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Review

Role of nanomaterials in plants under challenging environments[☆]

M. Nasir Khan[*], M. Mobin, Zahid Khorshid Abbas, Khalid A. AlMutairi, Zahid H. Siddiqui

Department of Biology, Faculty of Science, University of Tabuk, Tabuk 71491, Saudi Arabia

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ABSTRACT

The application of nanostructured materials, designed for sustainable crop production, reduces nutrient losses, suppresses disease and enhances the yields. Nanomaterials (NMs), with a particle size less than 100 nm, influence key life events of the plants that include seed germination, seedling vigor, root initiation, growth and photosynthesis to flowering. Additionally, NMs have been implicated in the protection of plants against oxidative stress as they mimic the role of antioxidative enzymes such as superoxide dismutase (SOD), catalase (CAT) and peroxidase (POX). However, besides their beneficial effects on plants, applications of NMs have been proved to be phytotoxic too as they enhance the generation of reactive oxygen species (ROS). The elevated level of ROS may damage the cellular membranes, proteins and nucleic acids. Therefore, in such a conflicting and ambiguous nature of NMs in plants, it is necessary to decipher the mechanism of cellular, biochemical and molecular protection render by NMs under stressful environmental conditions. This review systematically summarizes the role of NMs in plants under abiotic stresses such as drought, salt, temperature, metal, UV-B radiation and flooding. Furthermore, suitable strategies adopted by plants in presence of NMs under challenging environments are also being presented.

Contents

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[*] Corresponding author.

E-mail address: mo.khan@ut.edu.sa (M.N. Khan).

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Abbreviations

$^1O_2$	Singlet oxygen
APX	Ascorbate peroxidase
CaBPs	Calcium-binding proteins
CAT	Catalase
Chl	Chlorophyll
H_2O_2	Hydrogen peroxide
$HO_2^\bullet$	Hydroperoxy radical
HSPs	Heat shock proteins
HT	High temperature
LT	Low temperature
MDA	Malondialdehyde
MS	Metal stress
MWCNTs	Multi-walled carbon nanotubes
NMs	Nanomaterials
NO	Nitric oxide
NPs	Nanoparticles
$O_2^{\bullet -}$	Superoxide radical
$OH^\bullet$	Hydroxyl radical
POX	Peroxidase
QDs	Quantum dots
ROS	Reactive oxygen species
Rubisco	Ribulose bis-phosphate carboxylase
SOD	Superoxide dismutase
SWCNTs	Single-walled carbon nanotubes
ZVI	Zero-valent iron

1. Introduction

Nanomaterials (NMs), once called by Paul Ehrlich as “Magic Bullets” (Kreuter, 2007), are one of the most studied materials of the century that gave birth to a new branch of science known as ‘nanotechnology’. The specific quality of NMs which make these tiny entities unique, is their size which ranges between 1 and 100 nm (1 nm = 10^{-9} m) (Ball, 2002). Although, NMs can be prepared from the bulk size materials but small size and shape of these particles make their chemical action entirely different from their parent material (Brunner et al., 2006). Smaller size of NMs helps them to penetrate specific cellular locations and their additional surface area facilitates more adsorption and targeted delivery of substances (Kashyap et al., 2015). The NMs exist in volcanic dust, mineral composites (natural NMs) as well as in anthropogenic waste materials like coal combustion, diesel exhaust, welding fumes etc. (incidental NMs) (Monica and Cremonini, 2009). Moreover, engineered NMs manufactured with nanoscale dimensions are generally grouped into four types viz. carbon based NMs, metal based NMs, metal oxides, dendrimers and composites (Yu-Nam and Lead, 2008).

Engineered NMs have revolutionized almost every field of science and of course, plant science could not remain unaffected. These NMs have been shown to affect plants at every stage of their life cycle (Cañas et al., 2008; Lahiani et al., 2013; Siddiqui and Al-Whaibi, 2014; Liu et al., 2016). Fertilizers are integral part of agriculture that assist growth and development of plants. However, recently employed nano-fertilizers have been proved more efficient alternatives to regular fertilizers. Smaller size of nanoparticles (NPs) provides additional surface area which enhances the availability and facilitates more absorption of fertilizers by the plants and thus reduces losses of fertilizers due to leaching, emissions, and long-term incorporation by soil microorganisms (Liu et al., 2006; DeRosa et al., 2010). Moreover, nano-fertilizers are released at slower rates which help in maintaining soil fertility by decreasing the toxic effects associated with over-application of traditional chemical fertilizers (Suman et al., 2010).

Being sessile organisms, plants have no choice to escape or hide from adverse environmental conditions such as drought, salinity, water logging, extreme temperature, UV-radiation, etc. These stresses create oxidative stress by inducing generation of reactive oxygen species (ROS) such as singlet oxygen ($^1O_2$), superoxide radical ($O_2^{\bullet -}$), hydroperoxy radical ($HO_2^\bullet$), hydrogen peroxide (H_2O_2) and hydroxyl radical ($OH^\bullet$). Excessive accumulation of ROS damages membrane lipids, proteins and nucleic acids (Foyer and Noctor, 2000), triggers cytotoxicity, genotoxicity (; Shen et al., 2010a, b; Yadav et al., 2014) and suppresses growth (Begum et al., 2012). To counter oxidative stress, plants are fitted with a system of enzymatic antioxidants viz. superoxide dismutase (SOD), catalase (CAT), ascorbate peroxidase (APX), glutathione reductase (GR) and non-enzymatic antioxidants (glutathione, ascorbate) which continuously scavenge harmful ROS. Whereas, plants counter osmotic stress by enhancing the accumulation of organic osmolytes such as trehalose, polyols (glycerol, inositols, sorbitols etc.), amino acids (proline, glycine betaine and taurine) which maintain normal hydration level of cells. Under hypoxic conditions plants are deprived of proper supply of oxygen which causes energy depletion and settle the plants with low energy status, however, to maintain energy level plants alter their metabolism and switch over from carbohydrate metabolism to fermentation (Banti et al., 2013). To counteract metal stress plants synthesize metal-chelates, organic acids and polyphosphates that cause restriction and sequestration of toxic metals either in apoplasm or symplasm.

In addition to their role in plant growth and development, NPs play significant role in the protection of plants against various abiotic stresses (Table 1). The NPs mimic the activities of antioxidative enzymes and scavenge these ROS (Rico et al., 2013a, 2013b; Wei and Wang, 2013). Small size and large surface area of NPs provide access for toxic metals for binding and thus reduced availability and toxicity of metals (Worms et al., 2012). Under abiotic stresses, photosynthesis is highly susceptible cellular process, however NMs have been shown to protect photosynthetic system and improve photosynthesis by suppressing oxidative and osmotic stress (Haghighi and Pessarakli, 2013; Qi et al., 2013; Siddiqui et al., 2014). However, response of plants to NMs varies differently depending on plant species and NMs applied (Lin and Xing, 2007). Apart from their beneficial effects several NMs show toxicity symptoms (Slomberg and Schoenfisch, 2012; Begum and