Zinc biofortification of food grains in relation to food security and alleviation of zinc malnutrition

Rajendra Prasad

Exemplary agricultural research supported by good government policies has ensured food security in India. It is the right time to focus on micronutrient malnutrition in the country. Recently, Zn deficiency in diet especially of young children below 5 years of age has received global attention. Zn deficiency diseases in infants and children include diarrhoea, pneumonia, stunted growth, weak immune system and retarded mental growth. Zn deficiency in pregnant women can lead to these problems and even mortality in infants. Over 450 thousand infant deaths in the world during 2004 were ascribed to Zn deficiency. Although Zn deficiency to some extent can be cured by Zn supplementation and improvement in dietary composition, it is better to increase the Zn content in cereals, the staple food in India and as a matter of fact in the entire south and southeast Asia. This can be achieved by biofortification of foodgrains either by developing crop cultivars with high concentration of Zn in grains or by adequate Zn fertilization of crops grown on Zn-deficient soils. Animals also suffer from Zn malnutrition.

Keywords: Biofortification, food security, zinc malnutrition.

SINCE gaining independence in 1947, India's main thrust in agricultural research has been on food security and rightly so, because India has a history of devastating famines in the 19th century[1] and a virtual famine in 1966 which was averted through import of 10 million tonnes of wheat from USA under PL480 programme[2]. India's food grain production improved after the introduction of high yielding dwarf fertilizer responsive varieties of wheat during 1966–68. With a matching progress in the manufacture and consumption of fertilizers, increase in the area under irrigation and development of rural infrastructure, such as, roads, schools, etc., it has been possible to achieve food security in the country. There is of course no room for complacency and sincere efforts for maintaining food security must continue on all fronts (production, availability, access and absorption)[3]. Nevertheless it is high time that along with food security due attention is also paid to adequate micronutrient nutrition in India. The micronutrients in human and animal nutrition include vitamins (A, B, C, D, E and K) and 17 microminerals (Fe, Zn, Cu, Mn, I, Fl, B, Se, Mo, Ni, Cr, V, Si, As, Li, Sn, Co). Plants require only seven essential micronutrients (Fe, Mn, Zn, Cu, B, Mo, Cl).

Rajendra Prasad lives at C-309, Vardhman Apartments, Mayur Vihar Extension, Phase 1, New Delhi 110 091, India.
e-mail: rajuma36@gmail.com

Major micronutrient deficiencies in humans

Globally three major micronutrient deficiencies have been recognized[4] in humans. These are: (i) vitamin A deficiency leading to blindness, about 57% of pre-school children in India have subclinical vitamin A deficiency[5]; (ii) iron deficiency leading to anaemia; about 79% of the kids between 6 and 35 months of age and 56% of women between 15 and 49 years of age are anaemic in India[5] and (iii) iodine deficiency leading to goitre and cretinism is endemic in 85% districts in India[5]. Micronutrient deficiency of Zn has recently received global attention[6]. Data on global mortality in children under 5 years of age due to different micronutrient deficiencies in 2004 are given in Table 1. Vitamin A deficiency was responsible for the maximum number of deaths followed by Zn and Fe[7] deficiencies.

Table 1. Global mortality in children under 5 years of age in 2004

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

Source: Black *et al.*[7].

Causes for low Zn content in human diet and animal fodder in India

Cereals, especially rice and wheat constitute nearly two-thirds of the energy needs of humans in India. Dwarf high yielding varieties of wheat, which ushered the green revolution in India, also led to the development of rice–wheat cropping system (RWCS), which presently occupies about 10 million ha in the Indo-Gangetic Plain (IGP) of north India and is spread over the states of Punjab, Haryana, Uttar Pradesh, Bihar and West Bengal[8]. RWCS is the backbone of India's food security. In 2006–07, IGP's contribution to the country's rice and wheat production was 47.5% and 71.1% respectively[9]. What is more important is the fact that in 2006–07, Punjab alone contributed about 90% towards Government's rice procurement for public distribution system (PDS). The present total productivity (rice + wheat) of RWCS is reported to be 10.3 t/ha at Ludhiana (Punjab), 9.1 t/ha at Kanpur (UP) and 7.4 t/ha at 24 Parganas (West Bengal)[10]. In addition to RWCS, several other intensive multiple cropping systems have been developed and are being practised in the country. These intensive cropping systems remove large amounts of Zn. For example, Takkar[11] reported that a harvest of 8 t grain/ha/yr removed 384,744 and 320 g Zn/ha/yr in rice–wheat, maize–wheat and rice–rice cropping systems. Similarly a harvest of 6.5 t grain/ha/yr removed 416 g Zn/ha/yr in soybean–wheat cropping system. This heavy removal of Zn year after year without adequate Zn fertilization has depleted Zn from native soils and today 49% of Indian soils are Zn deficient[12]. Another factor responsible for Zn deficiency in Indian soils has been the decrease in the application of organic manures, the supply of which has considerably reduced due to decrease in the number of farm animals caused by increased mechanization of agriculture. Nevertheless, the need for integrated nutrient supply of plant nutrients (organic + chemical fertilizer + biofertilizers) has been repeatedly emphasized[13]. Organic manure is a good source of micronutrients including Zn and its continued use can help avoiding Zn deficiency in soils[14]. Recycling crop residues can help in alleviating Zn deficiency in soils[15].

Further, in conventional breeding, the emphasis has been on grain yield and not much attention is attached to the concentration of nutrients including micronutrients, which, in general, declines as the yield increases[16]. Also there have been efforts to breed cultivars capable of growing on Zn-stress soils. All this led to the development of crop cultivars with lower concentration of Zn in grain as well as straw.

Traditional agriculture relied on animals for farming and is an example of a unique socio-ecosystem, where men and animals toil in cultivating the land to produce food; men consume the harvested grain and the animals the straw. Increased area under high yielding cultivars of crops has resulted in Zn (and other micronutrients) malnutrition in animals. What has been ignored is that animals help in recycling plant nutrients including Zn and 'crop/crop residues–cattle–milk/meat–humans' cycle is the key to sustainable agriculture in India.

Functions of Zn and diseases caused by Zn deficiency

Zn is required by a large number of proteins in biological systems to maintain their structural stability functions and transcription factors. Zn is essential for gene regulation and expression under stress conditions and is therefore required for protection against infections and diseases. Todd *et al.*[17] produced the first evidence for the essentiality of Zn in rats, while Turner and Salmon[18] reported that Zn cured and prevented parakeratosis in pigs. Later O'Dell and Savage[19] showed that Zn is required for growth, feathering and skeletal development in poultry. Interest in Zn nutrition in humans followed the discovery[20] of the role of Zn in wound healing. Prasad *et al.*[21] were the first to report the relationship between dwarfism and hypogonadism and Zn malnutrition in boys in the middle east. It is now well established that Zn deficiency leads to diarrhoea and pneumonia in children[22,23]. Zn deficiency in grown-up children and adolescent males causes retarded growth and dwarfism, retarded sexual development, impaired sense of taste and poor appetite and mental lethargy[24–26]. Zn deficiency in humans has been reported from Iran and Egypt[27]. It is estimated that 60–70% of the population in Asia and sub-Saharan Africa could be at the risk of low Zn intake; in absolute numbers this translates into 2 billion people in Asia and 400 million people in sub-Saharan Africa[28]. Using disability adjusted life years (DALYs) technique, it has been found that Zn deficiency in India is a highly relevant health problem and responsible for a loss of 2.8 million DALYs[29].

According to Hotz and Brown[6], childhood stunting may be considered as an indicator of the human Zn nutritional deficiency and about 61 million children under the age of 15 are stunted. Pregnant women are also susceptible to Zn deficiency and a survey in Haryana on 285 pregnant women showed that 65% of them had Zn deficiency[30]. Poor dietary intake of Zn during pregnancy leads to severe consequences on infant development and child survival[31].

In animals, extreme sensitivity of appetite to Zn supply is expressed in all species[32]. In ewes, even mild Zn deficiency reduced both birth weight and number of offsprings[33]. Bowing of hind legs and stiffness of joints is reported in Zn-deficient calves[34], while skeletal abnormalities specially in the development of wings are a regular and a conspicuous feature in birds[35]. In addition, parakeratosis, i.e. the thickening, hardening and cracking of skin is a common sign of Zn deficiency in ruminants[36].

Daily dietary allowances of Zn

The dietary allowance of Zn for infants is 3–5 mg/day, while for children of 1–10 years it is 10 mg/day[37]. For adults, the dietary allowance is 15 mg/day for men, 12 mg/day for women and 16–19 mg/day for breast feeding women[38]. Zn requirement of animals depends upon the purpose for which they are raised[39]. In cattle, the signs of Zn deficiency occur when the pasture or fodder contains less than 18–42 mg/kg DM Zn[40].

Approaches to overcome Zn deficiency in humans

There are two approaches to overcome Zn deficiency in humans: (i) nutraceutical – through dietary supplements or by improving the diet by including more vegetables and fruits, and animal products, such as meat, fish, eggs, etc. and (ii) biofortification – increasing the Zn content of food grains, which could be achieved by breeding crop cultivars with higher Zn concentration in grains or by fertilizing crops with Zn. The nutraceutical approach requires programmes for creating public awareness and sustained funding from the government, which is not easy. Also, such programmes are most likely to help the easily accessible urban population. On the other hand, biofortification will help the rural as well as urban population.

Nutraceutical approach

Dietary Zn supplementation: A daily dose of 14–40 mg/day was found to considerably reduce the incidence of diarrhoea in infants in India[41,42], Bhutan[43], Indonesia[44], Bangladesh[45] and Nepal[46]. An Indonesian study even suggested a reduction in infant mortality due to Zn supplementation. Oral doses of Zn can accelerate the healing of chronic skin diseases[47]. Similarly, Zn supplements improved the growth and height of children from low income families in Guatemala, Bangladesh, Iran, Turkey, Ecuador and Chile[48,49].

Improving dietary composition: Zn deficiency is more widespread in developing countries than in developed countries and the major cause is the difference in diet composition. Indians especially suffer from Zn malnutrition due to the majority of them being vegetarian, depending mostly on cereals and pulses. South Asian countries and China are better placed in this regard, due to a wider range of foods including several marine products. Animal products such as, meat, fish and poultry contain more Zn than cereals (Table 2) and do not have phytates. So the best way to provide enough Zn is to increase the intake of proteinaceous foods such as meat, fish, poultry, cheese, milk, etc. Increasing the proportion of fruits and vegetables in diet can also help in meeting Zn requirements. Fruits and vegetables, especially those grown on sewage are rich in Zn[50].

Processing of food grains also affects Zn concentration. For example, although unhulled rice (paddy) contains 27–42 mg/kg Zn, polished rice contains only 13 mg/kg Zn (Table 2)[51–53]. Wheat on the other hand is mostly consumed as flour and most of the Zn is retained. Zn content in wheat grain varies from 38 to 47 mg/kg. Wheat also contains 11–12% protein, which is nearly twice that of polished rice. Since Zn is mostly associated with proteins, wheat consumers have a higher intake of Zn than rice eaters. However, cereal grains contain phytates, which reduce the bio-availability of Zn. Gibson[54] 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. He also reported that PZMR in the habitual diet of children in Kenya and Malawi was often about 30. Parboiling of paddy (unhulled rice) or even soaking paddy in water for a few hours may help reduce the phytate content and thus increase the bio-availability of Zn. Gibson suggested that soaking of seeds of cereals and legumes reduced the phytate content in maize porridge by 11–36% and reduced PZMR considerably. He further reported that fermentation of cereal porridge reduces the phytate content by hydrolysis via microbial phytases. Some of these techniques are already in practice in India, particularly in the south, but creating public awareness of the advantages of such practices can make them more popular. Also, data on the effect of such practices on Zn and phytate content in food products need to be generated and published.

A major setback is the lack of adequate laboratory facilities for Zn analysis in food materials. Such facilities need to be created.

Biofortification

Developing crop cultivars with grains richer in Zn: Developing crop cultivars with grains richer in Zn is a new

Table 2. Zn content of some foods

Food item	Zn (mg/kg)	Food item	Zn (mg/kg)
Rice grain			
Unhulled[51]	27–44	Green gram grain*	162
Brown rice[52]	18	Black gram*	117
Polished rice[52]	13	Chickpea grain*	86
Wheat grain[51]	32–59	Pigeonpea grain*	64
Baked beans[53]	17	Lentil grain*	118
Cheese-American[53]	41	Brinjal fruit	43 (56)**
Milk[53]	4.3	Spinach leaf	64 (398)**
Beef[70]	42.8	Radish root	121 (654)**
Pork[70]	19.5	Bottlegourd fruit	43 (56)**
Processed meat[70]	14.7	Papaya fruit	22 (46)**

*Personal communication from Dr A. N. Ganeshamurthy, IIHR, Bangalore; **Grown on sewage water (ref. 50).

Table 3. Zn content in rice and wheat grain as influenced by Zn fertilization

Zn applied (kg/ha)	Rice (mg/kg)	Wheat (mg/kg)
0	27.1	38.1
2.6	32.7	41.3
5.2	39.0	43.8
7.8	42.3	47.3

Source: Shivay *et al.*[67].

approach which is a contribution of conventional plant breeding and modern biotechnology methods and holds considerable promise. This approach has received considerable attention in recent years[55–58]. Rice is one of the priority crops for enhancement of the nutritional factors such as vitamin A, Zn and iron through international schemes such as Harvest Plus and Humanitarian Board[59] and about 1500 lines were screened for Zn tolerance at the International Rice Research Institute in Philippines[60]. Recently, bioavailability of Fe in rice has been increased by inserting a gene for heat resistant phytase from fungal sources that degrades phytate in plant[61]. This may also increase the Zn bioavailability in rice. Considerable progress has also been made by the plant physiologists in identifying mechanisms that the plant species and genotypes possess for efficient acquisition of Zn and the subject has been thoroughly reviewed[62,63].

Zn fertilization of crops (fertifortification): Good responses to Zn fertilization have been reported for a number of crops including rice and wheat[64,65]. Zn fertilization is now recommended for most regions of the country. Shivay and co-workers[66–68] have reported that Zn application to soil as zinc sulphate or zinc enriched/coated urea not only increased yield but also zinc concentration in rice and wheat grain (Table 3). Thus adequate fertilization of food crops can partly help in Zn intake by humans. Zn fertilization of crops on Zn-deficient soils helps attaining both food security and overcoming Zn malnutrition. Based on the estimates by Takkar *et al.*[69] and considering the fact that 49% of Indian soils are deficient in Zn, India will need about 6 lakh tonnes of Zn per year by 2025.

Conclusion

Zn malnutrition in humans is a serious problem and biofortification of rice and wheat grains with Zn can save 0.6–1.4 million DALYs each year in India[29]. It calls for a joint effort by agricultural and nutrition scientists. No estimates at present are available on the loss of animal life in India due to Zn malnutrition.

A word of caution needs be added at this point, and this is the fact the Zn is a micro-mineral in human nutrition and excessive consumption may lead to toxic effects. Fortification of human diet with Zn should therefore be done under strict medical supervision.

1. Randhawa, M. S., *A History of Indian Agriculture* (*1757–1947*), ICAR, New Delhi, 1983, vol. III, p. 422.
2. Swaminathan, M. S., *Sustainable Agriculture – Towards Evergreen Revolution*, Konark Pub. Pvt Ltd, New Delhi, 1996, p. 219.
3. Swaminathan, M. S., Achieving synergy between food security act and NREGA. Programme and abstracts, Symposium on Nutritional Security for India – Issues and Way Forward, Indian National Science Academy, New Delhi, 3–4 August 2009, pp. 1–4.
4. Latham, M. C., Malnutrition the planet problem. *Human Ecol. Forum*, 1986, **15**, 1–53.
5. Krishnaswamy, K., The problem and consequences of the double burden – A brief overview. Programme and abstracts, Symposium on Nutritional Security for India – Issues and Way Forward, Indian National Science Academy, New Delhi, 3–4 August 2009, pp. 5–6.
6. Hotz, C. and Brown, K. H., Assessment of the risk of zinc deficiency in populations and options for its control. *Food Nutr. Bull.*, 2004, **25**, 94–204.
7. Black, R. E. *et al.*, Maternal and child under nutrition: global and regional exposure and health consequences. *Lancet*, 2008, **371**, 243–260.
8. Prasad, R., Rice–wheat cropping systems. *Adv. Agron.*, 2005, **86**, 255–339.
9. Fertilizer Statistics 2007–2008, The Fertiliser Association of India, New Delhi, Indian National Science Academy, New Delhi, 2002, pp. 91–112.
10. Ladha, J. K. *et al.*, How extensive is yield in long-term rice-wheat experiments in Asia. *Field Crops Res.*, 2003, **81**, 159–180.
11. Takkar, P. N., Micronutrient research and sustainable agricultural production. *J. Indian Soc. Soil Sci.*, 1996, **44**, 563–581.
12. Behera, S. K., Singh, M. V. and Lakaria, B. L., Micronutrient deficiencies in India and their amelioration through fertilizers. *Indian Fmg.* 2009, **59**(2), 28–31.
13. Prasad, R., Integrated plant nutrient supply systems (IPNS) for sustainable agriculture. *Indian J. Fert.*, 2008, **4**(12), 71–90.
14. Biswas, C. R. and Benbi, D. K., Dept of Soils, Punjab Agricultural University, Ludhiana. *Res. Bull.*, 1997, **3**, 66.
15. Prasad, R., Recycle the plant nutrients on the farm to avoid nutrient deficiencies in soil. *Indian Fmg.*, 2008, **58**(7), 22–23.
16. Graham, R. D., Welch, R. M. and Bouis, H. E., Addressing micronutrient malnutrition through enriching the nutrient quality of staple foods: principles, perspectives and knowledge gap. *Adv. Agron.*, 2001, **70**, 77–142.
17. Todd, W. R., Elvehjem, C. A. and Hart, E. B., Zinc in the nutrition of rat. *Am. J. Physiol.*, 1934, **107**, 146.
18. Tucker, H. F. and Salmon, W. D., Parakeratosis or zinc deficiency disease in pigs. *Proc. Soc. Exp. Biol. Med.*, 1955, **88**, 613–616.
19. O'Dell, B. L. and Savage, J. E., Potassium, zinc and distillery dried solubles as supplements to poultry diet. *Poultry Sci.*, 1957, **36**, 489.
20. Pories, W. J. and Strain, W. H., Zinc and wound healing. In *Zinc Metabolism* (ed. Prasad, A. S.), Thomas, Springfield, Il, USA, 1966, p. 378.
21. Prasad, A. S., Halsted, J. A. and Madimi, M., Syndrome of iron deficiency anaemia, hepatosplenomegaly, hypogonadism, dwarfism geophagea. *Am. J. Med.*, 1961, **31**, 532.
22. Gibson, R. S., Hess, S. Y., Hotz, C. and Brown, K. H., Indication of zinc status at the population level, a review of the evidence. *Brit. J. Nutr.*, 2008, **99**, 14–23.
23. Walker, C. L. F. and Black, R. F., *Food Nutr. Bull.*, 2007, **23**, 454–479.
24. Hambridge, M., Human zinc deficiency. *J. Nutr.*, 2000, **130**, 1344S–1349S.

25. FAO/WHO. *Vitamin and Mineral Requirements in Human Nutrition*, World Health Organization, Geneva, 2005, 2nd edn.
26. Bell, R. W. and Dell, B., *Micronutrients for Sustainable Food, Feed, Fibre and Bioenergy Production*, International Fertilizer Industry Association, Paris, p. 175.
27. Ringstead, J., Aesth, J. and Alexander, J., Deficiency of mineral nutrients for mankind. In *Geomedicine* (ed. Lag, J.), CRC Press, Boca Raton, Florida, USA, 1990.
28. Bringing Hope, Improving Lives, Strategic Plan, 2007–2015, International Rice Research Institute, Manila, Philippines, 2007.
29. Stein, A. J., Nestel, P., Meenakshi, J. V., Qaim, M., Sachdev, H. P. S. and Bhutta, Z. A., Plant breeding to control zinc deficiency in India: how cost effective is biofortification. *Public Health Nutr*., 2007, **10**, 492–501.
30. Pathak, P., Kaoil, V., Dwivedi, S. N. and Singh, R., Serum zinc level amongst pregnant women in a rural block of Haryana state of India. *Asia Pacific J. Clin. Nutr*., 2008, **17**, 276–279.
31. King, J. C., Determination of marternal zinc status during pregnancy. *Am. J. Clin. Nutr*., 2000, **71**, 1334–1343.
32. Droke, E. A., Spears, J. W., Brown, T. T. and Quereshi, M. A., Influence of dietary zinc and dexamethasone on immune response. *Nutr. Res*., 1993, **13**, 1213–1216.
33. Masters, D. C. and Fels, H. E., *Biol. Trace Elem. Res*., 1980, **7**, 89–93.
34. Miller, J. K. and Miller, W. J., Experimental zinc deficiency and recovery of calves. *J. Nutr*., 1962, **76**, 467–472.
35. Park, S. Y., Birkhole, S. G., Kubena, L. F., Nisbet, D. J. and Ricke, S. C., Role of dietary zinc in poultry nutrition, immunity and reproduction. *Biol. Trace Element Res*., 2004, **101**, 147–163.
36. Mishra, A. S., Prasad, R. and Girdhar, N., Feeding of trace minerals and its significance in ruminants. *Indian Fmg*., 2009, **59**(9), 32–36.
37. Recommended Dietary Allowances, National Academy Sciences, USA, 1974, 8th edn.
38. Dietary Allowances for Americans, Dept of Health and Human Services and US Dept of Agriculture, Maryland, USA, 2005, 5th edn.
39. Underwood, E. J., *Trace Elements in Human and Animal Nutrition*, Academic Press, New York, 1971, 3rd edn, pp. 208–251.
40. Legg, S. P. and Sears, L., Zinc sulphate treatment for parakeratosis in cattle. *Nature*, 1980, **186**, 1061.
41. Sachdev, H. P., A controlled trial on utility of oral zinc supplementation in acute diarrhoea in infants. *J. Pediatr. Gastroenterol. Nutr*., 1988, **7**, 877–881.
42. Dutta, P., Impact of zinc supplementation in malnourished children with acute watery diarrhoea. *J. Trop. Pediatr.*, 2000, **46**, 259–263.
43. Bhatnagar, S., Zinc with oral rehydration therapy reduces stool output and duration of diarrhoea in hospitalised children: a randomized control trial. *J. Pediatr. Gastroenterol. Nutr*., 2004, **38**, 34–40.
44. Hidayat, A., Achadi, S. A. and Soedarno, S. P., The effect of zinc supplementation in children grown in sewage irrigated area. *Med. J. Indonesia*, 1998, **2**, 234–241.
45. Roy, S. K., Randomized controlled trial of zinc supplementation in malnourished Banbladeshi children with acute diarrhoea. *Arch. Dis. Child*., 1997, **77**, 196–200.
46. Chandyo, R. K., Zinc and childhood infections. In *Micronutrients in South and South East Asia* (eds Anderson, P. *et al.*), International Centre for Integrated Mountain Development, Kathmandu, Nepal, 2005, pp. 33–35.
47. Hussain, S. L., Oral zinc sulphate in leg ulcers. *Lancet*, 1969, **1**, 1069–1071.
48. Rivera, J. A., Ruel, M. T., Sanitzo, M. C., Lonnerdel, B. and Brown, K. H., Zinc supplementation improves the growth of stunted rural Guatamalan infants. *J. Nutr*., 1998, **128**, 556.
49. Gibson, R. S., Hotz, C., Temple, L., Yeudall, F., Mitimuni, B. and Ferguson, E., Dietary strategies to combat deficiencies of iron, zinc and vitamin A in developing countries. *Food Nutr. Bull*., 2000, **21**, 2219–2231.
50. Paul, P. P., Sarkar, D., Sahoo, A. K., Bhattacharya, B. and Gupta, S. K., Accumulation of nutrients in vegetables grown in sewage irrigated areas. *Indian J. Fert*., 2006, **1**(12), 51–54.
51. Shivay, Y. S., Kumar, D. and Prasad, R., Effect of zinc enriched urea on productivity, zinc uptake and efficiency of an aromatic rice-wheat cropping system. *Nutr. Cycl. Agroecosyst.*, 2008, **81**, 229–243.
52. Welch, R. M., Harvesting health: agricultural linkage for improving human health. In *Micronutrients in South and South East Asia* (eds Anderson, P. *et al.*), International Centre for Integrated Mountain Development, Kathmandu, Nepal, 2005, pp. 9–16.
53. Gormican, A., Inorganic elements in foods in hospital menus. *J. Am. Diet. Assoc.*, 1970, **56**, 397–401.
54. Gibson, R. S., Dietary strategies to enhance micronutrient adequacy: experiences in developing countries. In *Micronutrients in South and South East Asia* (eds Anderson, P. *et al.*), International Centre for Integrated Mountain Development, Kathmandu, Nepal, 2005, pp. 3–7.
55. Ruel, M. T. and Bouis, H. E., Plant breeding: a long term strategy for the control of Zn deficiency in vulnerable populations. *Am. J. Clin. Nutr.*, 1998, **68**, 488–494.
56. Welch, R. and Graham, R. D., A new paradigm for world of agriculture: meeting human needs, sustainable production and nutrition. *Field Crops Res*., 1999, **60**, 1–10.
57. Srivastava, S. P., Singh, S. K. and Mishra, B., Crop response and profitability to applied secondary and micronutrients in cereals. *Indian J. Fert*., 2006, **2**(8), 44–51.
58. Pfeiffer, W. H. and McClafferty, B., HarvestPlus: breeding crops for better nutrition. *Crop Sci*., 2007, **47**, S88–S105.
59. Gregorio, G. B., Senadhira, D., Htut, H. and Graham, R. D., Breeding for trace minerals in rice. *Food Nutr. Bull.*, 2000, **21**, 382–386.
60. Guerta-Quijano, C., Kirk, G. J. D., Portugal, A. M., Bartolome, V. I. and McLaren, G. C., Tolerance of rice germplasms to zinc deficiency. *Field Crops Res.*, 2002, **76**, 123–130.
61. Bhat, R. V. and Vasanthi, S., Food safety assessment issues of transgenic rice in the Indian context. In *Biosafety of Transgenic Rice* (eds Chopra, V. L., Shanthanam, S. and Sharma, R. P.), National Academy of Agricultural Sciences, New Delhi, 2005, pp. 65–74.
62. Bhupinder Singh, Natesan, S. K. A., Singh, B. K. and Usha, K., Improving zinc efficiency of cereals under zinc deficiency. *Curr. Sci*., 2005, **88**, 36–44.
63. Broadley, M. R., White, P. J., Hammond, J. P., Zelko, I. and Lux, A., Zinc in plants. *New Phytol*., 2007, **173**, 677–702.
64. Katyal, J. C. and Rattan, R. K., Secondary and micronutrients-research gaps and future needs. *Fert. News*, 2003, **48**(4), 9–20.
65. Prasad, R., Zinc in soils and in plant, human and animal nutrition. *Indian J. Fert*., 2006, **2**(4), 103–109.
66. Shivay, Y. S., Kumar, D. and Prasad, R., Relative efficiency of zinc sulphate and zinc oxide coated urea in rice-wheat cropping system. *Commu. Soil Sci. Pl. Anal*., 2008, **39**, 1154–1167.
67. Shivay, Y. S., Kumar, D., Prasad, R. and Ahlawat, I. P. S., Relative yield and zinc uptake by rice from zinc sulphate and zinc oxide coatings onto urea. *Nutr. Cycl. Agroecosyst*., 2008, **80**, 181–182.
68. Shivay, Y. S., Prasad, R. and Rahal, A., Relative efficiency of zinc oxide and zinc sulphate enriched urea for spring wheat. *Nutr. Cycl. Agroecosyst.*, 2008, **82**, 259–264.
69. Takkar, P. N., Singh, M. V. and Ganeshamurthy, A. N., In *Plant Nutrient Needs, Supply, Efficiency and Policy Issues: 2000–2025* (eds Kanwar, J. S. and Katyal, J. C.), National Academy of Agricultural Sciences, New Delhi, 1997, pp. 238–264.
70. USDA Research Service, National Nutrient Database Reference Release 21, Nutrient Data Laboratory Home Page, 2007; http://www.ars.usda.gov.nutrient.da

Received 4 March 2009; revised accepted 20 April 2010