and inhibitory effects upon plants and plant systems so as to broaden the horizon for sustainable agriculture production in terms of higher and safer yields; to our knowledge, this subject has not been addressed in the published literature as evident by recent reviews (Ditta and Arshad, 2016; Sarmast and Salehi, 2016; Schwab et al., 2016). Finally, suggestions are made for future research to improve our understanding of the potential for these materials to be used in agricultural systems.

2. Methods

The methodology employed in this research consisted of the five standard steps deployed in evidence-based medicine (Sackett et al., 1996). As a first step in this process, the work reported herein attempted to provide answers to the stimulatory and inhibitory effects of metallic nanomaterials, if any, upon plant systems. Finding the evidence, the second step in the process was sought using electronic search as the primary source and investigating the bibliographies of gathered experimental and reviewed articles as the secondary source. For the electronic search, five databases were utilized: ACS, Scopus, Academic Search Complete, Pubmed, and WebofKnowledge. The following keyword combinations and Boolean operators were employed in the search: (nanoparticle OR nanoparticle OR nanomaterial OR nanomaterial) AND (metal OR silver OR gold OR iron OR aluminum OR copper OR Ag OR Au OR nZVI OR Al OR Cu OR Mn OR Zn) AND (plant OR botany). This keyword manipulation allowed a larger number of articles to be included in the first output of electronic search. The idea was to err on having more than less. The initial list was further subjected to inclusion and exclusion criteria on the basis of reviewing the titles first, then the abstract, and finally the retrieved full articles. Thereafter, bibliographies of the final list of experimental studies as well as those from review articles were fully retrieved and applied the same inclusion and exclusion criteria. The final articles meeting the primary study goal constituted the source of evidence. This process ended on May 25, 2016 and only studies in English were included.

Appraising the evidence, the third step in the evidence base methodology, analyzed the experimental studies contributing evidence in terms of: (a) exposure, (b) subject population, (c) study outcome, and (d) main results. This was followed by applying the evidence to an analysis of the concentration levels in the gathered evidence with respect to the positive (e.g., stimulatory) and negative (e.g., inhibitory) effects of metallic ENPs. As part of the final step in the analysis, we evaluated responses to ENPs in the context of possible explanatory mechanisms for the stimulatory/inhibitory effects of metallic nanoparticles. This included an inquiry into the nano versus the ionic form to determine the root causes of the observed effects. In addition, gaps in the scientific literature were pointed out for consideration in future research.

3. Results

3.1. General analysis of evidence

Analysis of evidence suggests that there were studies on nZVI (Canivet et al., 2015; Jessick et al., 2013; Kim et al., 2014a; Kim et al., 2014b; Li et al., 2015), Ag (Ardakani, 2013; Barrena et al., 2009; De La Torre-Roche et al., 2013; Dimkpa et al., 2013; Feng et al., 2013; García-Sánchez et al., 2015; Geisler-Lee et al., 2012; Gubbins et al., 2011; Jo et al., 2015; Kaveh et al., 2013; Krishnaraj et al., 2012; Kumari et al., 2009; Larue et al., 2014; Lee et al., 2012; Li et al., 2012; Musante and White, 2012; Mustafa et al., 2015; Nair and Chung, 2014; Parveen and Rao, 2014; Pokhrel and Dubey, 2013; Qian et al., 2013; Sharif et al., 2013; Song et al., 2013; Stampoulis et al., 2009; Syu et al., 2014; Thuesombat et al., 2014; Wang et al., 2013; Yin et al., 2011; Yin et al.,