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Agronomic biofortification of major cereals with zinc and iron- A review

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ABSTRACT

Humans around the world suffer from micronutrient deficiency due to an inadequate intake of essential micronutrients in the daily diet. Agronomic biofortification offers the easiest and the quickest way for biofortification of cereal grains with zinc, iron or other micro mineral nutrients in developing countries especially Asia and Africa, where cereals form the staples. It is the only approach to reach the poorest of the poor rural masses, who can't afford to buy mineral supplements nor can afford animal by-products. From the agronomic biofortification viewpoint, foliar application is better and requires lesser amount of zinc and iron fertilizers than their soil application. Even when cultivars or GM crops with higher zinc and iron content in grains are developed, adequate zinc and iron fertilization will be necessary. Thus, for the long term, agronomic biofortification is a complimentary approach to plant breeding as well as modern biotechnology for increased micronutrients in the food basket.

Key words: Biofortification, Iron, Maize, Pearl millet, Rice, Sorghum, Wheat, Zinc.

Two billion people (more than one-in-three) around the world suffer from micronutrient deficiency (FAO, 2013), caused due to an inadequate intake of essential micronutrients in the daily diet, also known as "Hidden Hunger". Hidden hunger is lack of vitamins and minerals and occurs when the quality of the food people consume doesn't meet their nutritional requirements, as such the food is deficient in micronutrients. Nearly half of the world's micronutrient deficient population lives in India (USAID OMNI, 2005). Every day, more than 6,000 children below the age of five die in India and more than half of these deaths are caused due to malnutrition mainly via lack of zinc, iron, vitamin A, iodine and folic acid (Kotecha, 2008). To combat these deficiencies we can adopt food diversity, supplementation and food fortification but alas, rural communities have a limited access to these three. Biofortification offers a sustainable solution to the escalating micronutrient deficiencies in the population, especially for the poor. Biofortification is a process of enhancing the density of vitamins and minerals in a crop through plant breeding, transgenic techniques, or agronomic practices (use of fertilizers). Among the types of biofortification, agronomic biofortification is a short term approach and the easiest of all to enhance the micronutrient content in the diet. As zinc and iron deficiencies have emerged globally, this paper attempts to address these two in terms of agronomic biofortification.

Zinc and Iron Deficiency

Zinc: Zn deficiency is more common in developing countries than in developed countries and the major cause behind this is the difference in diet composition. Globally, about 0.8 million people and nearly about 0.45 million children are at a risk of dying each year from zinc deficiency (WHO, 2002). It is estimated that about 50% of the cereal-cultivated soils globally are deficient in plant-available zinc, leading to reductions in crop production and also nutritional quality of the harvested grains (Cakmak, 2008). Takkar (1996) reported that 47% of Indian soils are deficient in Zn when an analysis of 2,33,003 soil samples was done from different states. Analysis of 25,000 plant samples collected from different states in India showed that 44% of the plant samples contained inadequate Zn (Singh, 2007). Indians practicing vegetarianism, especially suffer from Zn malnutrition who utterly rely on cereals and pulses. Processing of food grains also affects Zn concentration as in rice and as a result, parboiling is recommended before milling in rice to avoid micronutrient loss (Prasad, 2010). Cereal grains also contain phytates, which reduces the bio-availability of Zn. It was reported that PZMR (phytate: Zn molar ratio) of less than 15 is associated with good Zn availability, whereas a ratio above 15 is associated with reduced Zn availability.

Iron: Fe is an essential trace element for all organisms and is the fourth most abundant element (5%) in the earth's crust. It is the third most limiting nutrient for plant growth primarily due to the low solubility of the oxidized ferric form in the aerobic environment. Iron deficiency is a common nutritional disorder in many crop plants, causing chlorosis, poor yield and reduced nutritional quality (Zhang *et al.* 2008). Iron

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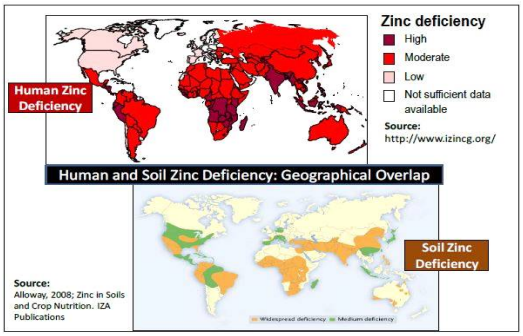
Table 1: Ten leading causes of illness and disease in low income countries (WHO, 2002).

Risk factors	Ratio (%)
Underweight	14.9
Unsafe sex	10.2
Unsafe water	5.5
Indoor smoke	3.7
Zinc deficiency	3.2
Iron deficiency	3.1
Vitamin A deficiency	3.0
Blood pressure	2.5
Tobacco	2.0
Cholesterol	1.9

Table 2: Global mortality in children under 5 years of age in 2004 (Prasad, 2010).

Deficiency	Deaths
Vitamin A	666,771
Zinc	453,207
Iron	20,854
Iodine	3,619

deficiency is a growing health concern in the developing world, and responsible for diverse of health complications including anaemia and impairments in immune system. More than 30% of the world's population has been reported to be anaemic (Stevens *et al*. 2013). Iron Deficiency Anaemia (IDA) contributes 50% of global anaemia (WHO, 2008). IDA can lead to maternal haemorrhage and is associated with 20% of all maternal death. In alkali soils, Fe availability is less because of its high pH and high bicarbonate concentration that lowers the solubility of Fe and reduces its uptake by plant roots. Several studies have indicated that soil application of inorganic Fe fertilizers to Fe deficient soil is usually ineffective because the applied Fe is quickly converted to unavailable Fe (III) forms.



Daily dietary allowances of zinc and iron: The RDA of Zinc (mg day^{-1}) for children (4–8 years) is 5 for adult males is 11 and for adult females is 8. The RDA of Iron (mg day^{-1}) for children (4–8 years is 10), for adult males is 8 and for adult females is 18 (USFNB, 2001). The intake of micronutrients in daily diet is far from satisfactory and largely less than 50% RDA is consumed by over 70% of Indian population (NNMB, 2002).

Agronomic biofortification: Agronomic biofortification of food crops is aimed to increase the micronutrient concentrations so as to reduce the dietary deficiency. Soil and foliar application of micronutrient fertilizers can be used for several different mineral micronutrients to varying effectiveness. The ferti-fortification of Zn is a promising and cost-effective measure to increase Zn concentration (agronomic biofortification) in cereal grain to combat Zn malnutrition (Rakshit *et al.* 2013; Singh and Prasad, 2014). Agronomic biofortification of some major cereals is discussed as under:

Rice: Soil application of Zn had very little effect on increasing Zn concentrations of brown rice while as foliar Zn application resulted in a much greater increase (Wissuwa *et al*. 2008). Foliar application of Zn at heading stage to rice improved Zn concentrations of white rice in a single trial in China (Fang *et al*., 2008). Pooniya and Shivay (2011) reported that foliar application of zinc sulphate (0.2%) gave higher grain and straw zinc concentration followed by application of 2% ZEU (zinc enriched urea) in basmati rice. Seed treatment in addition to foliar application of zinc and iron at panicle initiation and boot leaf stage can be recommended for the biofortification of micronutrient (Fe and Zn) in hybrid rice (Meena and Fathima, 2017). Hussain *et al.* 2018, in an experiment found that increase in Zn concentration due to the progressive increase in Zn levels to 5, 10, 15 and 20 mg Zn kg^{-1} was 43.5, 71.5. 79.5 and 80.4% over control during the year 2011, respectively. During the year 2012, the corresponding figures obtained were 47.8, 68.8, 74.8, 78.9%, respectively. Zn concentration in brown rice, hull, straw and roots on the whole was of the order of China 1039>Jhelum>China 1007>SR1. Grain Zn concen trations were more effectively increased by Zn fertilization (Table 3) especially with foliar Zn applications and more distinct increases in grain Zn by foliar Zn application were achieved when Zn was given after flowering time, e.g., at early milk plus dough stages (Phattarakul *et al.* 2012).

Singh *et al.* (2013) reported maximum Fe concentration in PR113 (234.4 mg kg^{-1}) and PR116 (289.2 mg kg^{-1}) cultivars with 0.5% and 1% levels of $FeSO_4.7H_2O$ spray, respectively on ferti fortification of iron at maximum tillering stage (Table 4). Fe increased significantly by an average of 15% with the application of N between 0 and 135 kg ha^{-1} (Zhang *et al.* 2008).

Wheat: Li *et al.* (2007) reported that on application of recommended dose of N and K from fertilizer sources to wheat plants resulted in higher grain and straw Zn and Fe concentration as compared to control, PK, NP, NPK, ½ org fertilizer + ½ N and organic fertilizer source. Combined application of soil and foliar zinc resulted in higher zinc concentration in grain and shoot followed by seed and foliar application rather than single soil, seed or foliar application in wheat (Yilmaz *et al*. 1997). In wheat grain, recommended

doses of fertilizers combined with *Providentia sp.* (plant growth promoting rhizobacteria) resulted in better accumulation of zinc and iron in comparison to other treatments (Rana *et al*. 2012). Foliar Zn application especially at later growth stages (e.g., early milk stage and dough stage) was most effective in increasing Zn concentration of both whole grain as well as of endosperm in wheat while as soil Zn applications remained least effective (Cakmak *et al.* 2010). Foliar application of Zn fertilizers enhanced grain Zn concentration by 2- or 3-fold depending on the plant availability of Zn in soils in wheat (Cakmak, 2008; Cakmak *et al.* 2010). Foliar Zn application alone or in combination with soil application, significantly increased grain Zn concentrations from 27 mg kg^{-1} at nil Zn to 48 and 49 mg kg^{-1} (Table 5) across all of 23 site-years, resulting in increases in grain Zn by 84% and 90%, respectively (Zhou *et al.* 2012). Among the cereals studied, wheat was by far the most responsive to foliar Zn spray in terms of increases in grain Zn (up to 83%). Rice showed an intermediate response to foliar Zn applications and exhibited moderate increases in grain Zn (up to 27%), whereas maize appeared to be less responsive (Zhou *et al.* 2012 and Phattarakul *et al*. 2012).

Foliar application of $FeSO_4$ or Fe chelates didn't increase grain Fe concentration by more than 36% in wheat (Zhang *et al*. 2010). Increasing soil N application significantly enhanced shoot and grain Fe concentrations both under field and greenhouse conditions (Cakmak *et al.* 2010; Kutman *et al.* 2010; Shi *et al.* 2010). Application of Fe fertilizers either in inorganic ($FeSO_4$) or in chelated form (e.g., Fe-EDDHA, Fe- EDTA or Fe-citrate) had only a small

Table 3: Zinc concentration of brown rice grown with different Zn fertilizer treatments in 9 locations of 5 countries in the field experiments conducted in 2008 to 2010.

Country	Location	Year	Variety and cultivation method[a]	Zn treatment[b]				Zn effect by f-test[c]
				Nil	Soil Zn	Foliar Zn	Soil + foliar Zn	
				Zn in brown rice (mg Zn kg^{-1})				
China	Anhui	2008	GLY No.6	17.6a	20.4b	24.3c	26.2c	***
	Zhejiang	2008	GLY No.6	23.3a	23.8a	26.6b	27.9b	***
India	Ludhiana	2009	PR 120	23.6a	26.7a	28.9b	30.3b	**
		2010	PR 120	16.3a	20.3ab	23.6b	25.2b	**
	Langroya	2009	PR 118	21.8a	25.1ab	27.0b	30.0b	**
	Kapurthala	2010	PR 118	18.1a	23.0b	29.0c	24.9b	**
Lao PDR	Vientiane	2009	TDK7	26.5a	28.1a	33.8b	34.2b	***
Thailand	Chiang Mai	2008	CNT1	20.6a	20.6a	25.8b	26.6b	*
		2009	CNT1	19.6a	20.4a	22.5b	24.3c	*
		2009	IR68144	31.0a	31.5a	32.1a	35.7b	*
	Takli	2008	CNT1	9.9a	8.9a	15.9b	17.5b	*
Turkey	Edirne	2008	OMC 97	17.1a	17.4ab	18.3ab	18.8b	**
		2008	OMC 97[A]	15.3a	15.3a	22.0b	23.0b	**
		2009	OMC 97	14.6a	14.7a	17.3b	17.9b	**
		2009	OMC 97[A]	15.5a	16.2a	18.4b	19.4b	**
Mean				19.4	20.8	24.4	25.5	
% increase in brown rice Zn over Nil					2.4	24.7	31.9	
Standard deviation for different trials					6.1	17.0	19.4	

[a]Grown as wetland rice, unless otherwise indicated as drip irrigated aerobic rice by superscript[A]

[b] Different letters after numbers in same row designated significant difference by $LSD_{P<0.05}$

[c] Significant effects: * at P<0.05; ** at P<0.01; *** at P<0.001

Table 4: Concentration of Fe (mg kg^{-1}) in different rice cultivars at maximum tillering stage.

Treatments	Rice cultivars				
	PR113	PR116	PR118	PR120	PAU 201
Control	197.5	199.8	201.1	203.0	174.0
0.5% $FeSO_4$	234.4	221.3	227.0	231.7	201.6
% Increase over control	18.6	10.7	12.8	14.1	15.8
1% $FeSO_4$	264.5	289.2	247.3	266.4	248.6
% Increase over control	33.9	44.7	22.9	31.2	42.8
CD (*P*=0.05)	15.3	13.6	8.2	16.	6 9.8

Interaction (Cultivars x Treatments) 9.0

positive impact on increasing Fe concentration in grain while as soil N application enhanced it by 47%. At a given Fe treatment, the high soil N supply enhanced shoot Fe concentrations by up to 70% (Fig 1) (Aciksoz *et al.* 2011). Foliar application of urea also improved grain Fe concentration (Kutman *et al.* 2010). Foliar application of $FeSO_4$ improved grain Fe concentration in wheat by about 28% in China (Zhang *et al.* 2010) and 21% in Iran, (Pahlavan-Rad and Pessarakli, 2009) whereas in Canada it remained ineffective (Gupta, 1991).

Maize: Zinc fertilization improved grain yield and Zn content of maize hybrids compared to synthetic variety

Table 5: Grain Zn concentration of wheat grown with Zn fertilizer treatments at 14 locations in seven countries during 2009–2010.

Country	Location	Year	Grain Zn concentration (mg kg^{-1})				F test	$LSD_{0.05}$
			Nil	Soil Zn	Foliar Zn	Soil + foliar Zn		
China	Quzhou	2009	27.7	32.4	47.2	53.9	**	3.5
		2010	29.5	40.9	44.3	52.0	**	6.8
	Yongshou	2009	18.8	21.0	26.5	22.5	**	3.8
		2010	19.5	22.1	31.4	34.0	***	3.5
India	Varanasi	2008	29.0	32.0	44.0	47.0	**	12.0
	Kapurthala	2010	49.0	52.0	64.8	65.3	**	7.4
		2011	31.4	30.2	51.1	49.1	**	7.9
	Ludhiana	2010	25.5	30.3	61.0	60.8	**	7.5
		2011	27.3	36.7	58.3	57.0	**	6.4
Kazakhstan	Shortandy	2009	23.0	33.0	63.0	62.0	***	5.0
		2010	20.0	26.0	73.0	91.0	***	7.0
Mexico	Yaqui Valley	2008	21.0	25.0	43.0	45.0	**	4.0
Pakistan	Ayub	2009	27.0	25.3	48.2	44.6	*	4.3
	Faisalabad	2008	29.0	29.0	60.0	59.0	***	9.0
	Muridke-I	2009	45.3	38.5	52.6	53.6	*	9.3
		2010	28.0	33.2	44.1	42.7	*	4.6
	Muridke-II	2009	40.5	46.2	50.9	49.3	*	5.7
		2010	37.3	46.7	53.5	54.7	*	4.3
Turkey	Eskisehir	2009	21.5	21.4	43.9	41.9	**	4.3
		2010	30.1	30.6	43.0	44.8	**	4.4
	Konya	2009	11.6	11.7	19.6	22.1	**	3.2
		2010	14.1	14.1	31.9	32.6	**	4.0
Zambia	Chisamba	2010	23.0	24.0	Nd	43.0	***	5.0
Grand mean			27.4	30.5	48.0	49.0		
			The P value of paired t test					
	Nil Zn		-	0.002	<0.001	<0.001		
	Soil Zn			-	<0.001	<0.001		
	foliar Zn				-	0.195		
	Soil + Foliar Zn	-						
			Increase (%) in grain Zn concentration over nil Zn treatment					
	Mean			12.3	83.5	89.7		
	Standard deviation for different trials			15.0	56.9	70.0		

Nd, no data. *, ** and ***, significant at P<0.05, P<0.01 and P<0.001 level, respectively.

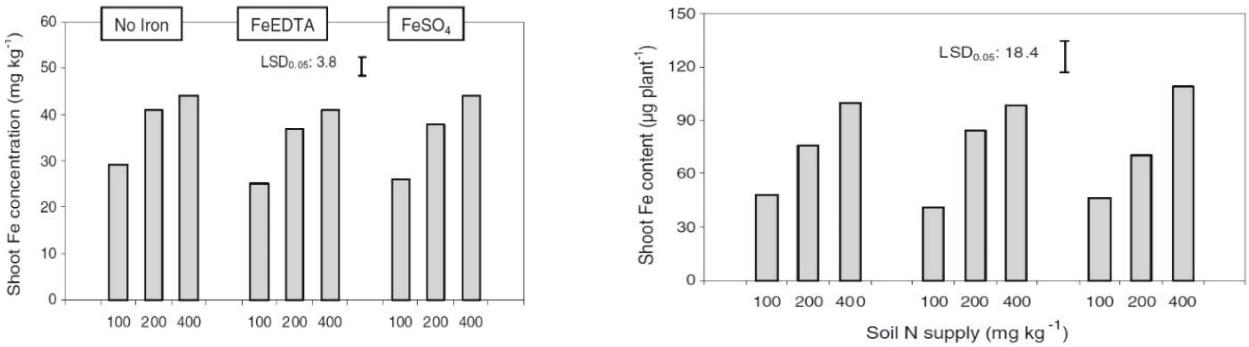


Fig 1: Effect of increasing the soil N supply on shoot concentration and shoot content (e.g., total accumulation) of Fe in durum wheat (*Triticum durum cv. Balcali* 2000) under different soil Fe treatments.

Table 6: Effect of Zn and Fe application on the zinc and iron contents of maize grain.

Treatments	Fe Content(mg kg^{-1})	% increase	Zn Content (mg kg^{-1})	% increase
NPK	74.1	—	14.3	—
NPK+10 kg Zn and Fe	91.6	23.6	18.3	28.0
NPK+20 kg Zn and Fe	107.6	45.2	23.2	62.2
NPK+30 kg Zn and Fe	122.7	65.6	25.1	75.5
NPK+ 0.1 % foliar spray of Zn and Fe	153.6	107.3	31.8	122.4

(Kanwal *et al.* 2010).The application of Zn and Fe increased the grain yield and Zn and Fe contents of maize (Table 6) and it was found that the foliar application of Zn and Fe proved a better way to increase the nutrients contents in maize grain in comparison to soil application (Saleem *et al.* 2016). The relative effectiveness of the Zn sources in increasing Zn concentration in maize plant was in the following order: Zn-EDTA (20 mg kg^{-1}) > Zn-EDDHA (20 mg kg^{-1}) ~ Zn-EDTA (10 mg kg^{-1}) > Zn-EDDHA (10 mg kg^{-1}) ~ Zn phenolate (both rates) ~ Zn-polyflavonoid (both rates) ~ Zn-lignosulfonate (both rates) ~Zn-glucoheptonate (bothrates) > untreated Zn (Alvarez and Gonzalez, 2006).

Pearl millet: Pearl millet is well known and widely cultivated staple for majority in semi- arid regions (Nagaraj *et al.* 2012). In terms of area, production and productivity it ranks first in millets in India and contributes around 8.89% to the total production of coarse cereals (NRAA, 2012). Semi-arid regions are characterized by extreme temperature and lesser amount of organic matter leading to poor soil fertility (Rego *et al.* 2003) and low nitrogen status. Nitrogen fertilization in combination to Zn fertilization increases the yield as well as zinc content in pearl millet grain (Prasad *et al.* 2014). Zn content in grain significantly varied with nitrogen and zinc rates and recorded maximum with 60 kg N ha^{-1} and 10 kg Zn ha^{-1}. However, nitrogen and zinc rate interact at 20 kg N ha^{-1} x 5 kg Zn ha^{-1} (Table 7) and recorded maximum zinc content (Prasad *et al.* 2015). Nitrogen fertilization caused an increase in plant growth and also altered the pH around the root zone which had a positive effect on the grain Zn concentration (Shafea and Saffari, 2011) and also positively affected root uptake, shoot translocation and grain deposition of Zn (Cakmak, 2012). Increasing nitrogen supply almost quadrupled the Zn uptake rate (Erenoglu *et al.* 2011).

Table 7: Effect of nitrogen and zinc levels on yield, zinc content and uptake in pearl millet grain.

Treatments	Grain		
	Yield (kg/ ha)	Zn content (mg/kg)	Zn uptake (kg/ha)
Nitrogen levels (kg ha^{-1})			
0	1428.76	11.82	1.73
20	1760.77	15.78	2.67
40	1966.32	16.60	3.46
60	2109.70	17.81	3.80
Zinc levels (kg ha^{-1})			
0	1551.30	13.57	2.23
5	1858.28	16..34	3.02
10	2039.59	16.59	3.50
Significance			
Nitrogen	149.93	1.81	0.38
Zinc	129.84	1.57	0.33
NxZn	ns	**	**

** Significant at 0.05 level
ns: not significant

Sorghum: Sorghum [*Sorghum bicolor* (L.) Moench] forms the fifth most important cereal staple food in the sub-tropical and semi-arid regions of Africa and Asia (Reddy *et al.* 2011). After pearl millet, it forms the second cheapest source of micronutrients and calories and a wide range of African and

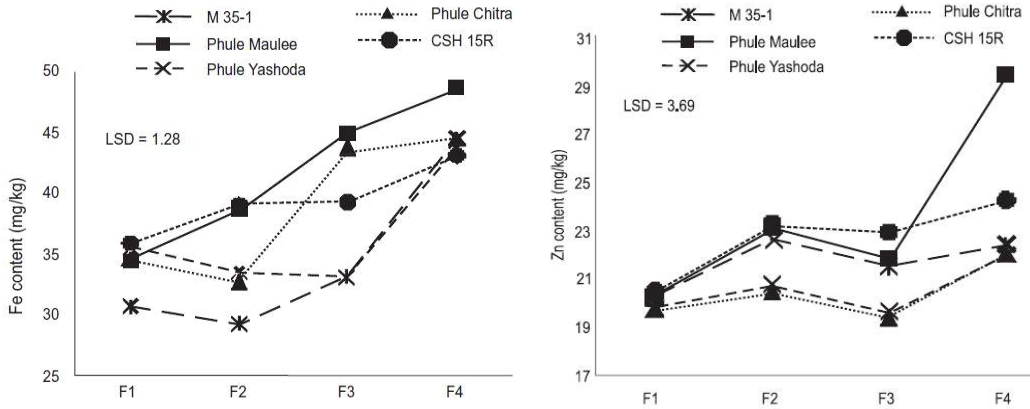


Fig 2: Grain Fe and Zn content in sorghum cultivars as affected by external application through fertilizers.F1- RDF (80:40:40 kg NPK/ ha), F2- RDF+ ZnSO4 @ 50 kg/ha (soil application), F3- RDF+ FeSO4 @ 50 kg/ha (soil application), F4- RDF+ ZnSO4 + FeSO4 (soil application) followed by foliar application (0.50%+1.0%) at 45 DAS.

Central Indian population depends on sorghum for their dietary energy and micronutrient requirements (Parthasarathy *et al*. 2006). Zinc and iron deficiency is prevalent in bulk of the sorghum growing soils of arid and semi-arid regions of India (Katyal and Vlek, 1985; Singh, 2001). Cooked sorghum grain has limited amounts of mineral concentration and its bioavailability (Kayode *et al*. 2006). Biofortification offers a practical solution for enhancing the mineral micronutrients (especially iron and zinc) in the sorghum grains to combat these deficiencies (Pfeiffer and McClafferty, 2007). In comparison to rainy season sorghums, Post-rainy (*Rabi*) sorghums were predominantly lower in Fe and Zn contents (Kumar *et al.* 2013). Sorghum cultivar Phule Maulee (Fig 2) with soil application of $ZnSO_4$ + $FeSO_4$ each at 50 kg ha^{-1} followed by their foliar application @ 0.50% + 1.0% respectively at 45 DAS in addition to the recommended dose of fertilizer (80:40:40 kg NPK ha^{-1}) is recommended for producing post-rainy sorghum with enhanced micronutrient content especially Zn and Fe (Mishra *et al.* 2015).

Limitations: The success of agronomical biofortification depends on a number of factors *viz*, mineral mobility, mineral accumulation within the plant species, soil composition at the specific geographical location of each crop. Agronomic biofortification involves recurrent cost because of continuous application of inputs (fertilizers) at regular intervals and is also labour intensive. Besides, it is not always possible to target the micronutrient into edible plant part like seed/ grain or fruit and can sometimes accumulate in non-desired plant parts, resulting in resource wastage and rendering the whole activity as futile. Moreover, the biggest of all constraints is that of the environmental degradation due to accumulation of fertilizers in the soil and water.

CONCLUSION

Agronomic biofortification offers sustainable solutions to the escalating micronutrient related malnutrition problems. Foliar sprays of Zn and Fe offers a practical and useful means for agronomic biofortification with Zn and Fe in rice and maize. The most promising cereal crop for increasing zinc in grains through foliar zinc fertilization was found to be wheat in comparison to rice and maize. Fe concentrations of durum wheat plants were only slightly affected by Fe fertilization. In contrast to Fe fertilization, increasing soil N fertilization enhanced shoot and grain Fe concentrations. Nitrogen and zinc fertilizer interact significantly and record higher zinc content in pearl millet. Soil application of $ZnSO_4$ + $FeSO_4$ followed by foliar application along with recommended dose of fertilizer is recommended for producing micronutrient (Fe and Zn) rich sorghum.

REFERENCES

Aciksoz, S. B., Yazici, A., Ozturk, L. and Cakmak, I. (2011). Biofortification of wheat with iron through soil and foliar application of nitrogen and iron fertilizers. *Plant and Soil*, **349**(1-2)**:** 215–225.

Alvarez, J. M. and Gonzalez, D. (2006). Zinc transformations in neutral soil and zinc efficiency in maize fertilization. *Journal of Agricultural and Food Chem*istry, **54:** 9488-9495.

Cakmak, I. (2008). Enrichment of cereal grains with zinc: agronomic or genetic biofortification? *Plant Soil*, **302:** 1–17.

Cakmak, I. (2012). Harvest plus zinc fertilizer project: Harvest zinc. *Better Crops with Plant Food,* **96**(20)**:** 17-19.

Cakmak, I., Kalayci, M., Kaya, Y., Torun, A.A., Aydin, N., Wang, Y., Arisoy, Z., Erdem, H., Gokmen, O., Ozturk, L. and Horst, W.J. (2010). Biofortification and localization of zinc in wheat grain. *Journal of Agricultural and Food Chem*istry, **58:** 9092–9102.

Erenoglu, E.B., Kutman, U.B., Ceylan, Y., Yildiz, B. and Cakmak, I. (2011). Improved nitrogen nutrition enhances root uptake, root-to-shoot translocation and remobilization of zinc (65Zn) in wheat. *New Phytologist*, **189:** 438–448.

Fang, Y., Wang, L., Xin, Z., Zhao, L., An, X. and Hu, Q. (2008). Effect of foliar application of zinc, selenium, and iron fertilizers on nutrients concentration and yield of rice grain in China. *Journal of Agricultural and Food Chem*istry, **56:** 2079–2084.

FAO, (2013). The State of Food and Agriculture, Food and Agriculture Organisation. Rome.

Gupta, U.C. (1991). Iron statues of crops in Prince-Edward-Island and effect of soil-pH on plant iron concentration. *Canadian Journal of Soil Sci*ence, **71:** 197–202.

Hussain, S.T., Bhat, M.A., Hussain, A., Dar, S.A., Dar, S.H., Ganai, M.A. and Telli, N.A. (2018). Zinc fertilization for improving grain yield, zinc concentration and uptake in different rice genotypes. *Journal of Pharmacognosy and Phytochemistry*, **7(2):** 287-291.

Kanwal, S., Rahmatullah, A.M. Ranjha and R. Ahmad (2010). Zinc partitioning in maize grain after soil fertilization with zinc sulfate. *Int. J. Agric. Biol*, **12:** 299–302.

Katyal, J. C. and Vlek, P. L. G. (1985). Micronutrient problems in tropical Asia. *Fertilizer Research*, **7:** 69–94.

Kayode, A. P. P., Linnemann, A. R. and Hounhouigan, J. D. (2006). Genetic and environmental impact on iron, zinc, and phytatein food sorghum grown in Benin. *Journal of Agricultural and Food Chemistry,* **54:** 256–62.

Kotecha, P.V. (2008). Micronutrient malnutrition in India: let us say "no" to it now. *Indian J. Community Med*, **33**(1)**:** 9-10.

Kumar, A.A., Reddy, B.V., Ramaiah, B., Sahrawat, K.L. and Pfeiffer, W.H. (2013). Gene effects and heterosis for grain iron and zinc concentration in sorghum [Sorghum bicolor (L.) Moench]. *Field Crops Research*, **146:** 86–95.

Kutman, U.B., Yildiz, B., Ozturk, L. and Cakmak, I. (2010). Biofortification of durum wheat with zinc through soil and foliar applications of nitrogen. *Cereal Chem*, **87:** 1–9.

Li, B.Y., Zhou, D.M., Cang, L., Zhang, H.L., Fan, X.H. and Qin, S.W. (2007). Soil micronutrient availability to crops as affected by long-term inorganic and organic fertilizer applications. *Soil and Tillage Research*, **96**(1-2)**:** 166-173.

Meena, N. and Fathima, P. S. (2017). Nutrient uptake of rice as influenced by agronomic biofortification of Zn and Fe under methods of rice cultivation. *Int. J. Pure App. Biosci,* **5** (5)**:** 456-459.

Mishra, J. S., Hariprasanna, K., Rao, S. S. and Patil, J. V. (2015). Biofortification of post-rainy sorghum (*Sorghum bicolor*) with zinc and iron through fertilization strategy. *Indian Journal of Agricultural Sciences,* **85** (5)**:** 721–4.

Nagaraj, N., Basavaraj, G., Rao, P.P. and Bantilan, C. (2012). Future outlook and options for target crops: the sorghum and pearl millet economy of India. ICRISAT, Patancheru, India. Policy Brief No. 15.

NNMB (National Nutrition Monitoring Bureau). (2002). Hyderabad: National Institute of Nutrition; 2002.

NRAA (National Rainfed Area Authority). (2012). Products, diversification, marketing and price discovery of pearlmillet in India. Policy Paper No.2, National Rainfed Area Authority Planning Commission, Government of India, NASC Complex, New Delhi.

Pahlavan-Rad, M. and Pessarakli, M. (2009). Response of wheat plants to zinc, iron and manganese applications and uptake and concentration of zinc, iron and manganese in wheat grains. *Communications in Soil Science and Plant Analysis,* **40:** 1322– 1332.

Parthasarathy, R. P., Birthal, B.S., Reddy, B.V.S., Rai, K.N. and Ramesh, S. (2006). Diagnostics of sorghum and pearl millet grains-based nutrition in India. *Inter. Sor. Mil. News let,* **47:** 93-96.

Pfeiffer, W. H. and McClafferty, B. (2007). HarvestPlus: Breeding crops for better nutrition. *Crop Science,* **47:** S88–S105.

Phattarakul, N., Rerkasem, B., Li, L.J., Wu, L.H., Zou, C.Q., Ram, H., Sohu, V.S., Kang, B.S., Surek, H., Kalayci, M., Yazici, A., Zhang, F.S. and Cakmak, I. (2012). Biofortification of rice grain with zinc through zinc fertilization in different countries. *Plant Soil*, **361:** 131–141.

Pooniya, V., Shivay, Y.S. (2011). Effect of green manuring and Zinc fertilization on productivity and nutrient uptake in Basmati rice (*Oryza sativa*)-wheat (*Triticum aestivum*) copping system. *Indian journal of Agronomy,* **56**(1)**:** 28-34.

Prasad, R. (2010). Zinc biofortification of food grains in relation to food security and alleviation of zinc malnutrition. *Current Science,* **98(10):** 1300-1304.

Prasad, S.K., Singh, M.K. and Singh, R. (2014). Effect of nitrogen and zinc fertilizer on pearl millet (*Pennisetum glaucum*) under agri-horti system of eastern Uttar Pradesh. *The Bioscan,* **9**(1)**:** 163-166.

Prasad, S.K., Singh, R., Singh, M.K. and Rakshit, A. (2015). Zinc biofortification and agronomic indices of pearl millet under semi-arid region. *International Journal of Agriculture, Environment and Biotechnology,* **8(1):** 171-175.

Rakshit, A., Pal, S., Rai, S., Rai, A., Bhowmick, M.K. and Singh, H.B. (2013). Micronutrient seed priming: a potential, tool in integrated nutrient management. *Satsa Mukhopatra,* **17:** 77- 89.

Rana, A., Joshi, M., Prasanna, R., Shivay, Y.S. and Nain, L. (2012). Biofortification of wheat through inoculation of plant growth promoting rhizobacteria and cyanobacteria. *European Journal of Soil Biology*, **50:** 118-126.

Reddy, B.V.S., Kumar, A.A., Ramesh, S. and Reddy, P.S. (2011). Breeding sorghum for coping with climate change. *Crop adaptation to climate change (Yadav SS, Redden B, Hatfield JL and Herman Lotze-Campen, eds.). Iowa, USA: John Wiley and Sons Inc,* 326-339.

Rego, T.J., Rao, V.N., Seeling, B., Pardhasaradhi, G. and Rao, J.K. (2003). Nutrient balances-a guide to improving sorghum and groundnut based dryland cropping systems in semi-arid tropical India. *Field Crops Research,* **81:** 53–68.

Saleem, I., Javid, S., Bibi, F., Ehsan, S., Niaz, A. and Ahmad, Z.A. (2016). Biofortification of maize grain with zinc and iron by using fertilizing approach. *Journal of Agriculture and Ecology Research International,* **7**(4)**:** 1-6.

Shafea, L. and Saffari, M. (2011). Effects of zinc ($ZnSO_4$) and nitrogen on chemical composition of maize grain. *International Journal of AgriScience,* **1**(6)**:** 323-328.

Shi, R., Zhang, Y., Chen, X., Sun, Q., Zhang, F., Romheld, V. and Zou, C. (2010). Influence of long-term nitrogen fertilization on micronutrient density in grain of winter wheat (*Triticum aestivum* L.). *Journal of Cereal Science,* **51**(1)**:** 165–170.

Singh, M.K. and Prasad, S.K. (2014). Agronomic aspects of zinc biofortification in rice (*Oryza sativa* L.). Proceedings of the National Academy of Sciences India Section B: *Biological Science B.,* **84**(3)**:** 613–623.

Singh, M.V. (2007). Micronutrient deficiencies in crops and soils in India. In: Micronutrient Deficiencies in Global Crop Production. Springer, Berlin. 93-125.

Singh, M.V. (2001). Evaluation of current micronutrient stocks in different agro-ecological zones of India for sustainable crops production. *Fertilizer News,* **42:** 25–42.

Singh, P., Dhaliwal, S.S., Sadana, U.S. and Manchanda, J.S. (2013). Enrichment of rice cultivars with Fe at different plant growth stages through ferti-fortification. *LS - An International Journal of Life Sciences*, **2**(2)**:** 140-148.

Stevens, Gretchen A., Mariel M. Finucane, Luz Maria De-Regil, Christopher J. Paciorek, Seth R. *et al* (2013). "Global, Regional, and National Trends in Haemoglobin Concentration and Prevalence of Total and Severe Anaemia in Children and Pregnant and Non-Pregnant Women for 1995–2011: A Systematic Analysis of Population-Representative Data." The Lancet Global Health 1 (1): e16–25. doi: 10.1016/S2214-109X(13)70001-9.

Takkar, P.N. (1996). Micronutrient research and sustainable agricultural productivity in India. *Journal of the Indian Society of Soil Science*, **44:** 562-581.

USAID OMNI, (2005). Micronutrient Fact Sheet, India. Available online at: http://www.cdc.gov/immpact/micronutrients/

USFNB, (2001). Dietary Reference Intake for Vitamin A, Vitamin K, Arsenic, Boron, Chromium, Copper, Iodine, Iron, Manganese, Molybdenum, Nickel, Silicon, Vanadium and Zinc. US Food and Nutrition Board, National Academy Press, Washington, DC.

Wissuwa, M., Ismail, A.M. and Graham, R.D. (2008). Rice grain zinc concentrations as affected by genotype, native soil-zinc availability, and zinc fertilization. *Plant Soil,* **306**(1-2)**:** 37–48.

WHO (World Health Organization). (2002). World Health Report 2002: Reducing Risks, Promoting Healthy Life. Geneva: WHO Worldwide prevalence of anamia 1993-2005. WHO global database on anamia Geneva, World Health Organization, 2008. www.who.int/nutrition/topics/micronutrients/en/2015

Yilmaz, A., Ekiz, H., Torun, B., Gultekin, I., Karanlik, S. and Bagci, S.A. and Cakmak, I. (1997). Effect of different zinc application methods on grain yield and zinc concentration in wheat cultivars grown on zinc-deficient calcareous soils. *Journal of Plant Nutrition*, **20**(4-5)**:** 461–471.

Zhang, J., Wu, L. H. and Wang, M. Y. (2008). Iron and zinc biofortification in polished rice and accumulation in rice plant (Oryza sativa L.) as affected by nitrogen fertilization. *Acta Agriculturae Scandinavica Section B–Soil and Plant Science*, **58**(3)**:** 267-272.

Zhang, Y., Shi, R., Md. Rezaul, K., Zhang, F. and Zou, C. (2010). Iron and zinc concentrations in grain and flour of winter wheat as affected by foliar application. *Journal of Agricultural and Food Chem*istry, **58**(23)**:** 12268–12274.

Zhou, C.Q., Zhang, Y.Q., Rashid, A., Ram, H., Savasli, E., Arisoy, R.Z.,Ortiz—Monasterio, I., *et al*. (2012). Biofortification of wheat with zinc through zinc fertilization in seven countries. *Plant and Soil*, **361**(1-2)**:** 119–130.