Assessment of photo-modulation, nutrient-use efficiency and toxicity of iron nanoparticles in Vigna radiata (2019)

Effect of FeNP and Fe on root and shoot length, fresh and dry weight of 15 days treated mung bean plants. Data represent means ± standard errors (no. of samples = 25).

Treatment	Control	0.05 mg/L	0.1 mg/L	0.5 mg/L	1 mg/L
Root length (cm)					
FeNP	3.98 ± 0.477	7.01 ± 0.45	6.65 ± 0.45	5.67 ± 0.32	4.01 ± 0.29
Fe		5.94 ± 0.01	4.23 ± 0.29	3.58 ± 0.27	1.99 ± 0.01
Shoot length (cm)					
FeNP	5.60 ± 0.294	7.98 ± 0.50	7.02 ± 0.45	6.37 ± 0.29	6.01 ± 0.15
Fe		6.33 ± 0.35	5.89 ± 0.12	4.28 ± 0.29	3.78 ± 0.014
Fresh weight (g)					
FeNP	0.29 ± 0.004	0.42 ± 0.001	0.39 ± 0.005	0.31 ± 0.009	0.30 ± 0.001
Fe		0.34 ± 0.007	0.31 ± 0.09	0.22 ± 0.01	0.19 ± 0.001
Dry weight (g)					
FeNP	0.017 ± 0.004	0.040 ± 0.004	0.032 ±0.001	0.030 ± 0.001	0.028 ±0.002
Fe		0.032 ± 0.003	0.025 ±0.0001	0.019 ± 0.0001	0.011 ±0.0001

To check the effect of FeNPs and Fe, treatments were started on 7 day old mung bean plants under identical experimental conditions in the laboratory for 15 days. The plants were uprooted thereafter to carry out the initial morphological assessment. In the treated plants, 0.05 mg L^{-1} FeNPs showed prominent improvement in all aspects of morphological parameters with respect to control and Fe treatments. Even at higher concentrations, FeNP treated plants did not show any kind of toxic effect unlike Fe treated plants. All FeNP treated plants were healthy and no notable symptoms of chlorosis or necrosis were observed.

Source: https://pubs.rsc.org/en/content/articlelanding/2019/en/c9en00559e/unauth#!divAbstract

Siderophore-Producing Rhizobacteria as a Promising Tool for Empowering Plants to Cope with Iron Limitation in Saline Soils: A Review (2019)

Studies providing experimental evidence of positive effects of plant growth-promoting rhizobacteria (PGPR) on salt-stressed plants

Study	PGPR	Plant(s)	Positive effect(s)
Gutiérrez Mañero	*Aureobacterium* spp., *Cellulomonas* spp.	Wild lupine	**Germination, root surface, N_2 fixation**
***et al.* (2003)**			
Vivas *et al.* (2003)	*Bacillus* sp., *Glomus* sp.	Lettuce	**Stomatal conductance**
Ashraf *et al.* (2004)	*Bacillus* sp., *Aeromonas hydrophila*,	Wheat	**Rhizospheric soil aggregation around**
	Aeromonas caviae		**roots, dry matter yield of roots and shoots, Na^+ exclusion**
Cheng *et al.* (2007)	*Pseudomonas putida*	Canola	**Salt tolerance, 1-aminocyclopropane-**
			1-carboxylate (ACC) deaminase
Saravanakumar and	*Pseudomonas fluorescens*	Groundnut	**Salt tolerance, ACC deaminase**
Samiyappan (2007)			
Estevez *et al.* (2009)	*Chryseobacterium balustinum*,	Common bean,	**Growth, N_2 fixation**
	Rhizobium tropici	soybean	
Naz *et al.* (2009)	Strains Rkh1–Rkh4	Soybean	**Growth, proline content**
Tank and Saraf	*Pseudomonas aeruginosa*, *Pseudomonas*	Tomato	**Root and shoot length, ACC deaminase,**
(2010)	*fluorescens*, *Pseudomonas stutzeri*		**indole-3-acetic acid (IAA), phosphate**
			solubilization, siderophores
Tiwari *et al.* (2011)	*Bacillus pumilus*, *Halomonas* sp.,	Wheat	**Root and shoot biomass, chlorophyll,**
	Arthrobacter sp.		**carotenoids, protein, IAA, ionic balance**
Ramadoss *et al.*	*Halobacillus* spp., *Bacillus*	Wheat	**Root length, dry weight**
(2013) **Younesi and Moradi**	*halodenitrificans* *Pseudomonas fluorescens*	Common bean	**Shoot biomass, proline, K^+, superoxide dis-**
(2014)			**mutase and catalase activities, Na^+ exclusion**
Mahmood *et al.*	*Enterobacter cloacae*, *Bacillus*	Mung bean	**Seed yield, dry biomass, plant height, leaf**
(2016)	*drentensis*		**area, relative water content, chlorophyll,**
			carotenoids, stomatal conductance,
			transpiration, salt tolerance
Khalid *et al.* (2017)	***Azospirillum brasilense***	**White clover**	**Phenols, polyphenols**

Source: https://sci-hub.tw/https://doi.org/10.1016/S1002-0160(19)60810-6

Vetiver grass is a potential candidate for phytoremediation of iron ore mine spoil dumps (2019)

Relative translocation (TF) and bioaccumulation (BF) of heavy metals in vetiver varieties (S2, S4, TH, and BL) grown on iron mine overburden soil.

	Time (Months)	Vetiver varieties	Treatment condition	Fe	Cu	Zn	Cr	Mn
TF	6	S2	Garden soil	0.434	1.289	0.389	0.422	0.699
			Mine soil	0.319	1.288	0.419	0.525	0.765
		S4	Garden soil	0.358	1.369	0.483	0.752	0.475
			Mine soil	0.301	1.345	0.605	0.679	0.457
		TH	Garden soil	0.374	1.355	0.436	0.471	0.627
			Mine soil	0.332	0.841	0.541	0.652	0.798
		BL	Garden soil	0.272	0.847	0.482	0.673	0.347
			Mine soil	0.335	0.828	0.582	0.494	0.457
	12	S2	Garden soil	0.272	1.604	0.480	0.607	0.583
			Mine soil	0.427	1.511	0.290	0.420	0.574
		S4	Garden soil	0.216	0.935	0.377	0.526	0.691
			Mine soil	0.283	1.578	0.419	0.543	0.437
		TH	Garden soil	0.304	1.230	0.424	0.713	0.630
			Mine soil	0.265	0.987	0.375	0.521	0.599
		BL	Garden soil	0.213	0.931	0.333	0.618	0.524
			Mine soil	0.300	0.972	0.403	0.329	0.343
BF_{shoot}	6	S2	Garden soil	0.236	0.935	0.087	0.158	0.185
			Mine soil	0.025	1.273	0.078	0.035	0.240
		S4	Garden soil	0.266	1.746	0.081	0.212	0.129
			Mine soil	0.025	1.645	0.085	0.035	0.156
		TH	Garden soil	0.248	1.167	0.080	0.207	0.180
			Mine soil	0.028	1.013	0.096	0.039	0.249
		BL	Garden soil	0.315	1.399	0.088	0.162	0.132
			Mine soil	0.029	1.253	0.091	0.031	0.184
	12	S2	Garden soil	0.350	1.815	0.152	0.451	0.312
			Mine soil	0.067	3.437	0.140	0.070	0.432
		S4	Garden soil	0.373	2.245	0.138	0.403	0.269
			Mine soil	0.054	4.441	0.154	0.070	0.280
		TH	Garden soil	0.409	1.910	0.147	0.461	0.260
			Mine soil	0.048	2.734	0.174	0.078	0.448
		BL	Garden soil	0.446	2.697	0.134	0.413	0.252
			Mine soil	0.062	3.383	0.165	0.062	0.332
BF_{root}	6	S2	Garden soil	0.545	0.726	0.223	0.374	0.264
			Mine soil	0.078	0.989	0.186	0.067	0.314
		S4	Garden soil	0.743	1.276	0.168	0.282	0.271
			Mine soil	0.084	1.223	0.141	0.052	0.341
		TH	Garden soil	0.662	0.861	0.184	0.438	0.287
			Mine soil	0.086	1.204	0.178	0.060	0.312
		BL	Garden soil	1.160	1.652	0.181	0.241	0.379
			Mine soil	0.087	1.513	0.157	0.062	0.403
	12	S2	Garden soil	1.286	1.132	0.316	0.742	0.535
			Mine soil	0.157	2.274	0.484	0.166	0.754
		S4	Garden soil	1.728	2.401	0.365	0.767	0.389
			Mine soil	0.193	2.814	0.367	0.129	0.642
		TH	Garden soil	1.347	1.553	0.347	0.646	0.412
			Mine soil	0.181	2.769	0.463	0.150	0.748
		BL	Garden soil	2.092	2.897	0.402	0.668	0.481
			Mine soil	0.208	3.479	0.408	0.187	0.968

The ability of translocation of metals from root to shoot was assessed using TF expressed as the ratio of [Metal]shoot/ [Metal]root (Maiti and Nandhini, 2006). In most of the genotypes the TF values of the metals Fe, Zn, Cu, Mn and Cr were lower than 1.

Source: https://www.sciencedirect.com/science/article/abs/pii/S0925857418303896

Acquisition and Homeostasis of Iron in Higher Plants and Their Probable Role in Abiotic Stress Tolerance (2018)

Table 1: Iron nutrition and drought stress tolerance.

Mode of Fe application	Plant species	Plant attributes	References
Foliar application of Iron	Soybean	Improvements in yield	Kobraee et al., 2011; Afshar et al., 2013
Foliar application of Iron	Wheat crop	Increases in 1,000 seed weight	Arif et al., 2006; Afshar et al., 2013
Foliar application of Iron with Zinc	Cumin	Diminishes oxidative stress by reducing H_2O_2 content and lessening lipid peroxidation	Akbari et al., 2013
Iron with zinc Spray	Calendula officinalis	Improves the leaf characters (weight, area and numbers) resulting into enhancement in the effects triggered by drought stress	Pirzad and Shokrani, 2012
Iron application with sulfur	Sesame	Improves growth, nutrient, yield, and their components	Mostafa et al., 2011
Nano-iron application	Cowpea	Improvement of protein quality being advantageous in increasing resistance to drought stress	Parhamfar, 2006; Afshar et al., 2012
Fe spraying	Creeping Bentgrass	Modifies drought resistance through its effects on root growth	Snyder and Schmidt, 1974; Glinski et al., 1992
Iron application	Turf grasses	Leads to color enrichment and growth improvement in Fe-deficient conditions	Deal and Engel, 1965; Minner and Butler, 1984; Glinski et al., 1992
Iron application	Turf grass	Gives darker green color for cool-season in Fe-sufficient condition	Snyder and Schmidt, 1974; Carrow et al., 1988; Schmidt and Snyder, 1984; Yust et al., 1984; Wehner and Haley, 1990; Glinski et al., 1992
Iron application	Legumes	Positive responses to iron nutrition	Slatni et al., 2008; Rotaru, 2011
Application of Iron with Zinc	Rapeseed (*Brassica napus*)	Influence on prolin, protein and nitrogen related metabolism of leaf	Pourgholam et al., 2013
Iron Foliar Fertilization	Sunflower	Improves yield of oil and growth and development of seeds	Elanz et al., 2011

Table 2: Iron-mediated up-regulation of antioxidative enzymes (SOD, APX, and CAT) and heavy-metal stress tolerance.

Metals against which iron used	Antioxidant defense machinery and iron assimilatory enzymes and iron plaque	Plant species	Responses	References
Cd	Iron plaque	Rice	Promotes enhancement in iron uptake by plant; reduces the damaging effect of Cd; helps in their ultimate sequestration on the root surface	Liu et al., 2007, 2008
		Rice	Fe-plaque formation altered significantly the accumulation of Se in the aerial part of the plant	Xin-Bin and Wei-Ming, 2007
		Rice	Formation of plaque increases the sequestration of Pb on root surface; thereby prevents their uptake and accumulation of Se inside the plant	Liu et al., 2011
	Iron fertilizer (EDTA·Na_2Fe) and $FeSO_4$	Rice	Soil/foliar application of Fe fertilizer (EDTA·Na_2Fe) and $FeSO_4$ reduces the adverse effect of Cd on rice root, shoot and rice grains	Shao et al., 2008
	Fe-nutrition	Rice	Cd uptake and accumulation inside the plant could be reduced by modifying the iron status of soil	Shao et al., 2007
As	Fe plaque	Rice	Fe-plaque increases As (III and IV) adsorption and its translocation to shoot; decreases the effect of root anatomy characteristic, on As uptake inside the root	Deng et al., 2010
		Spirodela polyrhiza L.	Arsenate uptake occurred through the phosphate uptake pathways in *S. polyrhiza* by physico-chemical adsorption on Fe-plaques of plant surface as well	Rahmana et al., 2008
P	Fe plaque	*Pilea cadierei*	Such plant in wetland condition removes the phosphorus from Fe-rich soil, hence suitable for construction of artificial wetland	Yang et al., 2011

Source: https://www.frontiersin.org/articles/10.3389/fenvs.2017.00086/full

Role of Iron in Alleviating Heavy Metal Stress (2017)

Table 1: Role of Fe in alleviating heavy metals stress in different plants.

Fe dosage	HM conc.	Plant species	Effect	References
Fe + EDTA at 5, 10, 20 ppm	Cd at 0, 50, 100 µM	Rice (*Oryza sativa* L.)	Improve plant growth, leaf area, and leaf water content; reduce Cd toxic effects, decrease proline, MDA content, antioxidant enzyme activities	Ali et al. (2014)
Fe at 2.77, 5.54, and 8.31 µM	Cd and Pb at 10 µM	*Typha latifolia*	Decrease Cd and Pb uptake and translocation in plant shoots and roots, absorb Pb on roots at maximum Fe	Rodriguez-Hernandez et al. (2015)
Fe at 1.89 and 16.8 mg L^{-1}	Cd at 5 µM	Rice (*Oryza sativa* L.)	Increased MDA content, improve plant growth and SPAD value, enhanced antioxidant enzyme activities	Shao et al. (2007)
Fe at 0.54–2.6 mg kg^{-1}	Pb at 45–199 mg kg^{-1} Cd at 1.1–3.5 mg kg^{-1}	Rice plant tissues	Promote metal deposition on root surfaces, limit Pb and Cd translocation, and distribution in plant tissues	Cheng et al. (2014)
Fe at 10, 30,50, 80, and 100 mg L^{-1}	Cd at 0.1 and 1 mg L^{-1}	Rice (*Oryza sativa* L.)	Decrease Cd supply in shoots and roots, inhibit Cd uptake and translocation within rice plant, decrease radioactivity of ^{109}Cd in shoots of seedlings	Liu et al. (2007)
Fe at 10 and 250 µM	Cd at 25 µM	Barley	Enhance antioxidant enzyme activities, improve plant growth and biochemical parameters, reduce Cd toxic effects	Sharma et al. (2004)
Fe at 40 µM	Cd as $Cdcl_2$	Indian mustard	Reduce oxidative stress and metal toxicity, stabilize thylakoid complex, retention of chloroplast and chlorophyll contents	Qureshi et al. (2010)

Source: Z. ul Hassan et al. DOI 10.1007/978-3-319-58841-4_13

Responses of rice to chronic and acute iron toxicity: genotypic differences and biofortification aspects (2016)

Table 1: Statistical analysis of the effects of chronic and acute Fe toxicity on visible symptom formation and growth parameters of six different rice genotypes on eight measuring days.

Variable	DAT	ANOVA results (Pr > F)			LS means (Treatment)		
		Treatment	Genotype	Interaction	Control	Acute	Chronic
Leaf bronzing score	28	0.4999	<0.0001	0.0481	n.d.	2.5	1.3
	35	0.1861	<0.0001	0.3260	n.d.	3.0	1.2
	42	0.5102	<0.0001	0.3090	n.d.	0.5	0.7
	49	0.0006	<0.0001	0.0508	n.d.	0.3b	0.6a
	56	0.0004	<0.0001	0.0023	n.d.	0.2b	0.5a
	63	0.0368	<0.0001	0.0028	n.d.	0.2b	0.3a
	70	<0.0001	0.0588	0.2020	n.d.	0.1b	0.6a
	77	<0.0001	0.0869	0.1905	n.d.	0.0b	0.6a
Plant height (cm)	28	0.1708	<0.0001	0.0193	52.6	49.6	50.8
	35	0.0684	<0.0001	0.0216	64.6	60.4	62.0
	42	0.0066	<0.0001	0.0316	73.6a	68.6b	72.3ab
	49	0.0088	<0.0001	0.0881	82.5a	77.0b	81.7a
	56	0.0109	<0.0001	0.1035	97.3ab	93.1b	100.2a
	63	0.0258	<0.0001	0.2828	103.7ab	100.8b	107.2a
	70	0.0434	<0.0001	0.1187	107.5ab	104.9b	111.0a
	77	0.0390	<0.0001	0.1530	112.9ab	108.9b	115.9a
Tiller number	28	0.3391	<0.0001	0.2006	2.0	1.6	1.5
	35	0.0584	<0.0001	0.4206	4.0	3.1	3.2
	42	0.3226	<0.0001	0.3487	5.3	4.7	4.3
	49	0.1750	<0.0001	0.5816	8.2	7.0	6.7
	56	0.5095	<0.0001	0.5376	10.9	9.4	9.8
	63	0.7687	<0.0001	0.4203	11.8	11.0	11.3
	70	0.7640	<0.0001	0.3720	11.7	10.9	11.6
	77	0.6730	<0.0001	0.5650	11.6	10.8	11.3

LS means = least square means; DAT = days after transplanting. LS mean values not sharing the same superscript letter within one line differ significantly from each other at P < 0.05. n.d. = not determined

Table 2: Statistical analysis of the effects of acute and chronic Fe toxicity on yields and yield components of six different rice genotypes.

Variable	ANOVA results (Pr > F)			LS means (Treatment)		
	Treatment	Genotype	Interaction	Control	Acute	Chronic
Grain yield (t ha^{-1})	0.0001	<0.0001	0.2068	4.9[a]	4.8[a]	4.0[b]
Straw yield (t ha^{-1})	0.0684	<0.0001	0.3513	7.5	8.0	7.3
Harvest index	0.0019	<0.0001	0.1876	0.40[a]	0.38[a]	0.36[b]
Panicles (number m^{-2})	0.2641	<0.0001	0.4191	198	207	199
Grains per panicle	<0.0001	<0.0001	0.6232	156[a]	159[a]	145[b]
Spikelet sterility (%)	0.0148	<0.0001	0.0400	23[a]	27[ab]	30[b]
Thousand kernel weight (g)	0.0496	>0.0001	0.3029	20.6[a]	20.5[ab]	20.0[b]
Grain Fe concentration (mg kg^{-1})	0.4037	<0.0001	0.0004	30	34	33
Grain Zn concentration (mg kg^{-1})	0.3151	<0.0001	0.6365	21		

LS means = least square means; LS mean values not sharing the same superscript letter within one line differ significantly from each other at $P < 0.05$

Source: https://link.springer.com/article/10.1007/s11104-016-2918-x