**Nanofertilizer possibilities for healthy soil, water and food in future: an overview**

**Supplementary Table 1.** Role of nanofertilizers on sustainable agriculture

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Stress condition | Plant | NFs | Concentration range | Impacts | Source |
| Drought | Soybean (*Glycine max* (L.) Merr.) | nCeO2 (+ charge) /PVP-CeO2 (-charge) | 100 ppm | Significantly enhanced efficiency of leaf gas exchange. Both NPs enhanced plant growth activities and yield. | Cao et al., 2018 |
| - | Radish (*Raphanus sativus* L.) | nCeO2 | 0 – 100 ppm | Enhanced plant weight, root area expansion (2%), photosynthetic pigments (12 – 13%), and enzyme activities in plant organs, i.e., roots and leaves | Gui et al., 2017 |
| - | Rice (*Oryza sativa* L.) | nCeO2 | 500 ppm | Rice grains decreased the Fe, S, prolamin, glutelin, lauric, valeric acids, starch and K, Ca, Na, protein albumin, and total sugars upregulated | Rico et al., 2013 |
| - | Wheat (*Triticum aestivum* L.) | nCeO2 | 0 - 500 ppm | The 1-generation (G) decreased the uptake of Ce, Fe, and Mn in plant roots. Treated plants in both generations found seeds with minimum Mn, Ca, K, Mg, and P content compared to 2G stressed plants. 1-G affects the plant morpho-physiological responses and nutritional profile of the 2-G plants | Rico et al., 2017 |
| - | Lettuce (*Lactuca sativa* L.) | nCeO2 | 50-1000 ppm | Excess application of NPs significantly decreased plant development, yield, and enzymatic activities disrupted | Gui et al., 2015 |
| - | Maize (*Zea mays* L.) | nCuO | 0.02–8 ppm | Improved plant growth parameters (51%), increased Cu uptake and accumulation. The activity of glucose-6-phosphate dehydrogenase was effectively enhanced in foliar and soil irrigation. nCu also boosted the growth and associated enzymes in maize plants. | Adhikari et al., 2016 |
| - | Soybean (*Glycine max* L.) | nCuO | 50-500 ppm | The size and range of NPs treatment depend on the severity of the toxicity. Changed antioxidative biomarkers with NPs application. | Yusefi-Tanha et al., 2020 |
| - | Tomato (*Solanum**lycopersicum* L.)  | nCuO | 10–500 ppm | Slightly enhanced the photosynthetic pigments and sugar content at 10 ppm. Then, these parameters declined after increasing the NPs. Enhanced enzymatic activities,  | Singh et al., 2017 |
| - | Cauliflower(*Brassica oleracea* var. botrytis) | nCuO | 10–500 ppm | Growth parameters, leaf chlorophyll index, and soluble sugar level were enhanced (10 ppm) relative to normal plants—application-dependent upregulation found in enzymatic responses. | Singh et al., 2017 |
| 1. Cu toxicity
 | 1. Barley
2. (*Hordeum sativum* distichum)
 | nCuO | 1000 ppm | Loss in germination rate, time, growth, development, changes in root morphological behavior, biomass, maximum chlorophyll fluorescence yield of PSII, and photosynthetic efficiency. nCuO affect the root, stomatal and cellular ultrastructure. The Cu content was found higher than normally grown plants. | Rajput et al., 2018a |
| - | Kidney bean(*Phaseolus vulgaris* L.) | nCu/ kinetin | 50, 100 ppm | Chlorophyll (22-30%) and minerals as Ca, Mn, and P (33-97%) were decreased, and enhanced root Cu uptake | Apodaca et al., 2017 |
| - | Maize (*Zea mays* L.) | nCu-chitosan | 400-1200 ppm | Increased growth and development by enhancing the activities of α-amylase and starch levels. | Saharan et al., 2016 |
| - | Tomato (*Solanum**lycopersicum* L.) | nCu–chitosan-PVA | 0.02–10 ppm | Enhanced solid content, titratable acidity, lycopene (37%), and enzymatic activities in fruits (10%). Significantly increased plant growth responses and fruit quality. The enhancement was found in leaf area expansion (17%), clusters (13%), and roots dry mass (30%).  | Hernandez et al., 2017 |
| Drought | Barley (*Hordeum vulgare*L.) | nChitosan | 30-90 ppm | Enhanced LRWC, the weight of seeds, seed protein, proline, SOD, and CAT activities  | Behboudi et al., 2018 |
| - | Wheat(*Triticum aestivum* L.) | nChitosan-NPK | 10–100 ppm | Enhanced the plant performance, harvest/crop index, and yield production concerning normal plants. | Abdel-Aziz et al., 2016 |
| As toxicity | Maize (*Zea mays* L.) | nSiO2 | 10 ppm | Reduce metal toxicity and uptake and increase the ascorbate-glutathione cycle. It is more effective to mitigate metal toxicity in maize plants | Tripathi et al., 2016 |
| Salinity | Strawberry(*Fragaria x ananassa*) | nSiO2 | 50-100 ppm | Development of vegetative growth phase enhanced, upregulated photosynthetic pigments, LRWC (%), canopy temperature (54%), and proline content (81%) | Avestan et al., 2019 |
| Salinity | Tomato (*Solanum lycopersicum* L.) | nSiO2 | 30-180 ppm | Stress-related genes were noted as up (AREB, TAS14, NCED3 & CRK1) and downregulated (RBOH1, APX2, MAPK2, ERF5, MAPK3 & DDF2) to assist in the alleviation of stress | Almutairi, 2016 |
| - | Cotton (*Gossypium* spp.) | nSiO2 | 10 -2000 ppm | Reduced plant growth biomass and affected the nutrient elements, i.e., Cu, Mg in shoots, and Na in roots. SOD and IAA content were significantly affected, SiNPs were found in the xylem sap, and roots transported from roots-shoots via xylem sap. | Le et al., 2014 |
| Drought | Barley (*Hordeum vulgare* L.) | nSiO2 | 125 – 250 ppm | Increased plant morpho-physiological, chlorophyll content (17%), enzymatic, and metabolic activities. | Ghorbanpour et al., 2020 |
| Drought  | Cotton (*Gossypium* spp.) | nSiO2 | 3200 ppm | Maintained plant performance and productivity. | Shallan et al., 2016 |
| Salinity and drought | Banana (*Musa acuminate* L.) Grand Nain | nSiO2 | 200-600 ppm | Improved plant development, photosynthetic efficiency (23%), balance K+/ Na+ ratio (14%), and reduced cell damage injury. | Mahmoud et al., 2020 |
| Freezing  | Sugarcane (*Saccharum officinarum* L.) | nSio2, nZnO, nSe and Graphene nanoribbons (GNRs) | 5-15 nm, < 100 nm, 100 mesh & 2-15 µm x 40-250 nm | NPs decreased the negative effects of freezing by upgrading the chlorophyll fluorescence yield (*Fv/Fm*), maximum photo-oxidizable PSI (Pm), and photosynthesis. The applied NPs enhanced the light-harvesting pigments in treated plants. The highest carotenoid increased the nonphotochemical quenching of photosystem II.  | Elsheery et al., 2020 |
| Heat  | Wheat (*Triticum aestivum* L.) | nSiO2 | ~ 100 ppm | Potentially restored the cellular ultrastructural distortions of the organelles such as chloroplast and the nucleus—enhanced photosynthesis as revealed by enhancement in PS II and chlorophyll content efficiency. The loss in MDA content significantly correlated with the cell membrane stability index.  | Younis et al., 2020 |
| UV-B  | Wheat (*Triticum aestivum* L.) | nSiO2 | 10 ppm | The improved antioxidative enzymatic machinery | Tripathi et al., 2017 |
|  | Spinach (*Spinacia oleracea* L.) | nFe2O3 | 100–200 ppm | Plant biomass and Fe accumulation upregulated concerning normal plants. | Jeyasubramanian et al., 2016 |
| Salinity | Peppermint (*Mentha piperita* L.) | nFe2O3 | 10-30 ppm | Decreased MDA and proline content and enhanced antioxidative enzymatic activities. An appropriate dose of NPs could be used for stress tolerance strategies | Askary et al., 2017 |
| - | Soybean (*Glycine max* L.) | nFe2O3 | 30-60 ppm | Positively enhanced the plant developmental stages and chlorophylls. | Ghafariyan et al., 2013 |
| - | Peanut (*Arachis hypogaea* L.) | nFe2O3 | 0-1000 ppm | Upgraded plant development and dry mass, leaf chlorophyll index plant hormones, enzymatic activities, and Fe uptake. | Rui et al., 2016 |
| - | Soybean (*Glycine max* L.) | nFe2O3 | 0-1000 ppm | Enhanced plant biomass, productivity (48%), and Zn accumulation | Sheykhbaglou et al., 2010 |
| - | Corn (*Zea mays* L.) | γ- Fe2O3 NPs | 20 ppm | Improved germination (27%), vigor index (40%), frequency, time, and root development (12%). Minimum concentration of NPs showed significant impacts on plant performance | Li et al., 2016 |
| - | Peanut (*Arachis hypogaea* L.) | γ- Fe2O3 NPs | 2 ppm | Upgraded photosynthetic CO2 assimilation rate and plant productivity | Alidoust and Isoda, 2013 |
| Flooding | Soybean (*Glycine max* L.) | nAl2O3 | 50 ppm | Enhanced length of seedlings and upregulated mitochondrial membrane protein | Mustafa and Komatsu, 2016 |
| Salinity | Tomato (*Solanum esculentum* Mill.) | nTiO2 | 0 - 40 ppm | Enhanced the carbonic anhydrase, NR, SOD, POX, accumulation of proline, glycine betaine, growth, and biomass activities. | Khan, 2016 |
| - | Barley (*Hordeum vulgare* L.) | nTiO2 | 0 - 1000 ppm | Improved amino acids (37-51%) and crude protein. Zn and Mn accumulation levels increased. | Poscic et al., 2016 |
| Drought | Linum (*Linum usitatissimum* L.) | nTiO2 | 10-500 ppm | Enhanced green pigments and carotenoids levels, reduced H2O2 and MDA content | Aghdam et al., 2016 |
| Drought | Wheat (*Triticum aestivum*L.) | nTiO2 | 100-300 ppm | Plant performance, productivity, and gluten content improved | Jaberzadeh et al., 2013 |
| Drought | Wheat (*Triticum aestivum* L.) | nTiO2 | 500-2000 ppm | Increased plant biomass, LRWC, activities of antioxidative enzymes, leaf pigments, and photosynthetic efficiency | Faraji and Sepehri, 2020 |
| Freezing  | Chickpea (*Cicer arietinum* L.) | nTiO2 | 2-10 ppm | Reduced membrane injury index and MDA contents | Mohammadi et al., 2013 |
| - | Peppermint (*Mentha piperita* L.) | nTiO2 | 0-250 ppm | Improved the growth, biomass, productivity (105%), leaf gas exchange (24%), Fv/ Fm (7%), photosynthetic pigments, and enzymatic and non-enzymatic activities, i.e., nitrate reductase (18%) and carbonic anhydrase (19%) | Ahmad et al., 2018 |
| 1. -
 | 1. Cucumber (*Cucumis sativus* L.)
 | nFe3O4 | 50 – 2000 ppm | Increase plant fitness, yield, and enzymatic capacities such as SOD and POD. Applied NPs enhance/ balance the proper nutrient management to overcome food security and safety. | Konate et al., 2018 |
| 1. Drought
 | 1. Strawberry (*Fragaria x ananassa* Duch.)
 | nFe3O4 | 0.8 ppm | Increased plant performance | Mozafari et al., 2018 |
| 1. -
 | 1. Ryegrass (*Lolium perenne* L.)
 | nFe3O4 | 30-500 ppm | Enhanced enzymatic and non-enzymatic activities, such as SOD, CAT, and MDA | Wang et al., 2011 |
| 1. -
 | 1. Barley
2. (*Hordeum vulgare* L.)
 | nFe3O4 | 125-1000 ppm | Increasing the concentration of nFe3O4­ was significantly enhanced the plant growth parameters with biomass (leaf-19%, root-88%). Even at applied excess quantity, no toxic effects were observed—significantly increased photosynthetic pigments, soluble protein, and no. of chloroplasts. Higher range of NPs reduced CAT and H2O2 content. Dramatic variations were found in the photosynthetic genes such as *Pet*A, *psa*A, BCA, and *psb*A. | Tombuloglu et al., 2019 |
| - | Common bean(*Phaseolus vulgaris* L.) | nAg | 0 – 60 ppm | Enhanced growth traits, biomass, productivity, balance plant hormones, and overall plant performance against normal plants | El-Batal et al., 2016 |
| Heat  | Wheat (*Triticum aestivum* L.) | nAg | 25-100 ppm | Upgraded length of stem (22%), roots (5%), leaf area (34%) and growth parameters, i.e. fresh (2%) & dry weight (0.60%) | Iqbal et al., 2019 |
| Salinity | Fenugreek (*Trigonella foenum-graecum* L.) | nAg | 10-40 ppm | Enhanced germination percentage, biomass, and productivity | Hojjat and Kamyab, 2017 |
| Flooding | Saffron (*Crocus sativus* L.) | nAg | 40 - 120 ppm | Enhanced growth characteristics with biomass yield | Rezvani et al., 2012 |
| Metal  | Cucumber (*Cucumis sativus* L.) | nAg | 300 ppm | Enhanced Ag content and growth and yield/ fruit capacity and quality | Shams et al., 2013 |
| - | Lettuce (*Lactuca sativa* L.) | nAg | 100 ppm | No phytotoxic symptoms were monitored. Ag significantly trapped on plant leaves. Entrapment of Ag-NPs penetration in the leaves by the stomatal cuticle. | Larue et al., 2014 |
| 1. -
 | 1. Soybean
2. (*Glycine max* (L.) Mell.)
 | nAg | 31.2 – 62.5 ppm | Downregulated plant performance and fixation of N.  | Ma et al., 2020 |
| 1. Heat
 | 1. Sorghum
2. (*Sorghum bicolor* (L.) Moench)
 | nSe | 10 ppm | Enhanced antioxidative defense systems and changes ultrastructural cell organelles  | Djanaguiraman et al., 2018a |
| 1. Low and high temperature
 | 1. Tomato (*Lycopersicum esculentum* Mill.)
 | nSe | 1-12 ppm | Increased plant growth, development, and productivity | Haghighi et al., 2014 |
| Heat | Corn (*Zea mays* L.) | nZnO | 50–1600 ppm | At various temperatures, nZnO enhanced the root growth (50%) morphology, Zn uptake, and APX activity (57%) | Lopez-Moreno et al., 2017 |
| - | Lettuce (*Lactuca sativa* L.) | nZnO | 1–100 ppm | Upgraded plant performance and photosynthesis, Zn uptake as relative to normal plants | Xu et al., 2018 |
| Mineral toxicity | Cotton(*Gossypium hirsutum* L.) | nZnO | 25–200 ppm | Positively enhanced plant growth (130%) and total biomass (131%), photosynthetic pigments (141%), carotenoids (139%), protein (179%), and antioxidant enzymes, i.e., POX (183%), SOD (264%) and reduced MDA content (68%). | Venkatachalam et al., 2017 |
| - | Pea (*Pisum sativum* L.) | nZnO | 250 - 1000 ppm | Enhance Zn level in roots and grains. Increased photosynthetic pigments, carotenoid, sucrose content, and overall plant development. | Mukherjee et al., 2016 |
| - | Pearl Millet (*Pennisetum americanum*) | nZn | Particle size 15 – 25 nm | Positively improved growth, biomass, pigments, and biochemical activities | Tarafdar et al., 2014 |
| - | Tomato (*Lycopersicum esculentum* Mill.) | nZnO | 2–16 ppm | Positively enhanced the plant performance, photosynthesis with carbonic anhydrase, and antioxidative enzyme activities of concentration- and time-dependent variables relative to normal plants. | Faizan et al., 2018 |
| - | Thalecress (*Arabidopsis thaliana* L.) | nAu | 10 - 80 ppm | Improve germination efficiency, growth rate, free radical scavenging responses. Overall plant productivity enhanced | Kumar et al., 2013 |
| Salinity | Cucumber (*Cucumis sativus* L.) | Mn3O4 | 20, 100 ppm | Increase plant performance, photosynthetic level, photosynthetic CO2 assimilation rate, and yield biomass. Improve endogenous antioxidative defense systems. | Lu et al., 2020 |
| - | Black-eyed peas (*Vigna unguiculata* L.) | nMg | 0.5 ppm | Enhanced photosynthetic performance and yield parameters | Delfani et al., 2014 |
| - | Mung bean (*Vigna radiata* L.) | Quantum dots | 50-75 ppm | Enhanced photosynthetic capacity by enhancing electron transfer rate (ETR) in thylakoid membranes | Chandra et al., 2014 |
| Control condition | Arabidopsis (*Arabidopsis thaliana* L.) | Functional carbon nanodots (FCNs) | 200-500 ppm | The positive correlation was found between the physiological traits of plants and the surface chemistries of NMs. The raw FCNs present maximum promotion capacity in plants biomass and length of roots, and the quantum-sized FCNs are easier to be absorbed by plants and generate more significant impacts on plants | Chen et al., 2020 |
| - | Lettuce (*Lactuca sativa* L.) | FCNs | 104-1750 ppm | Decreased length of roots at long-term duration | Canas et al., 2008 |
| - | Bitter melon(*Momordica charantia* L.) | Fullerol [C60(OH)20] | 943-47200 ppm | Enhanced plant growth, yield (54%), water content (24%), fruit number (59%), length (20%) and weight of the fruits (70%), increased anticancerous plant medicines, such as cucurbitacin-B (74%) and lycopene (82%), and antidiabetic plant medicines, i.e., charantin (20%) and insulin (91%) | Kole et al., 2013 |
| - | Corn (*Zea mays* L.) | Fullerenes C60 | 500 ppm | Plant biomass decreased (37%) | Torre-Roche et al., 2013 |
| - | Cabbage (*Brassica oleracea* L.*)*, Carrot (*Daucus carota* L.), Lettuce (*Lactuca sativa* L.), Onion (*Allium cepa* L.), Tomato (*Solanum lycopersicum* L.) | FCNs (single-walled) | 9, 56, 315, 1750 ppm | No effect | Canas et al., 2008 |
| - | Rice (*Oryza sativa* L.*)* | Single-walled carbon nanotube | 400 ppm | Reduces growth, productivity, and delayed flowering | Lin et al., 2009 |
| - | Mung (*Vigna radiata* L.) | CNPs | 25-200 ppm | Significantly increase growth, biomass (1.2 fold), yield, chlorophyll content (2 fold), protein (1.14 fold), proline, and antioxidative enzyme activities, such as SOD, GPX, APX, enhance stress-resistance capacity and phytoremediation efficiency of plants in the contaminated soil and/ or environment | Shekhawat et al., 2021 |
| - | Wheat (*Triticum aestivum* L.), Maize (*Zea mays* L.), Peanut (*Arachis hypogaea* L.), Garlic (*Allium sativum* L.) | MW-CNTs | 0-50 ppm | The significant effects were found in the root and shoot development of plants. The low concentration of CNTs was more efficient for plant performance | Srivastava and Rao, 2014 |

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