Silicon-based nanoparticles for mitigating the effect of potentially toxic elements and plant stress in agroecosystems: a sustainable pathway towards food security

Emmanuel Sunday Okeke [a,b,c] , Ekene John Nweze [c] , Tobechukwu Christian Ezike [c] , Charles Ogugua Nwuche [d] , Timothy Prince Chidike Ezeorba [c,e,f], Chidiebele Emmanuel Ikechukwu Nwankwo [b,d,g],**

[a]Institute of Environmental Health and Ecological Security, School of the Environment and Safety Engineering, Jiangsu University, Zhenjiang 212013, PR China [b]Natural Science Unit, School of General Studies, University of Nigeria, Nsukka, Enugu State 410001, Nigeria [c]Department of Biochemistry, Faculty of Biological Science University of Nigeria, Nsukka, Enugu State 410001, Nigeria [d]Department of Microbiology, Faculty of Biological Science University of Nigeria, Nsukka, Enugu State 410001, Nigeria [e]Department of Genetics and Biotechnology, Faculty of Biological Sciences, University of Nigeria, Nsukka 410001, Enugu State, Nigeria [f] Department of Environmental Health and Risk Management, College of Life and Environmental Sciences, University of Birmingham, B15 2TT Edgbaston, United Kingdom [g] Food and Biological Engineering, Jiangsu University, Zhenjiang 212013, PR China.

Abstract

Due to their size, flexibility, biocompatibility, large surface area, and variable functionality nanoparticles have enormous industrial, agricultural, pharmaceutical and biotechnological applications. This has led to their widespread use in various fields. The advancement of knowledge in this field of research has altered our way of life from medicine to agriculture. One of the rungs of this revolution, which has somewhat reduced the harmful consequences, is nanotechnology. A helpful ingredient for plants, silicon (Si), is well-known for its preventive properties under adverse environmental conditions. Several studies have shown how biogenic silica helps plants recover from biotic and abiotic stressors. The majority of research have demonstrated the benefits of silicon-based nanoparticles (Si-NPs) for plant growth and development, particularly under stressful environments. In order to minimize the release of brine, heavy metals, and radioactive chemicals into water, remove metals, non-metals, and radioactive components, and purify water, silica has also been used in environmental remediation. Potentially toxic elements (PTEs) have become a huge threat to food security through their negative impact on agroecosystem. Si-NPs have the potentials to remove PTEs from agroecosystem and promote food security via the promotion of plant growth and development. In this review, we have outlined the various sources and ecotoxicological consequences of PTEs in agroecosystems. The potentials of Si-NPs in mitigating PTEs were extensively discussed and other applications of Si-NPs in agriculture to foster food security were also highlighted.

Keywords: Silicon; nanoparticles; PTEs; agroecosystem; ecotoxicity; food security

1. Introduction

Agriculture is the primary source of food, a basic human need. However, anthropogenic activities has challenged agriculture variously; ranging from pollution (fertilizers, metals, pesticides) to climate change issues (A. Kumar & Sharma, 2022; Zhang, et al., 2023). With an estimated global population of 10 billion by 2050 (Kumawat et al., 2022), a 50% increase in food production is needed.

Potentially toxic elements (PTEs) are currently among the most harmful environmental contaminants on a global scale. Untreated wastewater from industries is released into water bodies, sometimes introducing high PTE concentrations to the environment (Dvorak et al., 2020). Further, agrofertilizers are constituted from certain chemicals; which end up in the agroecosystem as PTEs (Malyugina et al., 2021). This contamination is aggravated by the bio-accumulation and non-degradable properties of PTEs (Pandey & Tiwari, 2021). PTEs are toxic to biota, including humans (Inobeme, 2021). Similarly, PTEs upset the soil structure; soil microbial communities leading to altered microbial, biochemical, molecular and structural functions (Zhao et al., 2022). Consequently, soil microbial richness and diversity is altered with resultant decline in soil fertility, these distortions affect soil fertility.

Contaminant-mediated microbial evolution has also been reported. For example, surface water sources receiving industrial wastewater are breeding hotspots for metal-resistant bacteria (Chaturvedi et al., 2021). The various cell wall entry mechanisms and routes of toxins in bacterial (P. Sharma et al., 2022), elicit different resistance responses (Xavier et al., 2019). This could mean the evolution and release of mutant organisms into the ecosystem which has been identified as a critical concern, including emergence of pandemics (Sunday et al., 2022).

The need to employ efficient, eco-friendly tools to alleviate the environmental contamination of PTEs is important for reduced ecotoxicological consequences. Currently, nanoparticles are gaining prominence in agricultural, health and industrial sectors (Adeel et al., 2019). NPs with have been deployed based on peculiar requirements (Adeel et al., 2020). Overall, NPs are preferred due to their minute nature with increased surface reaction sites, high surface activity, as well as catalytic, optical and magnetic features (Y. Wang et al., 2019). Nanoparticles can improve crop quality and crop yield, vulnerability to oxidative stress, seed germination, photosynthesis, rhizome growth and development, (Kah et al., 2019). Further, NPs in nano-fertilizers and pesticides is preferred for easy plant intake and slow environmental release (B. Sharma et al., 2023; Hao et al., 2019; Lowry et al., 2019).

Silicon (Si) is 70% mass of soil (Siddiqui et al., 2020) with benefits to cyperaceous and gramineous plants (Wang et al., 2017). For example, Si reduces the severity of abiotic and biotic stress in plants. Si-NPs are novel sources of Si for plant resilience to environmental stress. Si-NPs may be affected by intrinsic features including size and shape (Rastogi et al., 2017) but most effective when administered through the soil (Suriyaprabha et al., 2014). For example, Si-NP application resulted in increased oil and improved growth in *Cymbopogon citratus* (Mukarram et al., 2021). Similarly, *Avena sativa* grew better with enhanced tissues lignification (Asgari et al., 2018) and improved seed germination and seedling growth in *Agropyron elongatum* (Azimi et al., 2014). Mechanism of improved conditions in plants from nano-SiO_2-based fertilizers is linked to N_2 and P levels respective regulations (Mejias et al., 2021). Improved photosynthesis through by altered pigmentation has been achieved with SiO_2-NPs (Mejias et al., 2021).

In this review, we evaluate the prospects of Si-NPs in alleviating the impact of PTEs and plant stressors in the agroecosystems. This paper highlights the origins and ecotoxicity of PTEs in the ecosystems and presents the potentials of Si-NPs in PTEs removal from soils and alleviating plant stress towards food security. In addition, Si-NPs applications for improved agriculture aimed at food security was discussed.

Though with enormous advantages, Si-NPs may raise some ecological risk assessment issues. To address these risks comprehensively, we outlined hazards associated with the application of Si-NPs within agroecosystems. This review also proposed future research perspectives towards the pragmatic and responsible use of Si-NPs.

2. Routes of PTEs entry to the agroecosystem

2.1 Agriculture

Agriculture continues to rely on pesticides, insecticides, herbicides and fertilizers for imporobed yield. These chemicals are implicated as important in the incidence and accumulation of PTEs (Fig. 1) in soil and plants (Hou et al., 2020; Zhang et al., 2023). Certain popular agricultural practices are sources of PTEs in soil. For example, irrigation is popular for all-season crop production and the use of wastewater in irrigation is common. This wastewater is identified as a source of PTEs like Pb in plants and upper soil (Singh et al., 2022). Phosphate fertilizers improve plant growth and prevent diseases but contribute high level of PTEs in soil(Weissengruber et al., 2018).

2.2 Mining

Studies have identified mining for the introduction of As and Hg into the agroecosystem (Zhang et al., 2023). Positive matrix factorization (PMF) and Hg isotope and techniques traced the Arsenic, mercury and Thallium to historic mining. Another study used the finite mixture distribution model (FMDM) and PMF to implicate a coal mine for PTEs contamination and public health consequences (Siddiqui et al., 2022).

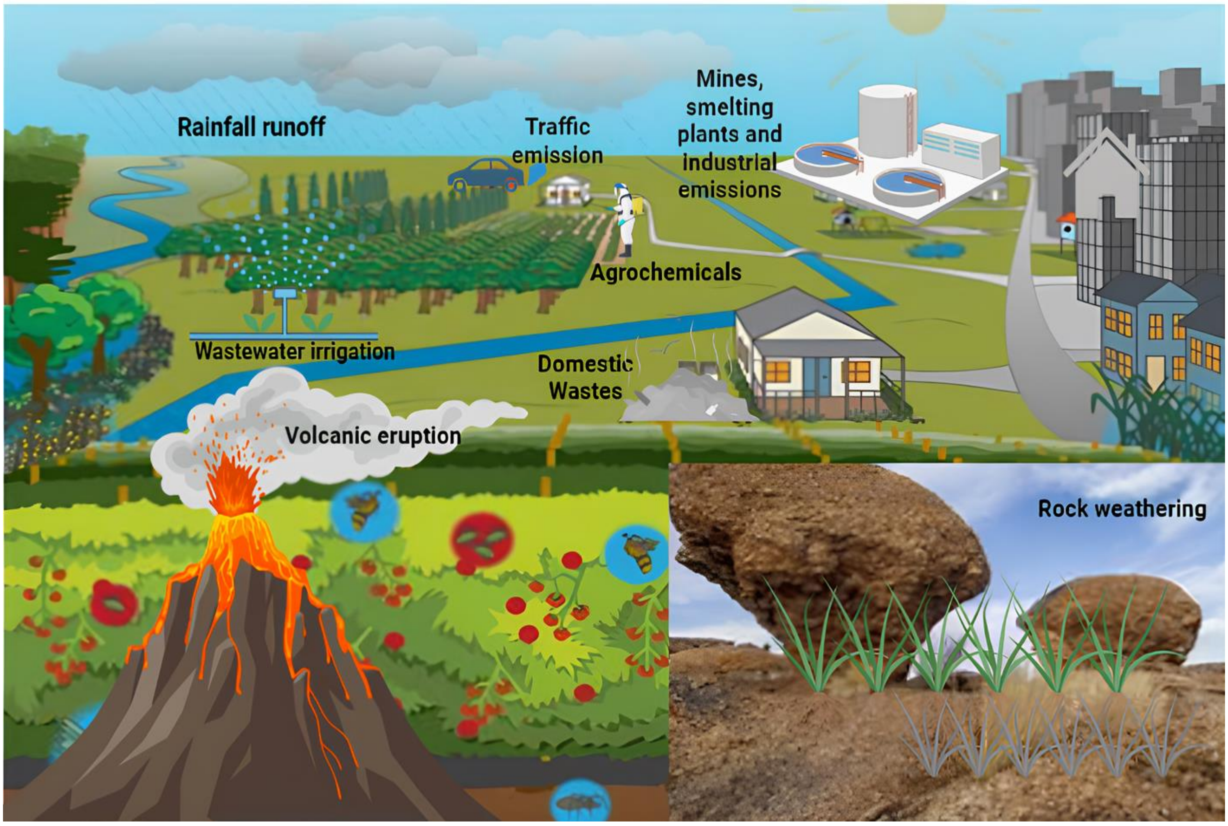

Figure 1: Routes of PTEs entry to the agroecosystem

2.3 Industries and traffic emissions

Industrial and traffic release of PTEs into the biosphere (Fig.1) represent as critical source of this important contaminants (Siddiqui et al., 2022; Zhang et al., 2023). Infact, industries and traffic sources of PTEs represent the highest introduction source to the agroecosystem (Wang et al., 2022). An interesting trend has been established in the relationship between the concentration of PTEs (like Cd, Pb and Zn) and traffic (Cowan et al., 2021). Further, traffic rank highest as a source of PTEs in Korea in 2021 (Jeong et al., 2021).

Industrial waste disposal by incineration, production and use of fossil fuel and industrial emissions release PTEs to the soil environment (Hu et al., 2021; Wang et al., 2022). Further, industrial effluents are often discharged without treatment, representing an important source of PTEs (P. Liu et al., 2020). A good instance is Cr discharge from leather and pharmaceutical industrial wastes into the agroecosystems.

2.4 Smelting plants

Scientific dating experiments has identified smelting as the origin of As, Cr, Zn, Pb , Ni, etc in the soil profile (Vejvodová et al., 2022). Example, Pb in soil for over 200 years has been linked to a smelting in France (Guillevic et al., 2023). Similar vegetable and soil contamination with PTEs due to smelting has been reported in Czech republic (Vejvodová et al., 2022) and Korea (Jeong et al., 2021).

2.5 PTEs from Nature

Apart from anthropogenic route, erosion, volcanoes and rock weathering (Fig. 1) are natural phenomena leading to the introduction of PTEs in the agroecosystem. Other natural activities such as rainfall roof run-off are important sources of PTEs (Siddiqui et al., 2022; Singh et al., 2022). Sedimentation, weathering and volcanic eruptions are lithogenic activities that release PTEs from soluble metals. The elements become secondary minerals following biochemical reactions to make them readily adsorbable (Palansooriya et al., 2020). Example weathering of carbonate rock is the source of limestone soil (Zhang et al., 2022) and volcanic ashes present abundant sources of PTEs in the agroecosystem (Palansooriya et al., 2020). Further, Al, As, Ba, Cu, Fe, Mn, Ni and Zn accumulate due to the weathering of amphibolite, feldspar, hematite and ilmenite (Kumar et al., 2022).

3. Ecotoxicity of PTEs in the agroecosystem

PTEs inhibit the normal agroecosystem through the disruption of biodegradation and biogeochemical cycles. This leads to distorted functions of the fauna and flora leading to ecosystem breakdown and posing a threat to food security (Singh et al., 2022).

3.1 Effects on agroecosystem flora

Some PTEs such as Zn, are key cofactors important for normal physiology but toxic at high concentrations (Ghori et al., 2019). Conversely, some such as As and Hg are toxic and result in plant pathologies (L. Chen et al., 2022). PTEs accumulate in plants, resulting to toxic effects (Angulo-Bejarano et al., 2021; P. Liu et al., 2020) and distorting normal physiological activities

(Chen et al., 2022). For example, metal accumulate in plants upsets pollination and infertility (Xun et al., 2018).

3.2 Effects on agroecosystem fauna

PTEs including As and Sb are harmful to fauna, such as microbes involved in normal agroecosystem functions (Huang et al., 2023). As in soil leads to distruptions in the soil microbial richness with negative impacts. Specifically, As in soil leads to increased *Chloroflexi* and *Acidobacteria* but decreased *Proteobacteria* populations, accounting for reductions in enzyme and nutrients (e.g. N_2) concentrations (Dong et al., 2021). This reductions is due to the distorted microbial populations, already highlighted; such that the usually least species became abundant at the expense of the most abundant *Proteobacteria*. Clearly stated, while *Proteobacteria* is critical to C, N_2 and P availability in soil (Mhete et al., 2020), *Acidobacteria* and *Chloroflexi* remove these nutrients (Speirs et al., 2019).

Similar adverse effects have been reported on microbial diversity from exposure to As and Sb (Huang et al., 2023), on earthworm due to Cd and thus leading to poor agroecosystem functions considering the importance of earthworm in the improvement of soil quality (Van Groenigen et al., 2019). This eventual distortion in soil fauna can lead to depletion in soil nutrients and consequently threaten food production and security.

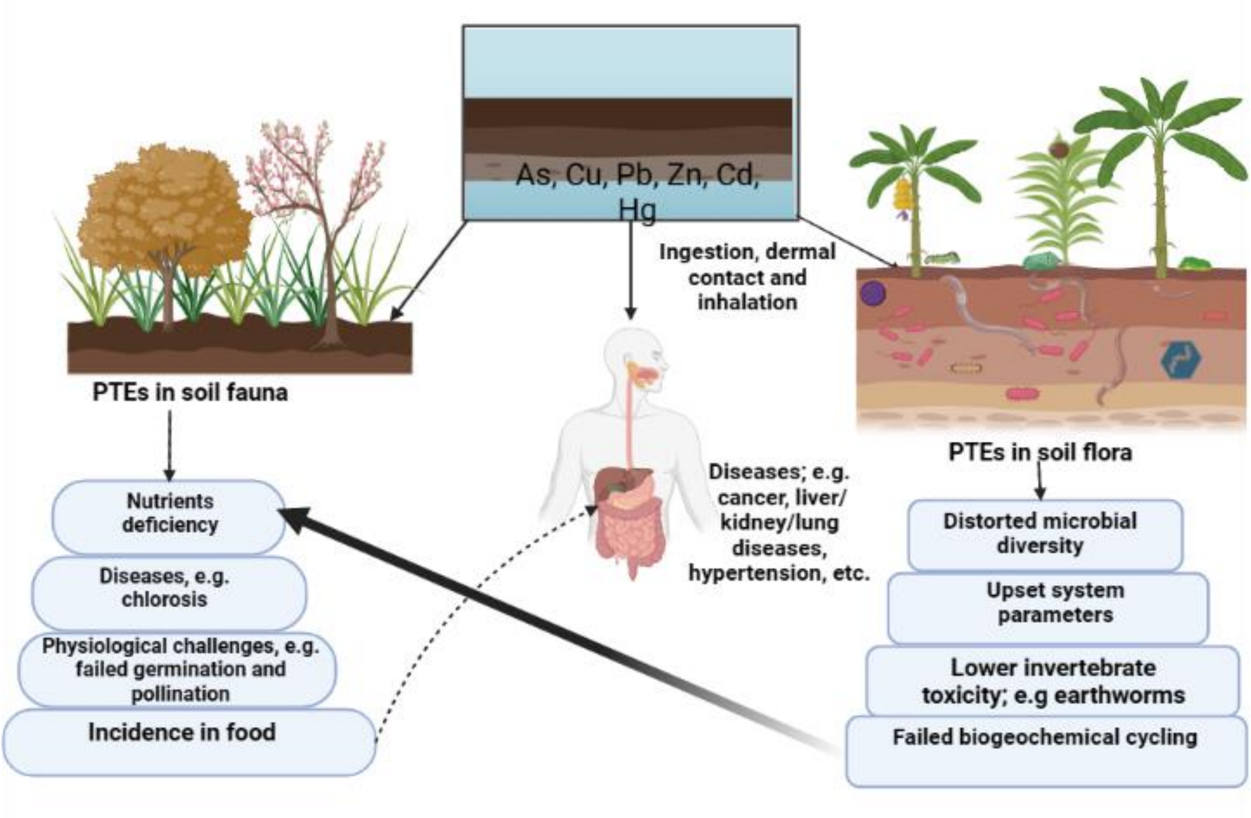

Figure 2: Ecotoxicity of PTEs in the agroecosystem

3.3 Effects on Public health

Cofactors are elements that aid enzyme actions in metabolism but deleterious at elevated levels (Banerjee et al., 2021). A good instance is Fe that allows for proper mitochondrial functions at the right concentrations but causes mutation and protein degeneration at high concentration (Astuti et al., 2022).

Cancer, gut disorders, liver /kidney impairments and hypertension are some human diseases that have been traced to PTEs (Astuti et al., 2022; Li et al., 2018; Qian et al., 2020). Contracted usually by inhalation, ingestion and dermal contact, the mechanisms of disease pathogenicity of PTEs include disruption of DNA synthesis and repair leading to cancer (Astuti et al., 2022; Taydé et al., 2023). The high bioavailability of PTEs in humans, depending on age and gender is also a cause for concern (Li et al., 2018).

4. Potentials of Silicon-based nanoparticles (Si-NPs) for mitigating/removal of PTEs and plant stress to promote food security in agroecosystem

The potential application of Si-NPs may be related to their abundance in nature as they are variously applied (Dhakate et al., 2022). The successful remediation of nanoplastics, heavy metals contamination and alleviation of soil stress due to climate change effects has been reported (Okeke, Ezeorba, et al., 2022; Pu et al., 2023). Toxic agroecosystem is implicated for distortion in physiology, decline in antioxidants leading to oxidative stress, stunted growth and distorted photosynthesis (Savchenko & Tikhonov, 2021).

In plants, oxidative stress results because of high level of reactive oxygen species (ROS), usually resulting from metabolic or environmental imbalance in redox reactions. Plant oxidative stress cause protein and nucleic acid damage and hampers the secretion of stress response mediators in plants (Enechi et al., 2022). Solutions to oxidative stress in plant are needed and studies beam greenlight to the use of Si-NPs as important tools (Bansal et al., 2022). Specifically, Si-NPs checkmate oxidative stress in plants by promoting antioxidant enzymes (ascorbate peroxidase and catalase) and antioxidant metabolites (anthocyanins, flavonoids, phenolics, glutathione) (Hasanuzzaman et al., 2020).

Further, the improvement of micro and macro nutrient absorption, photosynthesis and active contaminant removal are other mechanisms of Si-NPs actions in soil (Rastogi et al., 2019). More interestingly, there has been no reports of Si-NPs toxicity in plants instead plants exposed to Si-NPs display an increased expression of (*Lsi1*) gene responsible for silicon transport (Asgari et al., 2018).

4.1 Silicon nanoparticles and heavy metal-induced plant stress

Most PTEs in plants are metals (As, Cd, Cr, Ni, Pd) of high density and toxicity even at concentrations of parts per billion (ppb), leading to growth deficiencies and low yield. Si-Nps remarkably reduce PTEs toxicity in plants (Nweze et al., 2022). Si-NPs of 3 mM was used to mitigate the toxicity of Cd at 25 mg/kg concentration on Ujala wheat with resultant improvement in growth, photosynthesis, enzyme production and biomass (Thind et al., 2021). Overall, stress biomarkers, including superoxide radicals, hydrogen peroxide and malondialdehyde as well as electrolyte loss, drastically reduced following Si-NPs treatment. The successful PTE-induced stress mitigation was recorded in beans plant after Si-NPs and potassium silicate stimulation (El-Saadony et al., 2021). This treatment led to improved photosynthesis possibly resulting from membrane stability and conductance of the stomata.

The bioaccumulation of metal PTEs in plants leads to inhibition in nutrient uptake. For example, the accumulation of Cd in rice was noted but effectively treated by the application of 25 mM Si-NP, resulting in 31.6~64.9% success (R. Chen et al., 2018). This study also highlights the reduced translocation of Cd with corresponding increase in nutrient update following a dynamic switch in translocation factors (Table 1).

4.2 Effects of Si-NPs on PTEs stress in plants

Apart from PTEs, climate change, ultraviolet radiation, salinity are plants stressors that could impact on plant growth and yield negatively (Zhao et al., 2021). This has been demonstrated in garden pea; high salinity led to reduced water retention, stunted growth, destabilized antioxidants and eventual low yield was mitigated with Si-NP resulting in reduced toxic effects, restored system functions and better yield (Ismail et al., 2022). Similarly, oxidative stress induced by high NaCl concentration is soybeans resulting in increased peroxidation of lipids, overexpression of ROS and antioxidant enzymes, was managed by Si-NPs, resulting in normal functions (Farhangi-Abriz & Torabian, 2018).

Water deficiency due to drought stress plants and increase salinity with its resulting consequences. In a simulation study, hyper salinity due to water deficiency led to system

Table 1: Successful PTEs remediation using Si-NPs

Stressor classification	Plants	Specific stressors or PTEs/ exposure level	Stress impacts	Conc. of SiNPs	Impact of stress tolerance, adaptation and mitigation (Possible mechanisms)	Reference
Heavy metal-induced oxidative stress and toxicity	Pea seedlings (*Pisum sativum*)	Chromium - Cr (VI) - 100 µM	- ↓ plant growth - ↓ photosynthetic pigments and Chl fluorescence parameters like Fv/Fm, Fv/F0, and qP - ↑ NPQ, MDA - ↑ SOD and APx - ↓ CAT, GRT, DhAR	10 µM for 15 days	- ↓ Cr accumulation - ↑ antioxidant defense system - ↑ nutrient uptake (Mg, Ca, K and P and B, Cu, Fe, Mn, Na, Zn) - ↑ Chl, Carotenoids, Total N content, and protein	(Tripathi et al., 2015)

		- ↓ micro & macronutrients			
Rice plants (*Oryza sativa* L. cv. Xiangzaoxian 45)	Cadmium (Cd)	- Accumulation of Cd in the uppermost node of the plants	5~25 mM and 25 mM were the most effective	- Reduced the Cd concentrations in the mature grain by 31.6~64.9% ↑ Plant nutrients such as K, Mg, Fe, Ca, Zn, and Mn and their translocation factors ↓ Decrease in the translocation factor for Cd. - Summarily, SiNPs inhibit the translocation of Cd while enhancing the translocation of macro & micronutrients	(R. Chen et al., 2018)

Heavy metal-induced oxidative stress and toxicity	Ujala wheat variety	Cadmium (Cd) 25 mg kg^{-1}	- ↓ biomass production, - ↓ photosynthetic pigments, - ↓ TSP, FAA, TSS, and phenolic contents, -↑ APX, CAT, SOD, POD -↑ reducing sugar -↑ proline contents -↑ MDA, H_2O_2 content, -↑ electrolyte leakage	3 mM	- Improved growth - ↑ photosynthetic pigments, - ↑ levels of flavonoids, - ↑ TSP, phenolics, FAA, proline, TSS, - ↑ APX, CAT, POD, and SOD enzymes. - ↓ H_2O_2 and - ↓ MDA	(Thind et al., 2021)

Phaseolus vulgaris L.	Cd, Ni, and Pb	-	Bio-Si-NPs (5.0 mmol/L) and potassium silicate (10 mmol/L)	- ↑ Plant growth and production, - ↑ chlorophylls, - ↑ carotenoids, - ↑ transpiration rate, - ↑ net photosynthetic rate, - ↑ stomatal conductance, - ↑ membrane stability index, - ↑ relative water content, - ↑ free proline, - ↑ total soluble sugars, - ↑ N, P, K, Ca^{2+}, K^{+}/Na^{+},	(El-Saadony et al., 2021)

					- ↑ activities of POD, CAT, APx, and SOD. - ↓ electrolyte leakage, - ↓ malondialdehyde, - ↓ H_2O_2, $O_2^{\bullet-}$, - ↓ Na^+, Pb, Cd, and Ni	
Heavy metal-induced stress	*Zea mays L. cv. Nootan* and *Z. mays L. hyb. Shaktiman-4*	Arsenate (As^V; 25 and 50 μM)	- Growth reduction - ↑ Oxidative stress - ↓ activities of APx, GRT, DhAR - ↑ SOD - ↓ Ascorbate and glutathione	10 μM	- ↑ Plant growth and yield - ↑ component of Ascorbate and glutathione cycle - ↑ activities of APx, GRT, DhAR	(Tripathi et al., 2016)

	wheat (Triticum aestivum L.)	Cd	- ↑ Oxidative stress - ↑ H_2O_2 and superoxide - ↑ Electrolyte leakages	300 - 1200 mg/L	- Improved the dry biomass of the shoots, roots, spikes, and grains -enhance leaf gas exchanges - ↑ chlorophyll a and b - ↓ electrolyte leakages - ↑ SOD, POD activities - ↓ Cd content of shoots, roots, and grains	(Ali et al., 2019; Hussain et al., 2019)
	Tomato *(Solanum lycopersicum L.)*	arsenic (As) (3.2 mg L^{-1})	-↑ Arsenic bioaccumulation in roots, leaves, and stem - ↑ tomato yield at high conc	**250 and 1000 mg** $\mathbf{L^{-1}}$	- ↓ Arsenic translocation - ↓ Tomato yield - ↓ Root biomass - ↑ Photosynthetic pigments - ↑ CAT and APx activities	(González-Moscoso et al., 2022)

Coriander *(Coriandrum sativum L.)*	Lead (Pb) 500-1500 mg/kg of soil	- ↓ plant biomass and vitamin C - ↑ flavonoid, MDA - ↑ antioxidant enzyme activities - ↑ tissue Pb bioaccumulation	**1.5 mM (Foliar application)**	- ↓ Pb bioaccumulation - ↓ plant defense system - ↓ MDA - adjusted the POD, CAT, and SOD activities	(Fatemi et al., 2021)

dysfunction in banana which was corrected with Si-NP treatment. Specifically, increase in MDA and oxidative stress were corrected, evidenced by improved growth and yield (Mahmoud et al., 2020). Further, the post treatment of accumulation of Si-NPs in plant parts is considered advantageous to plant adaptation to drought stress (Alsaeedi et al., 2019).

Flooding is becoming a growing concern for plants, particularly in tropical regions. Flooding can lead to hypoxia in plants, causing oxidative and osmotic stress. In a recent study by Iqbal et al. (2021), simulated flooding conditions for Muscadine Grape (Muscadinia rotundifolia Michx.) resulted in hypoxia, increased oxidative markers, lipid oxidation, and reactive oxygen species (ROS). Additionally, an accumulation of osmolytes and inhibition of micronutrient uptake were observed. However, treating the flooded plants with Si-NPs restored their physiological and oxidative balance. Si-NPs were found to enhance the antioxidant defense system, increase osmoprotectants like proline and glycinebetaine, and improve nutrient uptake.

5. Hazard analysis for SI-NPs application in agroecosystem

The application of beneficial synthetic substances to the ecosystem sometimes constitutes a risk. Environmental risk assessment proceeds in four steps; hazard assessment, dose-response assessment, exposure assessment and risk characterization, aimed at risks evaluation with a view to alleviate the potential dangers (Rycroft et al., 2019). Ecotoxicity studies on the effect of chemicals substances on microbes, plants and entire niches are used to extrapolate the risks of human exposure. Mostly, the mechanism of the toxic effects of these substances depend on their adsorption and interaction with the cells, with cellular death, hibernation, death or migration among the identified consequences (Hegde et al., 2015).

In terms of Si-NPs, the risks of application centre on the nanoparticles and their tendency to adsorb to plant roots, with possibilities of clogging the pores to hamper nutrient transport (Cañas et al., 2008). Further, the risks of toxicity to biota including humans have been identified, owing to their broad applications in agriculture, heath and textile industries (Bhat *et al*., 2021). Though Si is considered beneficial to plants, the nanoparticles in Si-NPs tends to confer more toxicity comparatively, depending on charge, dispersity, size and shape (Fadeel & Garcia-Bennett, 2010).

Some of the risks associated with application of silicon-based nanoparticles have been reported. Si-NPs have been implicated in the reduction of carbon and nitrogen content of microbial biomass in the soil, it has been shown to modify the preferential microbial (bacterial) organization in the soil (Simonin & Richaume, 2015). Further, Si-NPs have led to reductios in the populations of N2 utilizing bacteria as well as cellulolytic, microscopic fungi and amylolytic bacteria.

Similarly, depletion in soil enzymes including peroxidase, polyphenoloxidase and urease have been reported due to Si-NPs (Lebedev et al., 2019). Further in the environmental community ladder, Si-NPs affect protein metabolism adversely, cause cyto- and geno-toxicity in earthworm and has been highlighted with synergistic toxicity with other contaminants (Lebedev et al., 2019; L. Zhang et al., 2017; Di Marzio et al., 2018). Overall, these could lead to a decrease in the soil community richness with consequences on soil structure and aggregate formation, modification of soil hydraulics and temperature conductivity (Maggi & Tang, 2021) The adherence of nanoparticles to plants leading to pores clogging has resulted in phytotoxicity in plants exposed to NP (Bhat et al., 2021). Another study has linked plant phytotoxicity to changes in soil pH due to Si-NPs treatment (Le et al., 2014). In dose response studies, a 250 to 500 mg/kg Si-NPs treatment induced phytotoxicity exceeding 20% (Lebedev et al., 2019), 100 mg/mL led to DNA damages in onions (Liman et al., 2020). Overall, the use of nanoparticles above 20 nm offers some respite from these short falls in the application of Si-NPs (Asgari et al., 2018).

6. Conclusion and future perspectives

Scientific developments have led to industrialization and urbanization, improving human living standards but also resulting in the discharge of pollutants into the environment. Potentially toxic elements (PTEs) are a major concern due to their harmful effects on health and the environment. Si-NPs have shown promise in removing PTEs and other contaminants, improving soil properties, and mitigating plant stress. PTEs come from natural and human activities and can bioaccumulate in the food chain, posing serious health risks. Traditional methods for PTE remediation have limitations, but the use of adsorbents like metal-organic frameworks has proven effective in treating polluted water. Si-NPs contribute to plant growth and development by enhancing seed germination, improving soil fertility, and resisting pesticide residues. They also promote the growth of beneficial microorganisms in the rhizosphere and help plants withstand abiotic stress. Si-NPs can reduce heavy metal uptake in plants, improve photosynthetic efficiency, and protect against heat stress. In agriculture, Si-NPs have various applications, including as fertilizers, herbicides, and pesticides. They can also be used for targeted delivery of agrochemicals and as nanosensors for detecting heavy metals in soil. The use of Si-NPs has the potential to revolution but there is need for further research to harness these valuable scientific tools maximally.

References

Adeel, M., Ma, C., Ullah, S., Rizwan, M., Hao, Y., Chen, C., Jilani, G., Shakoor, N., Li, M., Wang, L., Tsang, D. C. W., Rinklebe, J., Rui, Y., & Xing, B. (2019). Exposure to nickel oxide nanoparticles insinuates physiological, ultrastructural and oxidative damage: A life cycle study on Eisenia fetida. *Environmental Pollution*, *254*, 113032. https://doi.org/10.1016/J.ENVPOL.2019.113032

Adeel, M., Tingting, J., Hussain, T., He, X., Ahmad, M. A., Irshad, M. K., Shakoor, N., Zhang, P., Changjian, X., Hao, Y., Zhiyong, Z., Javed, R., & Rui, Y. (2020). Bioaccumulation of ytterbium oxide nanoparticles insinuate oxidative stress, inflammatory, and pathological lesions in ICR mice. *Environmental Science and Pollution Research*, *27*(26), 32944–32953. https://doi.org/10.1007/S11356-020-09565-8/FIGURES/5

alengabawy. (n.d.).

Alsaeedi, A., El-Ramady, H., Alshaal, T., El-Garawany, M., Elhawat, N., & Al-Otaibi, A. (2019). Silica nanoparticles boost growth and productivity of cucumber under water deficit and salinity stresses by balancing nutrients uptake. *Plant Physiology and Biochemistry*, *139*, 1–10. https://doi.org/10.1016/J.PLAPHY.2019.03.008

Angulo-Bejarano, P. I., Puente-Rivera, J., & Cruz-Ortega, R. (2021). Metal and Metalloid Toxicity in Plants: An Overview on Molecular Aspects. *Plants (Basel, Switzerland)*, *10*(4). https://doi.org/10.3390/plants10040635

Asgari, F., Majd, A., Jonoubi, P., & Najafi, F. (2018). Effects of silicon nanoparticles on molecular, chemical, structural and ultrastructural characteristics of oat (Avena sativa L.). *Plant Physiology and Biochemistry*, *127*, 152–160. https://doi.org/10.1016/J.PLAPHY.2018.03.021

Astuti, R. D. P., Mallongi, A., Choi, K., Amiruddin, R., Hatta, M., Tantrakarnapa, K., & Rauf, A. U. (2022). Health risks from multiroute exposure of potentially toxic elements in a coastal community: a probabilistic risk approach in Pangkep Regency, Indonesia. *Geomatics, Natural Hazards and Risk*, *13*(1), 705–735. https://doi.org/10.1080/19475705.2022.2041110

Azimi, R., Borzelabad, M. J., Feizi, H., & Azimi, A. (2014). Interaction of SiO2 nanoparticles with seed prechilling on germination and early seedling growth of tall wheatgrass (Agropyron Elongatum L.). *Polish Journal of Chemical Technology*, *16*(3), 25–29. https://doi.org/10.2478/PJCT-2014-0045

Banerjee, A., Singh, A., Sudarshan, M., & Roychoudhury, A. (2021). Silicon nanoparticlepulsing mitigates fluoride stress in rice by fine-tuning the ionomic and metabolomic balance and refining agronomic traits. *Chemosphere*, *262*, 127826. https://doi.org/10.1016/J.CHEMOSPHERE.2020.127826

Banerjee, R., Gouda, H., & Pillay, S. (2021). Redox-Linked Coordination Chemistry Directs Vitamin B(12) Trafficking. *Accounts of Chemical Research*, *54*(8), 2003–2013. https://doi.org/10.1021/acs.accounts.1c00083

Bansal, K., Hooda, V., Verma, N., Kharewal, T., Tehri, N., Dhull, V., & Gahlaut, A. (2022). Stress Alleviation and Crop Improvement Using Silicon Nanoparticles in Agriculture: a Review. *Silicon*, *14*(16), 10173–10186. https://doi.org/10.1007/S12633-022-01755-Y/METRICS

Bhat, J. A., Rajora, N., Raturi, G., Sharma, S., Dhiman, P., Sanand, S., Shivaraj, S. M., Sonah, H., & Deshmukh, R. (2021). Silicon nanoparticles (SiNPs) in sustainable agriculture: Major emphasis on the practicality, efficacy and concerns. *Nanoscale Advances*, *3*(14), 4019–4028. https://doi.org/10.1039/d1na00233c

Cañas, J. E., Long, M., Nations, S., Vadan, R., Dai, L., Luo, M., Ambikapathi, R., Lee, E. H., & Olszyk, D. (2008). Effects of functionalized and nonfunctionalized single-walled carbon nanotubes on root elongation of select crop species. *Environmental Toxicology and Chemistry*, *27*(9), 1922–1931. https://doi.org/10.1897/08-117.1

Chaturvedi, P., Chowdhary, P., Singh, A., Chaurasia, D., Pandey, A., Chandra, R., & Gupta, P. (2021). Dissemination of antibiotic resistance genes, mobile genetic elements, and efflux genes in anthropogenically impacted riverine environments. *Chemosphere*, *273*, 129693. https://doi.org/10.1016/J.CHEMOSPHERE.2021.129693

Chen, L., Beiyuan, J., Hu, W., Zhang, Z., Duan, C., Cui, Q., Zhu, X., He, H., Huang, X., & Fang, L. (2022). Phytoremediation of potentially toxic elements (PTEs) contaminated soils using alfalfa (Medicago sativa L.): A comprehensive review. *Chemosphere*, *293*(December 2021), 133577. https://doi.org/10.1016/j.chemosphere.2022.133577

Chen, R., Zhang, C., Zhao, Y., Huang, Y., & Liu, Z. (2018). Foliar application with nano-silicon reduced cadmium accumulation in grains by inhibiting cadmium translocation in rice plants. *Environmental Science and Pollution Research*, *25*(3), 2361–2368. https://doi.org/10.1007/S11356-017-0681-Z/FIGURES/3

Cowan, N., Blair, D., Malcolm, H., & Graham, M. (2021). A survey of heavy metal contents of rural and urban roadside dusts: comparisons at low, medium and high traffic sites in Central Scotland. *Environmental Science and Pollution Research*, *28*(6), 7365–7378. https://doi.org/10.1007/s11356-020-11081-8

Dhakate, P., Kandhol, N., Raturi, G., Ray, P., Bhardwaj, A., Srivastava, A., Kaushal, L., Singh, A., Pandey, S., Chauhan, D. K., Dubey, N. K., Sharma, S., Singh, V. P., Sahi, S., Grillo, R., Peralta-Videa, J., Deshmukh, R., & Tripathi, D. K. (2022). Silicon nanoforms in crop improvement and stress management. *Chemosphere*, *305*, 135165. https://doi.org/10.1016/J.CHEMOSPHERE.2022.135165

Di Marzio, W., Curieses, S., Scodeller, P., Alberdi, J., & Sáenz, M. (2018). Cyto and Genotoxicity of Positive and Negative Coated Silica Nanoparticles on Celomocytes of Earthworms Eisenia fetida (Oligochaeta, Annelida). *Advances in Environmental Studies*, *2*(2), 74–81. https://doi.org/10.36959/742/205

Dong, Y., Gao, M., Qiu, W., & Song, Z. (2021). Effect of microplastics and arsenic on nutrients and microorganisms in rice rhizosphere soil. *Ecotoxicology and Environmental Safety*, *211*, 111899. https://doi.org/10.1016/j.ecoenv.2021.111899

Dvorak, P., Roy, K., Andreji, J., Liskova, Z. D., & Mraz, J. (2020). Vulnerability assessment of wild fish population to heavy metals in military training area: Synthesis of a framework with example from Czech Republic. *Ecological Indicators*, *110*, 105920. https://doi.org/10.1016/J.ECOLIND.2019.105920

El-Saadony, M. T., Desoky, E. S. M., Saad, A. M., Eid, R. S. M., Selem, E., & Elrys, A. S. (2021). Biological silicon nanoparticles improve Phaseolus vulgaris L. yield and minimize its contaminant contents on a heavy metals-contaminated saline soil. *Journal of Environmental Sciences*, *106*, 1–14. https://doi.org/10.1016/J.JES.2021.01.012

Enechi, O. C., Okeke, E. S., Isiogugu, O. N., Umeh, B. U., Eze, C. G., Emencheta, S. C., Ezeorba, T. P., Izuchukwu, C., Agbo, N. C., Ugwu, L., & Iloh, C. V. (2022). Evaluation of the anti-inflammatory and antioxidant properties of flavonoid-rich seed extract of buchholzia coriacea engler (Capparaceae). *Tropical Journal of Natural Product Research*, *6*(10), 1727–1732. https://doi.org/10.26538/TJNPR/V6I10.29

Fadeel, B., & Garcia-Bennett, A. E. (2010). Better safe than sorry: Understanding the toxicological properties of inorganic nanoparticles manufactured for biomedical applications. *Advanced Drug Delivery Reviews*, *62*(3), 362–374. https://doi.org/10.1016/j.addr.2009.11.008

Farhangi-Abriz, S., & Torabian, S. (2018). Nano-silicon alters antioxidant activities of soybean seedlings under salt toxicity. *Protoplasma*, *255*(3), 953–962. https://doi.org/10.1007/S00709-017-1202-0/FIGURES/3

Ghori, N. H., Ghori, T., Hayat, M. Q., Imadi, S. R., Gul, A., Altay, V., & Ozturk, M. (2019). Heavy metal stress and responses in plants. *International Journal of Environmental Science and Technology*, *16*(3), 1807–1828. https://doi.org/10.1007/s13762-019-02215-8

Guillevic, F., Rossi, M., Develle, A. L., Spadini, L., Martins, J. M. F., Arnaud, F., & Poulenard, J. (2023). Pb dispersion pathways in mountain soils contaminated by ancient mining and smelting activities. *Applied Geochemistry*, *150*(June 2022). https://doi.org/10.1016/j.apgeochem.2022.105556

Hasanuzzaman, M., Bhuyan, M. H. M. B., Zulfiqar, F., Raza, A., Mohsin, S. M., Al

Mahmud, J., Fujita, M., & Fotopoulos, V. (2020). Reactive Oxygen Species and Antioxidant Defense in Plants under Abiotic Stress: Revisiting the Crucial Role of a Universal Defense Regulator. *Antioxidants*, *9*(8), 1–52. https://doi.org/10.3390/ANTIOX9080681

Hegde, K., Goswami, R., Sarma, S. J., Veeranki, V. D., Brar, S. K., & Surampalli, R. Y. (2015). Environmental hazards and risks of nanomaterials. *Nanomaterials in the Environment*, *November*, 357–382. https://doi.org/10.1061/9780784414088.ch14

Hou, Q., Yang, Z., Yu, T., You, Y., Dou, L., & Li, K. (2020). Impacts of parent material on distributions of potentially toxic elements in soils from Pearl River Delta in South China. *Scientific Reports*, *10*(1), 1–13. https://doi.org/10.1038/s41598-020-74490-2

Hu, B., Shao, S., Ni, H., Fu, Z., Huang, M., Chen, Q., & Shi, Z. (2021). Assessment of potentially toxic element pollution in soils and related health risks in 271 cities across China. *Environmental Pollution*, *270*, 116196. https://doi.org/10.1016/j.envpol.2020.116196

Huang, H., Lin, K., Lei, L., Li, Y., Li, Y., Liang, K., Shangguan, Y., & Xu, H. (2023). Microbial response to antimony-arsenic distribution and geochemical factors at arable soil around an antimony mining site. *Environmental Science and Pollution Research*, *0123456789*. https://doi.org/10.1007/s11356-023-25507-6

Inobeme, A. (2021). *Effect of Heavy Metals on Activities of Soil Microorganism*. 115–142. https://doi.org/10.1007/978-981-15-7459-7_6

Ismail, L. M., Soliman, M. I., Abd El-Aziz, M. H., & Abdel-Aziz, H. M. M. (2022). Impact of Silica Ions and Nano Silica on Growth and Productivity of Pea Plants under Salinity Stress. *Plants 2022, Vol. 11, Page 494*, *11*(4), 494. https://doi.org/10.3390/PLANTS11040494

Jeong, H., Choi, J. Y., & Ra, K. (2021). Potentially toxic elements pollution in road deposited sediments around the active smelting industry of Korea. *Scientific Reports*, *11*(1), 1–12. https://doi.org/10.1038/s41598-021-86698-x

Kah, M., Tufenkji, N., & White, J. C. (2019). Nano-enabled strategies to enhance crop nutrition and protection. *Nature Nanotechnology 2019 14:6*, *14*(6), 532–540. https://doi.org/10.1038/s41565-019-0439-5

Kumar, A., & Sharma, P. (2022). Impact of Climate Variation on Agricultural Productivity and Food Security in Rural India. *SSRN Electronic Journal*. https://doi.org/10.2139/SSRN.4144089

Kumar, S., Singh, R., Venkatesh, A. S., Udayabhanu, G., & Singh, T. B. N. (2022). Assessment of Potentially Toxic Elements Contamination on the Fertile Agricultural Soils Within Fluoride-Affected Areas of Jamui District, Indo-Gangetic Alluvial Plains, India. *Water, Air, and Soil Pollution*, *233*(2). https://doi.org/10.1007/s11270-021-05488-3

Kumawat, K. C., Razdan, N., & Saharan, K. (2022). Rhizospheric microbiome: Bio-based emerging strategies for sustainable agriculture development and future perspectives. *Microbiological Research*, *254*(October 2021), 126901. https://doi.org/10.1016/j.micres.2021.126901

Le, V. N., Rui, Y., Gui, X., Li, X., Liu, S., & Han, Y. (2014). Uptake, transport, distribution and Bio-effects of SiO2 nanoparticles in Bt-transgenic cotton. *Journal of Nanobiotechnology*, *12*(1), 1–15. https://doi.org/10.1186/s12951-014-0050-8

Lebedev, S. V., Gavrish, I. A., Galaktionova, L. V., Korotkova, A. M., & Sizova, E. A. (2019). Assessment of the toxicity of silicon nanooxide in relation to various components of the agroecosystem under the conditions of the model experiment. *Environmental Geochemistry and Health*, *41*(2), 769–782. https://doi.org/10.1007/s10653-018-0171-3

Li, Y. J., Wang, Z. K., Qin, F. X., Fang, Z. Q., Li, X. L., & Li, G. (2018). Potentially Toxic Elements and Health Risk Assessment in Farmland Systems around High-Concentrated Arsenic Coal Mining in Xingren, China. *Journal of Chemistry*, *2018*. https://doi.org/10.1155/2018/2198176

Liman, R., Acikbas, Y., Ciğerci, İ. H., Ali, M. M., & Kars, M. D. (2020). Cytotoxic and Genotoxic Assessment of Silicon Dioxide Nanoparticles by Allium and Comet Tests. *Bulletin of Environmental Contamination and Toxicology*, *104*(2), 215–221. https://doi.org/10.1007/s00128-020-02783-3

Liu, P., Zhang, Y., Feng, N., Zhu, M., & Tian, J. (2020). Potentially toxic element (PTE) levels in maize, soil, and irrigation water and health risks through maize consumption in northern Ningxia, China. *BMC Public Health*, *20*(1), 1–13. https://doi.org/10.1186/s12889-020-09845-5

Liu, W., Wang, K., Hao, H., Yan, Y., Zhang, H., Zhang, H., & Peng, C. (2023). Predicting potential climate change impacts of bioenergy from perennial grasses in 2050. *Resources, Conservation and Recycling*, *190*(March 2022), 106818. https://doi.org/10.1016/j.resconrec.2022.106818

Liu, W., Zhang, L., Wu, H., Wang, Y., Zhang, Y., Xu, J., Wei, D., Zhang, R., Yu, Y., Wu, D., & Xie, X. (2023). Strategy for cost-effective BMPs of non-point source pollution in the small agricultural watershed of Poyang Lake: A case study of the Zhuxi River. *Chemosphere*, *333*, 138949. https://doi.org/https://doi.org/10.1016/j.chemosphere.2023.138949

Lowry, G. V, Avellan, A., & Gilbertson, L. M. (2019). in the agri-tech revolution. *Nature Nanotechnology*, *14*(June). https://doi.org/10.1038/s41565-019-0461-7

Maggi, F., & Tang, F. H. M. (2021). Estimated decline in global earthworm population size caused by pesticide residue in soil. *Soil Security*, *5*(March), 100014.

https://doi.org/10.1016/j.soisec.2021.100014

Mahmoud, L. M., Dutt, M., Shalan, A. M., El-Kady, M. E., El-Boray, M. S., Shabana, Y. M., & Grosser, J. W. (2020). Silicon nanoparticles mitigate oxidative stress of in vitro-derived banana (Musa acuminata 'Grand Nain') under simulated water deficit or salinity stress. *South African Journal of Botany*, *132*, 155–163. https://doi.org/10.1016/J.SAJB.2020.04.027

Malyugina, S., Skalickova, S., Skladanka, J., Slama, P., & Horky, P. (2021). Biogenic Selenium Nanoparticles in Animal Nutrition: A Review. *Agriculture 2021, Vol. 11, Page 1244*, *11*(12), 1244. https://doi.org/10.3390/AGRICULTURE11121244

Mejias, J. H., Salazar, F., Pérez Amaro, L., Hube, S., Rodriguez, M., & Alfaro, M. (2021). Nanofertilizers: A Cutting-Edge Approach to Increase Nitrogen Use Efficiency in Grasslands. *Frontiers in Environmental Science*, *9*, 52. https://doi.org/10.3389/FENVS.2021.635114/BIBTEX

Mhete, M., Eze, P. N., Rahube, T. O., & Akinyemi, F. O. (2020). Soil properties influence bacterial abundance and diversity under different land-use regimes in semi-arid environments. *Scientific African*, *7*. https://doi.org/10.1016/j.sciaf.2019.e00246

Modabberi, S., Tashakor, M., Sharifi Soltani, N., & Hursthouse, A. S. (2018). Potentially toxic elements in urban soils: source apportionment and contamination assessment. *Environmental Monitoring and Assessment*, *190*(12). https://doi.org/10.1007/s10661-018-7066-8

Mukarram, M., Khan, M. M. A., & Corpas, F. J. (2021). Silicon nanoparticles elicit an increase in lemongrass (Cymbopogon flexuosus (Steud.) Wats) agronomic parameters with a higher essential oil yield. *Journal of Hazardous Materials*, *412*, 125254. https://doi.org/10.1016/J.JHAZMAT.2021.125254

Nweze, E. J., Ubani, C. S., Okeke, E. S., Ezeorba, T. P. C., & Arazu, A. V. (2022). Health

Risk Assessment of Heavy Metals Associated with Terminalia catappa Fruit Consumption Obtained from an Automobile Workshop Cluster in Nsukka, Nigeria. *Current Applied Science and Technology*, *22*(2). https://doi.org/10.4314/EJESM.V3I3.63962

Okagu, I. U., Ohanenye, I. C., Ezeorba, T. P. C., & Udenigwe, C. C. (2021). Phytoglycoproteins and Human Health: Current Knowledge and Future Applications. *Applied Sciences 2021, Vol. 11, Page 5532*, *11*(12), 5532. https://doi.org/10.3390/APP11125532

Okeke, E. S., Ezeorba, T. P. C., Mao, G., Chen, Y., Feng, W., & Wu, X. (2022). Nano-enabled agrochemicals/materials: Potential human health impact, risk assessment, management strategies and future prospects. *Environmental Pollution*, *295*, 118722. https://doi.org/10.1016/J.ENVPOL.2021.118722

Okeke, E. S., Okagu, I. U., Okoye, C. O., & Ezeorba, T. P. C. (2022). The use of calcium carbide in food and fruit ripening: Potential mechanisms of toxicity to humans and future prospects. *Toxicology*, *468*, 153112. https://doi.org/10.1016/J.TOX.2022.153112

Palansooriya, K. N., Shaheen, S. M., Chen, S. S., Tsang, D. C. W., Hashimoto, Y., Hou, D., Bolan, N. S., Rinklebe, J., & Ok, Y. S. (2020). Soil amendments for immobilization of potentially toxic elements in contaminated soils: A critical review. *Environment International*, *134*(April 2019), 105046. https://doi.org/10.1016/j.envint.2019.105046

Pandey, N., & Tiwari, A. (2021). Human health risk assessment of heavy metals in different soils and sediments. *Heavy Metals in the Environment: Impact, Assessment, and Remediation*, 143–163. https://doi.org/10.1016/B978-0-12-821656-9.00008-0

Pu, J., Ma, J., Li, J., Wang, S., & Zhang, W. (2023). Organosilicon and inorganic silica inhibit polystyrene nanoparticles uptake in rice. *Journal of Hazardous Materials*, *442*, 130012. https://doi.org/10.1016/J.JHAZMAT.2022.130012

Rastogi, A., Tripathi, D. K., Yadav, S., Chauhan, D. K., Živčák, M., Ghorbanpour, M., El-Sheery, N. I., & Brestic, M. (2019). Application of silicon nanoparticles in agriculture. *3 Biotech*, *9*(3), 1–11. https://doi.org/10.1007/S13205-019-1626-7/TABLES/3

Rastogi, A., Zivcak, M., Sytar, O., Kalaji, H. M., He, X., Mbarki, S., & Brestic, M. (2017). Impact of metal and metal oxide nanoparticles on plant: A critical review. *Frontiers in Chemistry*, *5*, 78. https://doi.org/10.3389/FCHEM.2017.00078/BIBTEX

Rui, M., Ma, C., White, J. C., Hao, Y., Wang, Y., Tang, X., Yang, J., Jiang, F., Ali, A., Rui, Y., Cao, W., Chen, G., & Xing, B. (2018). Metal oxide nanoparticles alter peanut (Arachis hypogaea L.) physiological response and reduce nutritional quality: a life cycle study. *Environmental Science: Nano*, *5*(9), 2088–2102. https://doi.org/10.1039/C8EN00436F

Rycroft, T., Hamilton, K., Haas, C. N., & Linkov, I. (2019). A quantitative risk assessment method for synthetic biology products in the environment. *The Science of the Total Environment*, *696*, 133940. https://doi.org/10.1016/j.scitotenv.2019.133940

Savchenko, T., & Tikhonov, K. (2021). Oxidative Stress-Induced Alteration of Plant Central Metabolism. *Life*, *11*(4). https://doi.org/10.3390/LIFE11040304

Sharma, B., Tiwari, S., Kumawat, K. C., & Cardinale, M. (2023). Nano-biofertilizers as bio-emerging strategies for sustainable agriculture development: Potentiality and their limitations. *Science of the Total Environment*, *860*(September 2022), 160476. https://doi.org/10.1016/j.scitotenv.2022.160476

Sharma, P., Singh, S. P., Parakh, S. K., & Tong, Y. W. (2022). Health hazards of hexavalent chromium (Cr (VI)) and its microbial reduction. *Https://Doi.Org/10.1080/21655979.2022.2037273*, *13*(3), 4923–4938. https://doi.org/10.1080/21655979.2022.2037273

Siddiqui, A. U., Jain, M. K., & Masto, R. E. (2022). Distribution of some potentially toxic elements in the soils of the Jharia Coalfield: A probabilistic approach for source identification and risk assessment. *Land Degradation and Development*, *33*(2), 333–345. https://doi.org/10.1002/ldr.4155

Siddiqui, H., Ahmed, K. B. M., Sami, F., & Hayat, S. (2020). *Silicon Nanoparticles and Plants: Current Knowledge and Future Perspectives*. 129–142. https://doi.org/10.1007/978-3-030-33996-8_7

Simonin, M., & Richaume, A. (2015). Impact of engineered nanoparticles on the activity, abundance, and diversity of soil microbial communities: a review. *Environmental Science and Pollution Research*, *22*(18), 13710–13723. https://doi.org/10.1007/s11356-015-4171-x

Singh, A., Chauhan, S., Varjani, S., Pandey, A., & Bhargava, P. C. (2022). Integrated approaches to mitigate threats from emerging potentially toxic elements: A way forward for sustainable environmental management. *Environmental Research*, *209*(December 2021), 112844. https://doi.org/10.1016/j.envres.2022.112844

SONOWAL, S., NAVA, A. R., JOSHI, S. J., BORAH, S. N., ISLAM, N. F., PANDIT, S., PRASAD, R., & SARMA, H. (2022). Biosurfactant-assisted phytoremediation of potentially toxic elements in soil: Green technology for meeting the United Nations Sustainable Development Goals. *Pedosphere*, *32*(1), 198–210. https://doi.org/10.1016/S1002-0160(21)60067-X

Speirs, L. B. M., Rice, D. T. F., Petrovski, S., & Seviour, R. J. (2019). The Phylogeny, Biodiversity, and Ecology of the Chloroflexi in Activated Sludge. *Frontiers in Microbiology*, *10*(September). https://doi.org/10.3389/fmicb.2019.02015

Sunday, E., Valerie, C., Ethel, N., Obinwanne, C., Emmanuel, C., Nwankwo, I., & Joshua, C. (2022). Heliyon Microbial ecology and evolution is key to pandemics : using the coronavirus model to mitigate future public health challenges. *Heliyon*, *8*(May), e09449.

https://doi.org/10.1016/j.heliyon.2022.e09449

Sunday Okeke, E., John Nweze, E., Samuel Ubani, C., Prince Chidike Ezeorba, T., & Vivian Arazu, A. (2021). Health Risk Assessment of Heavy Metals Associated with Terminalia catappa Fruit Consumption Obtained from an Automobile Workshop Cluster in Nsukka, Nigeria. *Current Applied Science and Technology*, *22*(2), 1–15. https://doi.org/10.55003/cast.2022.02.22.006

Suriyaprabha, R., Karunakaran, G., Yuvakkumar, R., Rajendran, V., & Kannan, N. (2014). Foliar Application of Silica Nanoparticles on the Phytochemical Responses of Maize (Zea mays L.) and Its Toxicological Behavior. *Http://Dx.Doi.Org/10.1080/15533174.2013.799197*. https://doi.org/10.1080/15533174.2013.799197

Taydé, N., Wong, R., Patricia, B., Vázquez, C., Alonso, J., Duarte, Y., Alejandra, M., Mondragón, C., Kidd, K. A., Shumilin, E., & Arellano, M. (2023). Human health risk assessment of metals and arsenic via consumption of commercial bivalves in the Gulf of California , Mexico. *Environmental Science and Pollution Research*. https://doi.org/10.1007/s11356-023-25841-9

Thind, S., Hussain, I., Rasheed, R., Ashraf, M. A., Perveen, A., Ditta, A., Hussain, S., Khalil, N., Ullah, Z., & Mahmood, Q. (2021). Alleviation of cadmium stress by silicon nanoparticles during different phenological stages of Ujala wheat variety. *Arabian Journal of Geosciences*, *14*(11), 1–15. https://doi.org/10.1007/S12517-021-07384-W/TABLES/5

Tsoraeva, E., Bekmurzov, A., Kozyrev, S., Khoziev, A., & Kozyrev, A. (2020). Environmental issues of agriculture as a consequence of the intensification of the development of agricultural industry. *E3S Web of Conferences*, *215*, 02003. https://doi.org/10.1051/E3SCONF/202021502003

Van Groenigen, J. W., Van Groenigen, K. J., Koopmans, G. F., Stokkermans, L., Vos, H. M. J., & Lubbers, I. M. (2019). How fertile are earthworm casts? A meta-analysis. *Geoderma*, *338*(July 2018), 525–535. https://doi.org/10.1016/j.geoderma.2018.11.001

Vats, S., Kumawat, S., Brar, J., Kaur, S., Yadav, K., Magar, S. G., Jadhav, P. V, Salvi, P., Sonah, H., Sharma, S., & Deshmukh, R. (2022). Opportunity and challenges for nanotechnology application for genome editing in plants. *Plant Nano Biology*, *1*, 100001. https://doi.org/https://doi.org/10.1016/j.plana.2022.100001

Vejvodová, K., Ash, C., Dajčl, J., Tejnecký, V., Johanis, H., Spasić, M., Polák, F., Praus, L., Borůvka, L., & Drábek, O. (2022). Assessment of potential exposure to As, Cd, Pb and Zn in vegetable garden soils and vegetables in a mining region. *Scientific Reports*, *12*(1), 1–9. https://doi.org/10.1038/s41598-022-17461-z

Wang, M., Gao, L., Dong, S., Sun, Y., Shen, Q., & Guo, S. (2017). Role of silicon on plant–pathogen interactions. *Frontiers in Plant Science*, *8*, 701. https://doi.org/10.3389/FPLS.2017.00701/BIBTEX

Wang, S., Wang, L., Huan, Y., Wang, R., & Liang, T. (2022). Concentrations, spatial distribution, sources and environmental health risks of potentially toxic elements in urban road dust across China. *Science of the Total Environment*, *805*, 150266. https://doi.org/10.1016/j.scitotenv.2021.150266

Wang, Y., Jiang, F., Ma, C., Rui, Y., Tsang, D. C. W., & Xing, B. (2019). Effect of metal oxide nanoparticles on amino acids in wheat grains (Triticum aestivum) in a life cycle study. *Journal of Environmental Management*, *241*, 319–327. https://doi.org/10.1016/J.JENVMAN.2019.04.041

Weissengruber, L., Möller, K., Puschenreiter, M., & Friedel, J. K. (2018). Long-term soil accumulation of potentially toxic elements and selected organic pollutants through application of recycled phosphorus fertilizers for organic farming conditions. *Nutrient*

Cycling in Agroecosystems, *110*(3), 427–449. https://doi.org/10.1007/s10705-018-9907-9

Xavier, J. C., Costa, P. E. S., Hissa, D. C., Melo, V. M. M., Falcão, R. M., Balbino, V. Q., Mendonça, L. A. R., Lima, M. G. S., Coutinho, H. D. M., & Verde, L. C. L. (2019). Evaluation of the microbial diversity and heavy metal resistance genes of a microbial community on contaminated environment. *Applied Geochemistry*, *105*, 1–6. https://doi.org/10.1016/J.APGEOCHEM.2019.04.012

Xun, E., Zhang, Y., Zhao, J., & Guo, J. (2018). Heavy metals in nectar modify behaviors of pollinators and nectar robbers: Consequences for plant fitness. *Environmental Pollution*, *242*, 1166–1175. https://doi.org/10.1016/j.envpol.2018.07.128

Zhang, C., Zou, X., Yang, H., Liang, J., & Zhu, T. (2022). Bioaccumulation and Risk Assessment of Potentially Toxic Elements in Soil-Rice System in Karst Area, Southwest China. *Frontiers in Environmental Science*, *10*(April), 1–12. https://doi.org/10.3389/fenvs.2022.866427

Zhang, L., Duan, X., He, N., Chen, X., Shi, J., Li, W., Xu, L., & Li, H. (2017). Exposure to lethal levels of benzo[a]pyrene or cadmium trigger distinct protein expression patterns in earthworms (Eisenia fetida). *Science of the Total Environment*, *595*(1), 733–742. https://doi.org/10.1016/j.scitotenv.2017.04.003

Zhang, X., Tian, K., Wang, Y., Hu, W., Liu, B., Yuan, X., Huang, B., & Wu, L. (2023). Identification of sources and their potential health risk of potential toxic elements in soils from a mercury-thallium polymetallic mining area in Southwest China: Insight from mercury isotopes and PMF model. *Science of The Total Environment*, *869*(January), 161774. https://doi.org/10.1016/j.scitotenv.2023.161774

Zhao, S., Zhang, Q., Liu, M., Zhou, H., Ma, C., & Wang, P. (2021). Regulation of Plant Responses to Salt Stress. *International Journal of Molecular Sciences*, *22*(9), 4609.

https://doi.org/10.3390/IJMS22094609

Zhao, W., Teng, M., Zhang, J., Wang, K., Zhang, J., Xu, Y., & Wang, C. (2022). Insights into the mechanisms of organic pollutant toxicity to earthworms: Advances and perspectives. *Environmental Pollution*, *303*, 119120. https://doi.org/10.1016/J.ENVPOL.2022.119120