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Can agronomic biofortification of zinc be benign for iron in cereals?

Susmit Saha [a,*], Biswapati Mandal [b], G.C. Hazra [b], Arup Dey [b], Mahasweta Chakraborty [b], B. Adhikari [c], S.K. Mukhopadhyay [b], R. Sadhukhan [b]

[a] College of Agriculture, Bidhan Chandra Krishi Viswavidyalaya, Burdwan Sadar, 713101, West Bengal, India
[b] Bidhan Chandra Krishi Viswavidyalaya, Kalyani, 741 235, West Bengal, India
[c] Chinsurah Rice Research Station, Chinsurah, Hoogly, 712101, West Bengal, India

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ABSTRACT

This study aimed at evaluating i) zinc sequestration potential of ninety seven (97), eighty (80) and twelve (12) cultivars of rice, wheat and maize respectively, ii) their response to agronomic Zn biofortification, iii) its impact on Fe concentration in grains and straw/stalk and iv) Zn and Fe concentration in the food prepared from Zn biofortified grains. Zinc and Fe were estimated following standard methods in soils and the harvested grains and straws/stalks and the breads and cooked rice prepared out of the grains of all the different cultivars of those three cereals raised with no zinc (Zn_0) and Zn fertilizer ($ZnSO_4$, $7H_2O$) applied through soil (as basal) + two foliar sprays at maximum tillering/6–8 leaf and flowering/silking stages (Zn_1) of the crops. Zinc fertilization yielded Zn densed but Fe starved grains and straws/stalks of most of the cultivars (~90%) of all the three cereals tested. Cultivars inherently high in Zn were stubborn to such Zn fertilization. Zinc fortified grains again yielded Zn enriched food products but with significant loss of both Zn and Fe (>60% in rice and 40% for wheat and maize) during their processing. Among the three cereals, wheat was most effective for Zn biofortification program.

1. Introduction

Zinc and Fe malnutrition affects over 3 billion human beings in the world (Dwivedi et al., 2012). It is also estimated that about 50% of world soils for cereal production have low available Zn, which reduces yield as well as nutritional quality of grains (Graham and Welch, 2004). Cereals, especially rice, wheat and maize which are typically low in Zn content constitute nearly two thirds of the energy intake of humans in the world particularly in the developing countries. The consumption of such cereal based foods as primary meals leads to the high prevalence of Zn deficiencies in its population (Cakmak, 2008). Fortification of widely used fertilizers with Zn (Cakmak, 2009) or enrichment of cereal cultivars with Zn (Palmgren et al., 2008; Borrill et al., 2014), germplasm screening with high bio-availability of Zn (Blair, 2014), and screening of elite cultivars efficient in Zn sequestration from soil would be an excellent investment for achieving Zn loading of cereal grains and straws. In the irrigated and favorable rain-fed lowland areas, rice–rice (R–R), rice–wheat (R–W), and rice–maize (R–M) are the predominant cropping systems in the south-east Asian countries (Timsina et al., 2010). Therefore, improving the sequestration potential of Zn of these cereals (rice, wheat and maize) in their grains and straws/stalks will provide benefits for the Zn nutrition of plants, animals as well as human beings. Agronomic biofortification of Zn, application of Zn along with fertilizers, offers a cost effective and sustainable approach to overcome such problem by producing Zn densed grains and straws (Cakmak, 2009). However, the cereals and also their cultivars may differ in their capacity for acquiring Zn from soils; some are highly efficient in producing Zn densed grains and straws while others are not so. Such efficiency is mainly governed by their genetic make-up; although external environment and other plant characteristics have also some role to play in this regard. Monitoring the status of Zn in edible (both to human and animal) parts of these cereals and their cultivars both with and without its (Zn) application may help to screen out those efficient in Zn enrichment. Again, the relationship between Zn and Fe concentration in parts of these cereals is obscure; sometimes indifferent (Qing et al., 2011), mostly antagonistic (Giordano and Mortvedt, 1972) and seldom synergistic (Zeidan et al., 2010; Aref, 2010). Loss of Fe, if occurs, during biofortification of Zn in cereals, cannot be compromised since the malnutrition due to deficiency of Fe is in no way less severe than that of Zn. Further, there is a

* Corresponding author.
E-mail address: susmit_saha1984@rediffmail.com (S. Saha).

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significant loss both of Zn and Fe from the grains of these cereals during their processing into food depending on the techniques and procedures used (Sunanda et al., 1995; Alloway, 2008). An attempt has, therefore, been made in the present study to estimate i) Zn sequestration potential of a number of cultivars of the three most widely used cereals (rice, wheat and maize) in the world, ii) the response of these cultivars to applied Zn in enriching their grains and straw/stalks with Zn, iii) the impact of Zn enrichment on Fe content in them, and iv) the ultimate effect of these onto the consumable end food products prepared out of the Zn enriched cereals.

2. Materials and methods

2.1. Experimental sites

The experiments were conducted in the University Research Farms situated at Kalyani (22°99′ N, 88°43′ E), Gayeshpur (22°58′ N, 88° 29′ E) and Chakdah (22°55′ N latitude, 88°13′E) experiencing hot and humid climate with annual average rainfall of ~1480 mm and maximum and minimum temperature of 36.2 ± 2.0 °C and 12.5 ± 1.0 °C respectively. The soils were Aeric endoaquepts with loamy texture, neutral in reaction, medium in available N (415–440 kg ha^{-1}), P (20–25 kg ha^{-1}), K (150–165 kg ha^{-1}) and marginal in available Zn requiring Zn application.

2.2. Cultivars used

Eighty (80) wheat cultivars comprising of forty (40) timely and late sown types each, twelve (12) hybrid maize cultivars and ninety seven (97) rice cultivars comprising of forty seven (47) locals, thirty (30) high yielding and twenty (20) hybrids were used for this study. They were taken from the gene banks of the different projects of the Indian Council of Agricultural Research operating at the University.

2.3. Management practices

2.3.1. Wheat

The seeds of all the 80 cultivars were sown at the rate of 120 kg ha^{-1} in the field at Kalyani during 20 to 22nd November (for timely sown cultivars) and on 12th December (for late sown cultivars) at 22.5 cm row to row spacing. Five irrigations were given (80 L water/m^2/irrigation) at the time of sowing, crown root initiation, maximum tillering, flowering and grain filling stages.

2.3.2. Maize

The seeds of all the 12 cultivars were sown at the rate of 20 kg ha^{-1} in the field at Gayeshpur during 4 to 5th April at 60.0 cm row to row and 30.0 cm plant to plant spacing. Four irrigations (125 L water/m^2/irrigation) were given at the time of sowing, 6–8 leaf stage, silking and grain filling stages.

2.3.3. Rice

Three numbers of 21-day old seedlings per hill of all the 97 cultivars were transplanted in the field at Chakdah from 6 to 8th July at 25.0 cm row to row and 20.0 cm hill to hill spacing. Water level up to 5.0 cm height (700 L water/m^2/growing season) was maintained in the rice plots throughout from transplanting to grain filling stage.

The plot size used in the experiments for all the cereals was 20.0 m^2 (5.0 m × 4.0 m) and there were six replications for each cultivar (three replications for each set of Zn treatments i.e. Zn_0 and Zn_1). The design followed for the experiments was split-plot

Table 1
Influence of Zn application on zinc sequestration potential and Fe concentration (mg kg^{-1}) in grains and straws/stalks with their shoot to grain transfer coefficients in different cultivars of the cereals.

Element	Crops	Treatments/type	Zn_0		Zn_1		Zn_0	Zn_1	% Change over control	% Change over control
			Grain	Straw/stalk	Grain	Straw/stalk	Shoot to grain transfer coefficient		Grain	Straw/stalk
Zn	Rice	Local	16.1 ± 1.0	35.2 ± 3.3	22.3 ± 2.2	55.7 ± 6.3	0.46^{de}	0.43^{de}	38.5	58.2
		High yielding	29.1 ± 4.5	34.1 ± 4.0	40.7 ± 4.2	46.4 ± 4.1	0.85^{c}	0.88^{c}	39.9	36.1
		Hybrid	20.7 ± 2.2	41.9 ± 4.3	31.9 ± 6.4	75.5 ± 16.7	0.49^{d}	0.47^{d}	54.1	80.2
	Wheat	Timely sown	25.0 ± 4.0	22.1 ± 4.0	36.1 ± 3.7	35.0 ± 4.0	1.13^{a}	1.03^{b}	44.4	58.4
		Late sown	25.9 ± 2.8	22.7 ± 3.4	37.4 ± 5.4	33.5 ± 4.9	1.14^{a}	1.12^{a}	44.4	47.6
	Maize	Hybrid	27.9 ± 4.2	25.3 ± 4.5	37.9 ± 4.2	38.7 ± 4.8	1.10^{ab}	0.98^{bc}	35.8	52.9
	LSD(0.05)			**Zn**	**Variety**	**Zn × Var.**				
		Rice	Grain	1.78	1.66	2.34				
			Straw	7.80	27.61	ns				
		Wheat	Grain	2.87	2.28	3.23				
			Straw	8.22	5.32	ns				
		Maize	Grain	4.45	1.92	2.71				
			Stalk	7.04	7.03	ns				
Fe	Rice	Local	42.7 ± 12.2	144.0 ± 37.6	23.1 ± 8.3	102.2 ± 31.9	0.31^{bc}	0.32^{b}	−45.9	−29.0
		High yielding	36.6 ± 9.2	125.2 ± 38.3	19.9 ± 5.3	77.6 ± 28.5	0.34^{b}	0.32^{b}	−45.6	−38.0
		Hybrid	35.2 ± 16.7	124.8 ± 10.9	26.1 ± 8.1	73.8 ± 10.6	0.30^{bc}	0.30^{bc}	−25.9	−40.9
	Wheat	Timely sown	57.7 ± 10.1	102.4 ± 19.2	27.7 ± 16.0	62.3 ± 23.2	0.50^{ab}	0.47^{a}	−51.9	−39.2
		Late sown	55.9 ± 5.4	93.2 ± 10.6	40.4 ± 12.5	47.1 ± 18.7	0.52^{a}	0.46^{a}	−27.7	−49.5
	Maize	Hybrid	45.1 ± 11.4	136.0 ± 33.8	40.6 ± 8.9	118.1 ± 28.4	0.34^{b}	0.33^{b}	−9.9	−13.2
	LSD(0.05)			**Zn**	**Variety**	**Zn × Var.**				
		Rice	Grain	2.71	4.73	6.69				
			Straw	1.64	22.24	ns				
		Wheat	Grain	2.91	10.75	15.20				
			Straw	1.88	24.14	ns				
		Maize	Grain	0.68	6.63	9.37				
			Stalk	1.10	21.85	ns				

Zn_0 = No zinc and Zn_1 = Soil Zn (basal) + 2 foliar Zn at maximum tillering/6–8 leaf and flowering/silking stages.
Different letters are statistically significant at 5% level.