Nanoparticles mitigate arsenic stress in plant by modulating defence mechanisms

Thorny Chanu Thounaojam\textsuperscript{a}, Zesmin Khan\textsuperscript{a}, Thounaojam Thomas Meetei\textsuperscript{b}, Sanjib Kumar Panda\textsuperscript{c}, Hrishikesh Upadhyaya\textsuperscript{a*}

\textsuperscript{a}Department of Botany, Cotton University, Guwahati-781001, Assam, India.
\textsuperscript{b}Department of Soil Science and Agricultural Chemistry, Lovely Professional University, Jalandhar, Punjab – 144411, India.
\textsuperscript{c}Department of Biochemistry, Central University of Rajasthan, Ajmer – 305817, Rajasthan, India.

*Correspondence: drhkubot.cu@gmail.com
Abstract

Arsenic stress greatly affects plant production, threatening food security, and also human health through food chain. Arsenic alters various physiological processes that subsequently affect plant’s normal metabolism. Plant has different mechanisms to protect from stress, where nanoparticles improve plant metabolisms and defence system, thereby alleviating arsenic stress in plant. Therefore, this review discusses the effects of arsenic in plant at different levels, and the roles of NPs in modulating plant defence system against As stress. This review will be encouraging in future research on plant protective mechanisms against stress and the significance of NPs in plant science and agriculture.

Keywords: Arsenic, plant, nanoparticles, mitigation
Introduction

The toxic and carcinogen arsenic (As) is omnipresent, released to the environment by natural process, as well as by anthropogenic activity\(^1\). The residues remain in the soil, and get dissolved in groundwater, contaminating both soil and water. Irrigation with As-contaminated groundwater also becomes an important route of As exposure, threatening plant growth and production.

The toxic arsenic is taken up by plants as inorganic arsenite As(III), arsenate As(V) and organic monomethylarsonic acid (MMA), and dimethylarsinic acid (DMA). Different transporters are involved in the uptake and transportation of different species of As from soil to root and root to the above ground parts of the plant body. AsV, the predominate form of As under oxidizing condition, are transported by phosphate transporters due to the structural similarity with Pi. While, the dominant form in anaerobic environments, AsIII, is an analogue of silicon and the analogy make plants to uptake the non essential toxic As through aquaglyceroporin channels by competing with the element. Being a non essential element, As induced toxicity to plant even at low concentration. AsIII reacts with sulfhydryl groups of many proteins and enzymes, altering their conformation and activity, while, AsV replaces inorganic phosphate (Pi) in various metabolisms, affecting the normal metabolisms. As also induces formation of reactive oxygen species (ROS), affecting ROS homeostasis and eventually oxidative damaged to DNA, RNA, proteins and lipids\(^2\). Moreover, As gets accumulated in plant tissues, for example, 2.24 mg/kg As can be accumulated in rice grain, however, the maximum contaminant level (MCL) of As in rice grain is 200 μg/kg for white rice and 400 μg/kg for brown rice\(^3,4\). Hence, As toxicity not only affects plants, but also human health through food chain.

Arsenic stress in plants and its mitigation becomes a major concern globally. Increased ROS production by As exposure is counteracted by the stimulation of antioxidant
enzymes as reported in many studies, revealing strong association of antioxidant enzymes and metabolites with As tolerance in plant\textsuperscript{5,6}. Moreover, supplementation of essential elements is also found to be an important strategy for mitigation of As stress in plant as it reduced As bioavailability and uptake in plant\textsuperscript{7,8}. The study of Li \textit{et al.}\textsuperscript{9} in ryegrass under As stress revealed the major association of nutrient absorption and antioxidant enzymes with As stress tolerance. Minimization of As uptake and detoxification of As induced- ROS are important strategies for As stress mitigation in plants.

Nanoparticles (NPs), the particles in nanometer size, because of their outstanding properties such as high surface energy and high catalytic efficiency with strong adsorption ability, become a prominent tool against abiotic stress in plants\textsuperscript{3}. NPs increase nutrients uptake and ROS scavenging enzymes in plants. It has been reported that application of essential elements in the form of NPs effectively increased their absorption and activity of antioxidants while reducing the uptake and toxicity of As in plants\textsuperscript{10}. Bidi \textit{et al.}\textsuperscript{11} also demonstrated FeNPs alleviated As stress in rice by improving Fe uptake and strengthening antioxidant defence system, revealing the significant role of the NPs in alleviating As phytotoxicity in plant. Utilization of NPs found to be a promising tool against As stress in plants, therefore, this review is on the impact of As in plant morphology, physiology, biochemical, and genetical changes and the promising roles of NPs in the mitigation of As stress in plants, which is quite essential to bring food security.

**Arsenic metabolism and toxicity in plant**

As arsenic is a non essential and toxic metalloid, it has no essential function in plant metabolism. It alters the normal metabolism of plant by entering into plant tissues through various transporters of essential elements. Plant has different mechanisms to protect them from the toxicity induced by As, where the important mechanisms include activation of
antioxidant enzymes and non enzymic antioxidants that can scavenge ROS; complexation with ligands and vacuolar sequestration. However, As stress induced morphological, physiological, biochemical and molecular changes in plant (fig 2).

**Morphological changes**

Arsenic exposure leads to morphological changes in different plant. Niazi *et al.*\(^\text{12}\) observed significant reduction in plant height, leaf area and number of leaves in *Brassica napus* and *Brassica juncea* under As treatment. 63% and 82% reduction in root length of mung bean seedlings under 10 and 50 µM As, respectively was reported by Singh *et al.*\(^\text{13}\) which is consistent with the finding of Nath *et al.*\(^\text{14}\), where rice root length was reduced by 2 fold under 100 µM As with respect to control. Thounaojam *et al.*\(^\text{15}\) demonstrated the detrimental effect of As on germination and length of radical and plumule of rice seedlings, which could be due to the toxic effect of As on seed metabolic activities. Arsenic causes wilting, curling and senescence of leaf, leaf chlorosis and necrosis and reduction in leaves number, reviewed by Sharma *et al.*\(^\text{16}\). Morphological alterations induced by As on the root system architecture of rice was reported by Ronzan *et al.*\(^\text{17}\), where 100 µM As significantly reduced adventitious root length and lateral root primordial formation with respect to control, which is due to an interruption of IAA biosynthesis and transport. The study of Atabaki *et al.*\(^\text{18}\) also provided insight on the impact of different concentrations of As on the morphological characteristics of water mimosas. It has been reported that As reduced the number and growth ratio of leaves and roots, and also root and shoot diameters with the increase of concentration and duration of treatments. Moreover, the As treatments caused changes in colour of leaves and roots as leaves turned yellow from green and root turned brown to pinkish over time, which led to wilting of the plant and consequently death.
Biochemical and physiological changes

Arsenic induces ROS generation mainly through the mitochondrial electron transport chain, reviewed by Hu et al.\textsuperscript{19} It inhibits activity of enzyme succinic dehydrogenase that resulted into uncoupling of oxidative phosphorylation with the significant generation of ROS. Moreover, during the reduction of As\textsubscript{V} to As\textsubscript{III} and synthesis of PC, ROS are formed\textsuperscript{20} that lead to oxidative damage to plant biomolecules. Excessive ROS cause lipid peroxidation, protein carbonylation and DNA base oxidation. Besides, the literature explain that the generated ROS can also alter cell signal transduction, of which some of them are Nrf2-antioxidant response element (ARE) signaling pathway, microRNAs (miRNAs), mitophagy pathway, tyrosine phosphorylation system, mitogen-activated protein kinases (MAPKs), nuclear factor κB (NF-κB), and activator protein-1 (AP-1). As\textsubscript{III} inhibited the activity of photosynthetic enzyme, ribulose 1,5-bisphosphate carboxylase/oxygenase (Rubisco) by binding with the vicinal dithiol (Cys172-Cys192) of the enzyme, affecting fixation of CO\textsubscript{2} in plant\textsuperscript{21}. As\textsubscript{III} also binded with co-factor of enzyme complexes and inhibited the complexes, as in the study of Bergquist et al.\textsuperscript{22}, where As\textsubscript{III} binded with lipoic acids, the co-factor of pyruvate dehydrogenase complexes and \(\alpha\)-oxoglutarate dehydrogenase complex (OGDC), affecting the cellular respiration. Study of Gusman et al.\textsuperscript{23} also observed inhibition of photosynthetic rate in lettuce plant by As treatments with the inhibition of CO\textsubscript{2} fixation process, which could be due to the decrease in the number and activity of RUBISCO. As can affect both photochemical and biochemical phases of photosynthesis by interfering the enzyme activity involved in the two phases. Inhibition of photosynthetic rate by As in plant is also reviewed by Abbas et al.\textsuperscript{1}. Impact of As on photosynthesis has been explained where photosystem I and II, synthesis of chlorophyll, chloroplast membrane and CO\textsubscript{2} fixation are affected by As, which leads to decline in photosynthetic rate and yield. As also affected nitrogen metabolism in plants by altering activities of enzyme such as nitrate reductase,
nitrite reductase, and glutamate dehydrogenase, thereby, reducing NO$_3^-$ and NO$_2^-$ contents and glutamic acid and glutamine ratio$^{24,25}$. AsV uncouples oxidative phosphorylation, which resulted into the inhibition of ATP synthesis$^{26}$. ATP is formed by phosphorylation of ADP in mitochondria, but due to the interference of AsV with the mitochondrial enzymes, F$_1$F$_o$ ATP synthase, the enzyme reacts with AsV and formed ADP-AsV and thereby inhibiting the normal metabolism. AsV interferes the activity of polynucleotide phosphorylase enzyme (PNPase), the enzyme that catalyze phosphorolysis and also the exchange of the terminal phosphate group of ADP and Pi. In presence of AsV, PNPase catalyze the arsenolysis of RNA and ADP giving AMP-arsenate$^{27}$. AsV also alters the activity of glycolytic enzymes by substituting the Pi group. Glyceraldehyde-3-phosphate dehydrogenase (GAPDH) is the glycolytic enzyme that catalyzes the oxidative phosphorylation of D-glyceraldehyde 3-phosphate (G3P) to 1,3-biphospho-D-glycerate (1,3BPG), but presence of AsV inhibited the formation of 1,3BPG, and formed 1-arseno-3-phosphoglycerate (1As3PG)$^{28}$. The study of Tariang et al.$^{29}$ also revealed that As altered activity of hexokinase, phosphofructokinase and pyruvate kinase enzymes, which might have caused to inhibition of carbohydrate metabolism.

**Genetical changes**

In the study of Pandey et al.$^{30}$, As stress altered gene expression of Osa-miR156j in rice, which is highly influenced by duration of As exposure and plant tissues. It has been observed that the expression of Osa-miR156j was down-regulation in the different plant tissues in different developmental stages, where the down-regulation was more pronounced in root tissues at seedlings developmental stage. Study of Marotti et al.$^{31}$ also reported a massive reduction of gene expression by ultrahigh diluted As$_2$O$_3$ in wheat plant with respect to control plant. As$_2$O$_3$ application down-regulated 71% probe sets involve in the growth of the seedlings, revealing under-expression of the majority of the affected genes by As$_2$O$_3$. 
However, genes responsive to stress hormones including auxins, brassinosteroids, and jasmonate and enzyme phenylalanine ammonia lyase were activated with the application of As$_2$O$_3$, providing evidence for a strong gene altering effect of As in wheat seedlings. Pan et al.$^{32}$ investigated the dynamics of gene expression of As(III)-related transporters, OsLsi1, OsLsi2 and OsABCC1 genes in rice plant. The relative expression of the OsABCC1 gene found to be linearly positively related to OsLsi1 and OsLsi2, maximum at 9 weeks of treatment. The relatively high expression of OsLsi2, OsLsi1 and OsABCC1 genes in root and OsLsi3/OsLsi6 and OsABCC1 expression in nodes/leaves and husks and suppression of OsABCC1 expression in roots in 18-20 weeks lead to high accumulation of As in root and shoot respectively. As alters expressions of transporters (Lsi1 and Lsi2) in rice, demonstrated by Chen et al.$^{33}$, where As treatment induced a down-regulation of the expression of Lsi1 and Lsi2 transporters in rice with respect to control. The differential expression of PHTs in different genotypes of barley by As stress was reported by Zvobgo et al.$^{34}$. Up-regulation of PHTs in As sensitive genotypes and down-regulation in tolerant genotypes to a greater extend was observed, suggesting suppression of the expression of PHTs is the major mechanism for the tolerance to As. It has also been reported that As stress induced transposon burst with the repression of As(V)/Pi transporter PHT1;1., thereby, restricting As uptake in Arabidopsis$^{35}$ They found that WRKY6 is responsible for the repression in response to As stress, highlighting the WRKY6 is an essential component of As(V) repression of As(V)/Pi transporters. Significant changes in the expression profile of 14-3-3 protein family in response to As stress in AMF colonized rice was demonstrated by Pathare et al.$^{36}$. The expression of OsGF14c, OsGF14e and OsGF14g genes was significantly declined after 1 days of As treatment, while at 3 days of As stress, maximum down-regulation of expression was shown by OsGF14a, followed by OsGF14b, OsGF14h, OsGF14c and OsGF14d, revealing the impact of As stress on the expression is time depended. As treatment
significantly increased the expression of the genes OsASA2 and OsYUCCA2 while inhibited the expression of the IAA influx carrier AUX1 and efflux carrier PIN5 (Ronzan et al. 17). As stress also altered expression of nitrogen absorption and assimilation related genes in rice plant. The expression of the genes NR, NiR, ad GOGAT was down-regulated under As treatment in both root and shoot with respect to control, while the expression of NiR, NRT2 and AMT1 genes was found to be up-regulated in root and down-regulated in shoot under As stress. 37.

Nanoparticles on mitigation of arsenic

Mitigation of As stress in plant is one of the important challenges to ensure food security. Plants adopt important mechanisms to combat stress such as restriction of uptake and the internal mechanism, antioxidant defence system. It has been observed from various studies that NPs restrict As uptake with the increase of nutrient intake and antioxidant activities, thereby, mitigate As stress in plants. The antioxidant defence system is found to be the prominent mechanism to cope with As stress.

Alleviation of heavy metal stress in different plants by NPs through acting as source of essential elements, absorption of the toxic heavy metals, and increased of antioxidant enzymes, thereby reducing accumulation of ROS and oxidative damage, has been recently reviewed by Zhou et al. 38. Ahmad et al.12 reported that application of zinc oxide nanoparticles (ZnO NPs) ameliorate As toxicity in soybean plant by restricting As uptake and modulating antioxidant enzymes, glyoxalase system and ascorbate-glutathione cycle. Similar observation of the ameliorating effects of ZnO NPs against As stress was reported in rice by reducing As uptake rice while enhancing biomass, germination and nutrients of Zn39,40. The mitigating effect of iron oxide nanoparticle (IONPs) against As stress was reported by Mushtaq et al.41 where activity of peroxidase (POD) and superoxide dismutase (SOD)
enzymes was found to be increased under IONPs treatment in *Cucurbita moschata* plant, while reducing the levels of electrolyte leakage (EL), hydrogen peroxide (H$_2$O$_2$) and malondialdehyde (MDA). Exogenous application of Fe$_3$O$_4$ NPs augmented antioxidant enzymes, protein content and photosynthetic pigment under As stress in Indian mustard plant (*Brassica juncea* L.) as experimented by Praveen *et al.*\textsuperscript{42}. They added that the ability of Fe$_3$O$_4$ NPs to restrict entry of As inside the plant might lead to decrease stress related parameters. They explained that IONPs act as nanoadsorbents in amelioration of As stress. The *Bacillus subtilus*-synthesized Fe$_3$O$_4$ NPs also act as nano-adsorbents in lowering the effect of As toxicity in rice plants and improved its growth\textsuperscript{43}.

Ti NPs also has the potential to mitigate As stress by perking up the antioxidant genes expression as reported by Katiyar *et al.*\textsuperscript{44}. TiNPs specially the green manufactured one conferred tolerance to As-induced oxidative damages by augmenting the antioxidant machinery. Activation of plant antioxidant defence system by the application of Ti NPs was also supported by the study of Salar *et al.*\textsuperscript{45} in *Dracocephalum kotschyi* Boiss, where the antioxidant enzymes SOD, CAT and APX were significantly increased under Ti NPs treatment. Wu *et al.*\textsuperscript{46} investigated the effect of Rutile nano-TiO$_2$ (NRT) in amelioration of As stress in rice. They found that 1000 mg/L of Rutile nano-TiO$_2$ (NRT) reduced As uptake in the exposed rice seedling without causing any significant oxidative stress in the plants. Accumulation of As in plants reduced by 40–90% by the application of Nano-TiO$_2$ due to its strong sorption process. SiNPs augmented pectin synthesis and the mechanical force of the cell wall to inhibit uptake of As into rice suspension cells as studied by Cui *et al.*\textsuperscript{47}. Their work provides the mechanism of inhibiting As uptake into rice at the single cell level by SiO$_2$. By the treatment of SiO$_2$ NPs, pectin methylesterase (PME) activity, cation exchange capacity (CEC), pectin content and thickness of the cell was increased. Thus maintained the integrity of the cell undergoing As stress. It also improved the mechanical force of the rice
cell walls by decreasing degree of pectin methylesterification. The SiO$_2$ NPs treated cell show higher expression of OsNIP1; 1 and OsNIP3; 3 and lower expression of OsLis1 and OsLis2 genes. These findings provide the possibility of using SiO$_2$ NPs in As-contaminated paddy soil. It has been reported that many other abiotic stresses such as salinity stress, drought and Cd stresses were mitigated by different NPs by increasing antioxidant enzyme activities while lowering ROS$^{48, 49}$. The recent study of Hussain et al.$^{50}$ on the use of different NPs (ZnO, FeO and Si) under Cd stress in wheat plant also revealed that NPs ameliorate Cd stress by increasing nutrient uptake and antioxidant enzyme activities, while reducing Cd intake by the plant. The prospective of NPs to mitigate abiotic stress in crop plant was reviewed by Das and Das$^{51}$ where the significant roles of NPs in mediating different stresses have been explained. Abiotic stress such as drought, flood or salinity stress was mediated by different NPs including Ag, Al$_2$O$_3$, Fe$_3$O$_4$, TiO$_2$, SiO$_2$, ZnO NPs in different plants by increasing essential nutrient content and enzymic and non-enzymic antioxidant, altogether increased total antioxidant capacity of plant. Gohari et al.$^{48}$, Duo et al.$^{52}$ and Mahammadi et al.$^{53}$ also demonstrated stimulation of antioxidant enzymes with the supplementation of NPs, enhancing plant defence system and tolerance against salt, drought and cold stress respectively. NPs possess great potential towards amelioration of different stresses by counteracting stress induced oxidative damage with the increase of antioxidant activities. Studies of Khan et al.$^{54}$ and Praveen et al.$^{55}$, also revealed the prominent role of antioxidants in the mitigation of As in plants.

**Conclusion and future perspective**

One of the major problems facing the world today is to achieve food security for the growing population, which is fundamentally depended on agricultural food production.
However, plant production is hindered by many factors, of which arsenic (As) stress caused significant reduction in plant growth and yield. However, as describe in this review, the impact of As stress could be mitigated by NPs with the stimulation of plant defence mechanisms. NPs restrict the uptake of As while enhancing nutrient contents. Moreover, NPs improve antioxidant system, which strictly regulates ROS concentration preventing oxidative stress in plant. It is understood from the review that NPs could be used as a promising particles for mitigation As stress in plants, however, effect of NPs is mainly a concentration based property, therefore, it is quite essential to find out the effective concentrations of NPs for the successful mitigation of As stress. Since uptake is regulated by different transporters, it is needed to understand the different transporters involve in As uptake for better uptake restriction and how NPs influence the transporters to restrict the uptake of As, while enhancing essential elements. Therefore, future research needs to focus on NPs in plant antioxidant system and transporters for better results on mitigating of As stress in plant, which could be supportive in agriculture in achieving food security.

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Table 1: Regulation of uptake and antioxidant system by NPs to mitigate As and other heavy metal stress in plant

<table>
<thead>
<tr>
<th>Sl no.</th>
<th>Concentration of treatment</th>
<th>Duration of treatment</th>
<th>Plant types</th>
<th>Effects</th>
<th>NPs</th>
<th>Mitigating effects</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10 ad 20 μM As</td>
<td>60 days</td>
<td>Soybean</td>
<td>Inhibited growth, and induced oxidative stress</td>
<td>ZnO NPs</td>
<td>Increased enzymes involved in the ascorbate–glutathione cycle including SOD, CAT, APX and GR</td>
<td>Ahmad et al.¹⁰</td>
</tr>
<tr>
<td>2</td>
<td>6.76 mg/kg As</td>
<td>45 days</td>
<td>Rice</td>
<td></td>
<td>ZnONPs (100 mg/Kg)</td>
<td>Lowered As accumulation</td>
<td>Ma et al.³⁹</td>
</tr>
<tr>
<td>3</td>
<td>10, 20, and 30 mg/L As</td>
<td>60 days</td>
<td>Cucurbita moschata</td>
<td>Oxidative stress</td>
<td>IONPs (5, 10, 15, and 20 mg/L)</td>
<td>Increased activity of antioxidant enzymes</td>
<td>Mushtaq et al.⁴¹</td>
</tr>
<tr>
<td>4</td>
<td>150 μM As</td>
<td>96 h</td>
<td>Indian mustard</td>
<td>Inhibited germination, growth ad induced oxidative stress</td>
<td>Fe₃O₄ NPs (500 mg L⁻¹ Fe₃O₄)</td>
<td>Restricted entry of As and stimulated antioxidant enzymes</td>
<td>Praveen et al.⁴²</td>
</tr>
<tr>
<td>5</td>
<td>5, 10 and 15 ppm As</td>
<td>14 days</td>
<td>Rice</td>
<td>Inhibited germination and growth of seedlings</td>
<td>Fe₃O₄ NPs (5 ppm)</td>
<td>Restricted As uptake</td>
<td>Khan et al.⁴³</td>
</tr>
<tr>
<td>6</td>
<td>10 mM of As</td>
<td>5 days</td>
<td>Vigna radiata L</td>
<td>Exaggeration of ROS production leading to</td>
<td>TiNPs (0.1%)</td>
<td>Inhibition of As uptake ad reduction</td>
<td>Katiyar et al.⁴⁴</td>
</tr>
</tbody>
</table>

References:

Ahmad et al.¹⁰
Ma et al.³⁹
Mushtaq et al.⁴¹
Praveen et al.⁴²
Khan et al.⁴³
Katiyar et al.⁴⁴
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<tr>
<th></th>
<th>Antimicrobial Agent</th>
<th>Exposure Duration</th>
<th>Host Plant</th>
<th>Effect on Host Plant</th>
<th>Mechanism</th>
<th>Antioxidant Intervention</th>
<th>Outcome</th>
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<tr>
<td>7</td>
<td>10, 20, 40 and 80 μM As</td>
<td>24h</td>
<td>Rice</td>
<td>Caused oxidative damage; destroyed integrity of cell</td>
<td></td>
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<td>SiO₂ NPs (0.1 and 1 mM)</td>
<td>Inhibited As uptake and transport and significantly decreased As induced oxidative stress</td>
<td>Cui et al.⁴⁷</td>
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<tr>
<td>8</td>
<td>Cd</td>
<td>80 days</td>
<td>Wheat</td>
<td>Caused oxidative stress</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>Fe NPs 25, 50 and 100 mg/kg</td>
<td>Inhibited Cd uptake, enhanced Fe content</td>
<td>Adrees et al.⁴⁹</td>
<td></td>
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<tr>
<td>9</td>
<td>10 mg/kg Cd</td>
<td>30 days</td>
<td>Rice</td>
<td>Induced oxidative stress and inhibited plant growth</td>
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<td></td>
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<td></td>
<td></td>
<td>IONPs, HGNPs 25, 50, 100 mg/kg</td>
<td>Increased nutrient and antioxidant contents</td>
<td>Ahmed et al.⁵⁶</td>
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<tr>
<td>10</td>
<td>Cd</td>
<td>55 days</td>
<td>Rice</td>
<td>Affected growth and photosynthesis</td>
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<td>Fe NPs 10, 20, 30 mg/L</td>
<td>Significantly decreased Cd intake</td>
<td>Rizwa et al.⁵⁷</td>
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<td>11</td>
<td>0.93 mg/kg Cd</td>
<td>80 days</td>
<td>Wheat</td>
<td>Reduced growth and induced oxidative stress</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>ZnO NPs 25, 50, 75, and 100 mg L⁻¹</td>
<td>Reduced Cd concentration while increased Zn concentration ad antioxidant enzymes</td>
<td>Hussain et al.⁵⁸</td>
<td></td>
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<td>12</td>
<td>50 μM Cd</td>
<td>14 days</td>
<td>Rice</td>
<td>Induced oxidative stress</td>
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<td></td>
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<td></td>
<td></td>
<td>CeO₂ NPs</td>
<td>triggered the</td>
<td>Wang et al.⁵⁹</td>
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<tr>
<td>No.</td>
<td>Cadmium Concentration</td>
<td>Exposure Period</td>
<td>Plant</td>
<td>Effect</td>
<td>Nanoparticles Treatment</td>
<td>Effect on Antioxidant Enzymes and Oxidative Stress</td>
<td></td>
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<tr>
<td>13</td>
<td>7.86 mg/kg Cd</td>
<td>75 days</td>
<td>Maize</td>
<td>Caused oxidative stress</td>
<td>ZnO NPs 50, 75, 100 mg/L</td>
<td>Reduced Cd concentration while reducing Zn concentration, increased antioxidant enzymes activities</td>
<td></td>
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<tr>
<td>14</td>
<td>1.21 mg/kg Cd</td>
<td>80 days</td>
<td>Wheat</td>
<td>Inhibition of growth, photosynthesis, induced oxidative stress</td>
<td>Si NPs 25, 50 100 mg/kg</td>
<td>Counteracted oxidative stress with the increased of antioxidant enzymes</td>
<td></td>
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<tr>
<td>15</td>
<td>12 and 25 mg/kg Al</td>
<td>21 days</td>
<td>Maize</td>
<td>Inhibited growth, photosynthesis ad induced oxidative stress</td>
<td>SNPs 4mg/kg</td>
<td>Improved ROS scavenging system by activating antioxidant contents and activities</td>
<td></td>
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Rizwan et al., 60

Khan et al., 61

De Souza et al., 62
Figure caption

Fig 1: Effects of arsenic at different levels in plant

Fig 2: Mitigation of arsenic stress in plant with the application of NPs. A. Arsenic induced toxicity with its accumulation in different tissues. B. Restriction of As uptake and activation of antioxidant defence mechanism by NPs, thereby mitigating As stress in plant
Fig: 1
Fig: 2

A: As uptake and accumulation in plant tissues, inducing toxicity in plant

B: Stimulation of antioxidant system, mitigating the toxic effects of As

Restriction of As uptake and accumulation