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Electronic Supplementary Information

Foliar application of nanoparticles: Mechanism of absorption, transfer, and multiple impacts

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Table S1. Effects of foliar applications of engineered nanoparticles on plants. References follow those in the main text.

Nanoparticles	Concentration	Plant	Effects	Particle size	Ref
Citrate-Au NPs	280 ng per plant	Wheat (*Triticum aestivum* cv. cumberland), foliar exposure	1) Mainly accumulating on the outside of the plant leaves; 2) Overall neutral or beneficial impacts.	Size (3, 10, or 50 nm)	23
PVP-Au NPs (Polyvinylpyrrolidone)	280 ng per plant		1) Crossing the cuticle layer and interacting with (in or on) the mesophyll cells; 2) Impairing leaf photosynthesis.	Size (3, 10, or 50 nm)	
Ceria NPs	0, 40, 80, 160 mg Ce L^{-1}	Common bean (*Phaseolus vulgaris*), foliar application	1) Dose-dependent oxidative damages in the leaves; 2) Ce^{3+} ions were significantly more toxic than equimolar ceria NPs.	6.9 ± 0.4 nm by TEM; Hydrodynamic diameter: 40.2 ± 7.2 nm	12
Ce^{3+} ions	0, 40, 80, 160 mg Ce L^{-1}				
As NPs	0, 10, 50 mg per plant	Spinach (*Spinacia oleracea*), foliar application	1) Plant dry biomass (up to 84%) and pigment contents (up to 38%) were reduced significantly; 2) Antioxidative enzymes activities were increased (SOD, CAT, POD).	Lying in the range of 40–60 nm	24

PbO NPs	0, 10, 50 mg per plant	Spinach, foliar application	1) Significantly decreased in pigment contents and dry weight; 2) Activation of antioxidative enzymes were induced; 3) ROS production and lipid peroxidation did not alter.	Particle size < 100 nm.	13
Au NPs (Green-Synthesized)	Au in the Au NP priming solution was 5.4 μgmL^{-1}	Onion seeds. (*Allium cepa* L.)	1) Significant change in emergence percentage; 2) Increased chlorophyll content in the leaves and reduced pungency level in the bulbs.	93.68 ± 2.06 nm	53
Ag^0 NPs	10 mg mL^{-1}	Rice (*Oryza sativa* L.), root surface of wetland plants	1) Iron plaque had contrasting effects: Ag uptake was enhanced upon Ag_2S NP exposure but inhibited upon Ag^0 NP exposure; 2) Ag NP phytoavailability to wetland plants depends on Ag NP species (Ag^0 NPs vs. Ag_2S NPs) and the amount of iron plaque; 3) Ag^0 NPs were more bioavailable than Ag_2S NPs.	Average diameter of 12.2 ± 3.1 nm measured by TEM; 20.3 ± 1.4 nm measured by spICP-MS	33
Ag_2S NPs	100 mg mL^{-1}			83.7 ± 24.7 nm measured by TEM; average size was 73.0 ± 1.5 nm measured by spICP-MS	

Ag NPs (used for comparison with the uptake and accumulation of Ag via root exposure)	0.1, 0.5, and 1 mg L^{-1}	Lettuce (*Lactuca sativa*)	1) The Ag NPs (particle) contributed more to toxicity than Ag NPs (ion); 2) Adverse impacts on the growth; 3) Root exposure to Ag NPs had a stronger negative effect than foliar exposure when biomass was selected as the endpoint of assessment.	Nominal size of 20 nm;	5
Ag NPs (used to study the effects of foliar application)	1, 10, and 50 mg L^{-1}		3) Enrichment factors of Ag NPs (total): root exposure > foliar exposure > exposure via single leaf immersion.		
Au NP coated with citrate	100 mg L^{-1}	Broad bean (*Viciafaba* cv. Windsor), leaves via drop deposition	Randomly covered the plant leaves.	TEM diameter: 12.6 ± 1.0 nm	40
Au NP coated with bovine serum albumin (BSA)			Specific affinity for trichomes.	TEM diameter: 14.0 ± 1.0 nm	
Au NP coated with LM6-M			Strongly adhered to the stomata and remained on the leaf surface.	TEM Diameter: 11.6 ± 1.2 nm	
Ag@$CoFe_2O_4$ NPs	0, 5, 10, 25, 50, 100, and 200 mg kg^{-1}	Wheat seeds (*Triticum aestivum* var. Roelfs).	1) Seed germination was not affected; 2) Seedling growth diminished; 3) Oxidative damage by reactive	SEM: lesser agglomeration particles of ~10 nm	27

			oxygen species generation.		
ZnO NPs	1000, 2000 mg L^{-1}	Habanero pepper plants (*Capsicum chinense* Jacq.), foliar applications	1) 1000 mg L^{-1} positively affected plant height, stem diameter, chlorophyll content, and increased fruit yield and biomass accumulation; 2) 2000 mg L^{-1} negatively affected plant growth but significantly increased fruit quality, content of total phenols and total flavonoids in fruits, which resulted in higher antioxidant capacity.	Most of the particles (75%) had diameters of 12 to 24 nm	14
CeO_2 NPs	50 mg L^{-1}	Monocotyledons (Corn (*Zea mays* cv. Trinity), Rice (*Oryza sativa* cv. Nipponbare)); Dicotyledons (Tomato (*Solanum lycopersicum* cv. Roma), Lettuce (*Lactuca sativa* cv. Buttercrunch))	1) Positively charged CeO_2 NPs associated to the roots more than the negatively charged NPs; 2) Positive NPs remained primarily adhered to the roots untransformed, the neutral and negative NPs were more efficiently translocated from the roots to shoots; 3) Positive and neutral Ce clusters outside of the main vasculature in the mesophyll; negative primarily in the main vasculature of the leaves.	~4 nm	30
SiO_2 NPs	300 ppm	Sugarcane (*Saccharum officinarum* L.),	1) Reduced the adverse effects of chilling by maintaining the maximum photochemical efficiency;	5–15 nm	16
ZnO NPs	50 ppm			<100 nm	

Se NPs	15 ppm	foliar application	2) Light harvesting pigments (chlorophylls and carotenoids) content were increased; 3) SiO_2 NPs showed higher amelioration effects.	100 mesh	
Graphene nanoribbons (GNRs)	50 ppm			2–15 µm × 40–250 nm	
TiO_2 NPs	0, 100, 250 mg L^{-1}	Maize (*Zea mays* L.), foliar exposure	1) Foliar exposure to TiO_2 NPs significantly reduced the uptake and translocation of Cd and TiO_2 NPs; 2) Root exposure to TiO_2 NPs exerted greater phytotoxicity to maize, and lead to the NPs accumulation in the aerial part of plants;	6.5 ± 0.76 nm	25
CeO_2 NPs	0, 50, and 250 mg L^{-1}	Tomato (*Solanum lycopersicum*)	1) 250 mg L^{-1} increased the fruit dry weight and lycopene content in infested plants; 2) Minimal negative effects of CeO_2 NPs on the nutritional value of tomato fruit while simultaneously suppressing Fusarium wilt disease.	Primary size of 8 ± 1 nm	30
Si NPs	5, 10, and 20 mg L^{-1}	Rice (*Oryza sativa* L.), foliage application	1) Combined application of Se and Si was more effective in reducing the Cd and Pb contents; 2) Foliar application of both NPs	18.04 ± 3 nm	16
Se NPs				12.26 ± 2 nm	

			improved the rice growth and quality; 3) Foliage supplementation of Se and Si NPs alleviate the Cd and Pb toxicity.		
TiO_2 NPs	Control, sole Cd treatment, Cd+100 mg nTiO_2 L^{-1} and Cd+200 mg nTiO_2 L^{-1}	Cowpea (*Vigna unguiculata* (L.) Walp.), foliar-intervention	1) Significantly promoted chlorophyll b and total chlorophyll contents after Cd stress; 2) Promoted stress enzymes activity in both roots and leaves; 3) Significant ameliorative potential for Cd toxicity.	<100 nm	25
La_2O_3 NPs	0, 5, 10 , 50 mg L^{-1}	C_3 (Soybean (*Glycine max* (L.) Merr.)), C_4 (Maize (*Zea mays* L.))	1) Net photosynthetic rate was reduced significantly by 8.77% and 55.52% in soybean and maize; 2) Inhibited the photosynthesis of soybean by hindering the light utilization and electron transport, maize was mainly restricted carbon fixation.	Sizes of the rod-shaped La_2O_3 NPs range from 30 nm to 150 nm by TEM	28
CdS NPs	0, 10, and 100 mg CdS NPs per kg soil	Broad bean (*Vicia faba* L.)	1) Several antioxidative metabolites were significant up-regulation; 2) Plants reprogram of carbon and nitrogen metabolism alleviated the toxicity of CdS NPs.	Hydrodynamic diameter: 140–615 nm with an average of 294 nm; 10 to 100 nm as determined by	128

				TEM	
Zn NPs (green synthesis)	0, 1000, 2000, and 4000 ppm	Basil (*Ocimum basilicum* L.), foliar application	1) Significantly affected concentrations of total chlorophyll and carotenoid in the leaves; 2) Obtaining better quantity and quality in basil; 3) Significantly affected morphological and biochemical attributes.	less than 100 nm (SEM)	54
Cu NPs (green synthesis)					