

ORIGINAL ARTICLE

Genetic enhancement of grain iron and zinc content in pearl millet

Kedar N. Rai, Mahalingam Govindaraj & Aluri S. Rao

International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, Andhra Pradesh, India

Keywords

correlation; genetics; germplasm; micronutrients; pearl millet; variability; yield.

Correspondence:

Kedar N. Rai, International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru 502 324, Andhra Pradesh, India.
Tel: +91 040 30713323;
Fax: +91 40 30713074;
E-mail: k.raai@cgiar.org

Received 15 November 2011; Revised 16 January 2012; Accepted 5 April 2012.

doi: 10.1111/j.1757-837X.2012.00135.x

Abstract

Introduction Pearl millet [*Pennisetum glaucum* (L.) R. Br.] is a highly nutritious warm season cereal. In a major initiative to further improve its nutritive value, a partnership based research has been under way at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) to eventually develop high-yielding hybrids with higher levels of iron (Fe) and zinc (Zn) contents. **Objective** We investigated some of the factors that can enhance breeding efficiency for these micronutrients. **Methods** Grain samples from various trials were harvested and analyzed using inductively coupled plasma optical emission spectroscopy, near-infrared reflectance spectrometry and energy-dispersive X-ray fluorescence (EDXRF) screening techniques. **Results** Large variability for and high levels of both Fe and Zn content were observed in breeding lines and populations (>80 ppm Fe and >60 ppm Zn). The Fe and Zn contents were positively and highly significantly correlated ($r = 0.49$ to 0.71). There were negative correlations ($r = -0.39$ to -0.58) between these micronutrients and grain yield, though significant only in the case of Fe content and in only three of the six trials. These micronutrients were not correlated with seed size and time to flower. Both Fe and Zn content were largely under additive genetic control with the predictability ratio of 0.91. **Conclusion** These results showed that effective selection for both Fe and Zn content is possible without compromising on grain yield and seed size, and the rapid and cost-effective EDXRF screening technique can accelerate the breeding efficiency. The additive gene action for these micronutrients would require their incorporation in both parental lines of the hybrids.

RAI KN, GOVINDARAJ M, RAO AS (2012). Genetic enhancement of grain iron and zinc content in pearl millet. *Quality Assurance and Safety of Crops & Foods*, 4, 119–125.

Introduction

Micronutrient malnutrition arising from dietary deficiency of one or more essential micronutrients affects two thirds of the world's population (White & Broadley, 2009; Stein, 2010). The mineral elements most commonly lacking in human diets are iron (Fe) and zinc (Zn), which rank fifth and sixth, respectively, among the top 10 risk factors contributing to burden of disease, especially in the developing countries (WHO, 2002). Crop biofortification is a sustainable and cost-effective approach to address micronutrient malnutrition,

especially in the developing world (Stein *et al.*, 2007; Bouis *et al.*, 2011). It has the potential to help alleviate the suffering, death, disability and failures to achieve human potential, which result from micronutrient deficiency-related diseases. In comparison with other strategies (fortification, supplementation or dietary diversification), it provides a truly feasible means of reaching out to remote and rural areas to deliver naturally fortified foods to population groups with limited access to diverse diets, supplements and commercially fortified foods (Bouis *et al.*, 2011). Moreover, as the trace mineral requirements in human and plant nutrition are

similar, biofortification could improve human nutrition as well as farm productivity (Ma, 2007).

Pearl millet [*Pennisetum glaucum* (L.) R. Br.] is a major warm-season cereal grown on more than 27 million ha in some of the harshest environments in the arid and semi-arid tropical regions of Africa (17 million ha) and Asia (10 million ha), with India being the largest producer, cultivating this crop on about 9 million ha. In these regions, pearl millet is a staple food of more than 90 million people. Pearl millet is a highly nutritious cereal with high levels of metabolizable energy and protein, and a balanced amino acid profile (Andrews & Kumar, 1992). Processing technologies for preparing various types of alternative and health food products have been developed. These products have been shown to have lower glycemic index than similar products produced from wheat (Sehgal *et al.*, 2004), thus increasing the food value of pearl millet for those prone to diabetics. Pearl millet grains lack gluten, unlike the triticeae cereals, thus enhancing its health value for those allergic to gluten (Dahlberg *et al.*, 2004). Pearl millet is less prone to aflatoxin contamination than say sorghum and maize. It has been reported that eggs produced from layers fed on pearl millet-based diets have lower levels of low-density lipoprotein (Collins *et al.*, 1997), thus providing for production of designer eggs for those with high cholesterol. These findings, not widely known, suggest that pearl millet can play an important role not only towards contributing to the food and nutritional security of the poor in the pearl millet growing areas of India and sub-Saharan Africa, but could also have potential health value for the affluent.

A preliminary study conducted with a limited number of 27 genotypes at International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) had shown high levels of and large variability for both iron (40 to 580 ppm) and zinc content (10 to 66 ppm) in pearl millet grains (Jambunathan & Subramanian, 1988). These were much higher than those in other cereals. Pearl millet is a significant source of these micronutrients both in India and sub-Saharan Africa. For instance, it accounts for 15–63% of the total cereal consumption in some of the major pearl millet growing states of India such as Maharashtra, Gujarat and Rajasthan; and it accounts for 19–63% of the Fe and 16–56% of the Zn intake from all food sources (Parthasarathy Rao *et al.*, 2006). It is also the cheapest source of these micronutrients as compared with other cereals and vegetables.

Considering the high nutritional value of pearl millet and the potential contribution it can make to improving the nutrition of those heavily dependent on it as a major food crop, ICRISAT, supported by the HarvestPlus Challenge

Program of the Consultative Group on International Agricultural Research (CGIAR), initiated a research program to breed improved breeding lines and hybrid parents with elevated levels of Fe and Zn for eventual use by its partners to develop high-yielding hybrids with higher levels of these micronutrients. Much of the work done so far has dealt with the factors that have a direct bearing on enhanced breeding efficiency. In this paper, we report the results of studies related to the magnitude of variability for Fe and Zn content, character association, the genetics of these micronutrients, and methods for their analysis.

Materials and methods

Micronutrient variability trials

The variability for grain Fe and Zn content was evaluated in two sets of breeding lines planted in randomized complete block design with two replications in Alfisols at Patancheru during the 2011 rainy season. Each plot consisted of one-row of 4 m length, with 75 cm spacing between the rows and 10 cm spacing within the rows. Normal crop management practices were followed, with 80 kg ha⁻¹ of applied N and 40 kg ha⁻¹ of P₂O₅. Set I consisted of 386 advanced breeding lines (mostly F₇ onwards) from the conventional hybrid parents breeding program where Fe and Zn are not the selection criteria. Set II consisted of 232 early-generation progenies (S₁–S₃) derived from seven populations that had earlier been identified as sources of high Fe and Zn contents.

Character association trials

Four initial hybrid trials (IHTs) and two advance hybrid trials (AHTs) were conducted in Alfisols at Patancheru. Planting and crop management procedures were the same as for the micronutrient variability trials. All four IHTs were planted in two-row plots and both AHTs in four-row plots of 4 m length, replicated three times in randomized complete block design. Panicles harvested at maturity were threshed, dried and grain yield recorded. Random samples of 200 grains were used to estimate 1000-seed weight. Plots were visually assessed for days to 50% flowering when main panicles of 50% of the plants in the plot had fully emerged stigmas.

Line × tester trial

This trial consisted of 72 hybrids developed from crosses between eight lines and nine testers. These were planted in one-row plots of 2 m length, replicated two times in a randomized complete block design. The 17 inbred lines involved

Table 1 Variability for grain iron (Fe) and zinc (Zn) content in pearl millet, 2011 rainy season, Patancheru

		Percent entries in micronutrient (ppm) class					
Material	No. of entries	≤40	41–60	61–80	81–100	101–120	≥121
Fe content							
Advance breeding lines	386	25	47	23	5	0	0
Population progenies	232	0	2	28	50	17	3
Zn content							
Advance breeding lines	386	48	49	3	0	0	0
Population progenies	232	0	50	46	4	0	0

in these hybrids were also planted by the side of the hybrid trial in the same design and same plot size and replications. These trials were conducted during the 2009 summer season as a part of a PhD research. Planting and crop management practices for these two trials were similar to those mentioned for the micronutrient variability trial except that there was 60 cm spacing between the rows in both trial.

Micronutrient analysis

Grain samples collected from all the said experiments were sun dried for 7–10 days and stored for 1–2 months at room temperature before laboratory analysis of Fe and Zn contents. Until 2010, most of these analyses were done using inductively coupled plasma optical emission spectroscopy (ICP-OES) method (Wheal *et al.*, 2011) at the Waite Analytical Services laboratory, Adelaide, Australia. Thus, the grain samples of the combining ability trial conducted in 2009 were analyzed using ICP-OES. Although highly precise, this method is costly (about US\$18/sample), analyzes no more than 200 samples per day and involves a month of the data turnover time. In search for a rapid and cost-effective screening technique, a near-infrared reflectance spectrometry (NIRS) at the International Livestock Research Institute laboratory, Patancheru, was evaluated for its effectiveness using grain samples from eight trials (a designated B-line trial of 98 entries, three population progeny trials of 146–260 entries and four hybrid trials of 32–44 entries) which had already been analyzed for Fe and Zn content using the ICP-OES technique. The grain samples of these eight trials were also analyzed at ICRISAT using an energy-dispersive X-ray fluorescence (EDXRF) spectrometry method that had been standardized at the Flinders University, Australia (Paltridge *et al.*, 2012).

Statistical analysis

Fixed model analysis of variance of all the trials and correlations was done following Gomez & Gomez (1984).

Line × tester analysis of combining ability was done following Kempthorne (1957) and Arunachalam (1974).

Results and discussion

Large variability was observed both for Fe and Zn content, with Fe ranging from 18 to 97 ppm and Zn varying from 22 to 69 ppm in the advance breeding lines; and Fe ranging from 52 to 135 ppm and Zn ranging from 40 to 92 ppm in the population progenies (data not presented). While 72% of the advance breeding lines had <60 ppm Fe, 70% of the population progenies had >80 ppm Fe, with 20% of these exceeding 100 ppm level (Table 1). A similar pattern was observed for Zn content, with 48% of the breeding lines having ≤40 ppm Zn, and 50% of the population progenies having >60 ppm content. This was not unexpected as, unlike most of the advance breeding lines, the progenies were all derived from seven diverse population (including open-pollinated varieties released in India) that are largely or entirely based on *iniari* germplasm. This germplasm in an earlier study was found as the most promising source of both high Fe and Zn contents (Velu *et al.*, 2007). These results suggest that while 61–80 ppm Fe and 41–60 ppm Zn can be found in a significant number of breeding lines in elite genetic backgrounds for their direct use in hybrid parents development, population progenies with much higher levels are available as donor sources further genetic enhancement of these micronutrients.

Consistently positive and highly significant correlations between Fe and Zn content ($r = 0.49$ to 0.71 ; $P < 0.01$) were observed in all the six trials (Table 2). Earlier pearl millet studies have also shown highly significant and positive correlations between the Fe and Zn contents (Velu *et al.*, 2007, 2008b; Gupta *et al.*, 2009). Positive correlations between these two minerals have also been reported in maize (Maziya-Dixon *et al.*, 2000; Long *et al.*, 2004), sorghum (Reddy *et al.*, 2005; Ashok Kumar *et al.*, 2009), wheat (Monasterio & Graham, 2000; Morgounov *et al.*, 2007; Peleg *et al.*, 2008; Velu

Table 2 Correlation among grain iron (Fe) and zinc (Zn) content, grain yield (GY), 1000-seed weight (SW) and days to 50% flower (DTF) in four initial hybrid trials (IHTs) and two advance hybrid trials (AHTs) of pearl millet, 2011 rainy season, Patancheru

Trial	No. of entries	Correlation coefficient (<i>r</i>) between						
		Fe versus Zn	Fe versus GY	Zn versus GY	Fe versus SW	Zn versus SW	Fe versus DTF	Zn versus DTF
AHT-A	24	0.53**	−0.13	0.17	−0.01	0.05	−0.05	0.34
AHT-B	28	0.49**	−0.24	−0.32	0.21	0.02	−0.59**	−0.22
IHT-A1	30	0.67**	−0.58**	−0.24	0.32	0.22	−0.16	0.19
IHT-A2	26	0.67**	−0.39*	−0.04	0.12	−0.05	−0.20	0.08
IHT-B1	36	0.71**	−0.27	−0.18	0.04	0.29	−0.26	−0.09
IHT-B2	34	0.58**	−0.48**	−0.28	−0.15	0.07	−0.26	−0.18

*, **, significant at $P \leq 0.05$ and $P \leq 0.01$ probability level, respectively.

et al., 2011a) and rice (Doesthale *et al.*, 1979; Kabir *et al.*, 2003). These results would imply that simultaneous selection for high levels of both Fe and Zn contents is possible. While there was no correlation between the Zn content and grain yield, there were significant negative correlations between the Fe content and grain yield in three of the six trials ($r = -0.39$ to -0.58). An earlier pearl millet study also showed that neither Fe nor Zn content was correlated with grain yield (Gupta *et al.*, 2009). Studies in other cereals such as sorghum (Reddy *et al.*, 2005; Ashok Kumar *et al.*, 2009), wheat (Morgounov *et al.*, 2007) showed both micronutrients to be significantly negatively correlated with grain yield. Chakraborti *et al.* (2009) observed significant negative correlation between Fe content and grain yield, but no correlation between Zn content and grain yield in maize. Neither Fe content nor Zn content was associated with seed size and time to flower in the present study, supporting the results of earlier pearl millet studies (Velu *et al.*, 2008b; Gupta *et al.*, 2009). These results indicate that both Fe and Zn contents in pearl millet can be genetically enhanced without compromising on grain yield, large seed size and earliness.

In the line \times tester trial, there were highly significant differences ($P < 0.01$) among the parents and among the hybrids, for both Fe and Zn contents (Table 3). While the main effects due to lines as well as due to testers were highly significant for both micronutrients, the line \times tester interaction was nonsignificant for Fe content; and though significant for Zn content, it accounted for much less of the variability as compared with the main effects. This clearly showed up in the variance due to general combining ability (σ^2_{gca}) as the more predominant component and predictability ratio closer to unity, implying a larger role of additive gene action in controlling both micronutrients. An earlier pearl millet study also reported largely additive gene action for these two micronutrients (Velu *et al.*, 2011b). This nature of gene action was further supported by highly significant and positive correlation between the mid-parental values

Table 3 Analysis of variance for combining ability for grain iron (Fe) and zinc (Zn) content in line \times tester trial, 2009 summer season, Patancheru

Source of variation	df	Mean square	
		Fe (ppm)	Zn (ppm)
Parental trial			
Replication	1	368.9	0.3
Parents	16	1340.6**	632.5**
Error	16	113.6	26.7
Hybrid trial			
Replication	1	0.1	2.8
Crosses	71	288.4**	218.8**
Lines	7	990.9**	771.3**
Testers	8	1132.8**	938.0**
Lines \times Testers	56	80.0	47.0*
Error	71	55.6	26.9
σ^2_{gca}		60.2	49.7
σ^2_{sca}		12.2	10.0
Predictability ratio		0.91	0.91

*, **, significant at $P \leq 0.05$ and $P \leq 0.01$ probability levels, respectively.

and hybrid performance for both micronutrients ($r = 0.70$ for Fe and $r = 0.80$ for Zn) (Figure 1). This would imply that to breed hybrids with high levels of Fe and Zn content would require incorporating these traits in both parental lines of the hybrids. It was also observed that there was highly significant and positive correlation between the performance *per se* of the lines and their general combining ability for both micronutrients ($r = 0.77$ for Fe and 0.86 for Zn), implying that based on the performance of the lines *per se*, about 40–50% of the poor general combiners can be discarded without testing for their general combining ability (Figure 2), and thus saving on the resources otherwise required for general combining ability evaluation. Largely additive gene action for Fe and Zn has also been reported in maize (Brkić *et al.*, 2003; Long *et al.*, 2004) and rice (Zhang *et al.*, 2004). However, another study on maize (Chakraborti *et al.*, 2010) reported largely additive gene action for Fe content, but largely non-additive gene action for Zn content.

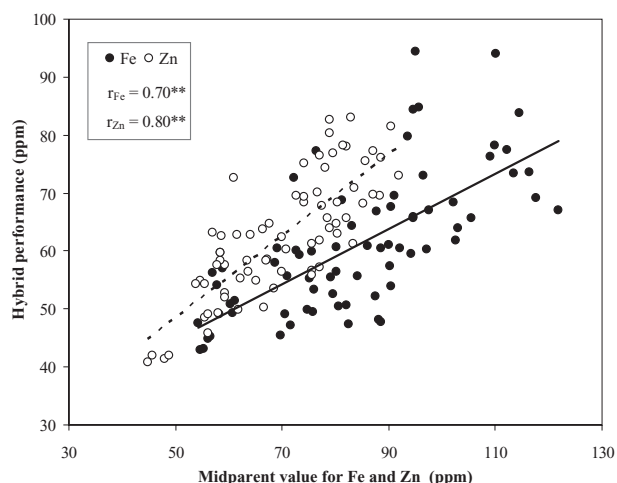


Figure 1 Relationship between midparent values and hybrid performance for grain iron (Fe) and zinc (Zn) content in line \times tester trial, 2009 summer season, Patancheru.

**Highly significant at $P < 0.01$ probability level.

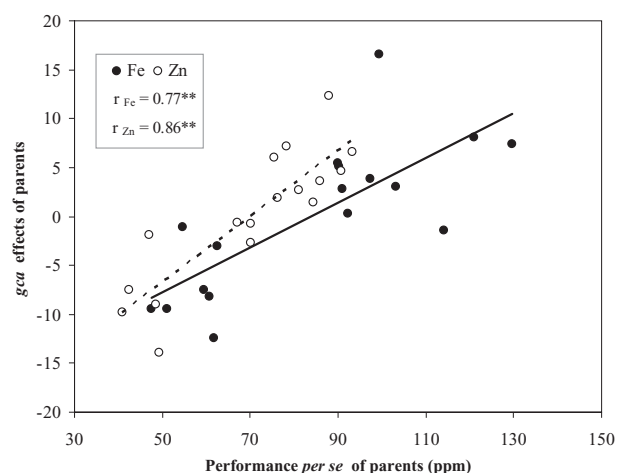


Figure 2 Relationship between performance per se of parents and their *gca* effects for grain iron (Fe) and zinc (Zn) content in line \times tester trial, 2009 summer season, Patancheru.

**Highly significant at $P < 0.01$ probability level.

In search for rapid and cost-effective methods for mineral analysis, Perl's Prussian Blue staining, a calorimetric method, was standardized for Fe content (Velu *et al.*, 2006) and dithizone staining for Zn content (Velu *et al.*, 2008a) in pearl millet. While both methods were effective in discarding lines with low mineral contents, they could only categorize lines into low, medium and high mineral content groups, and were not able to clearly distinguish the lines with average mineral content from those having high content of these micronutrients. An evaluation of the NIRS technique using grain

samples from eight trials that had previously been analyzed for the Fe and Zn content using ICP-OES method showed that it generally overestimated the Fe content by 26% to 55% as compared with the ICP-OES method (reference precision analysis) (data not presented). A similar pattern of overestimation was observed for Zn content. The correlation between the ICP-OES values and NIRS values were highly significant, ranging from 0.34 to 0.75 for Fe and 0.24 to 0.52 for Zn content (Table 4). The EDXRF method overestimated Fe content by 4% to 9% in four trials, underestimated it by 2% to 4% in three trials and had similar Fe value as for the ICP-OES method in one trial. A similar pattern was found for the Zn content. The correlations between the ICP-OES and EDXRF values were highly significant both for Fe and Zn content ($r = 0.90$ to 0.95 for Fe content and $r = 0.88$ to 0.98 for the Zn content). In the validation study of pearl millet grain samples, Paltridge *et al.* (2012) found very high correlations between the ICP-OES and EDXRF methods, both for Fe content ($r = 0.97$) and Zn content ($r = 0.98$). In comparison with the ICP-OES method, the EDXRF method costs much less (US\$2 per sample), enables the analysis of large number of samples (300 samples per day) and has high degree of precision, which is good enough for application in a genetic enhancement program.

Conclusions

The pearl millet biofortification research reported in this paper showed large variability for and high levels of both grain Fe and Zn contents. Lines identified for high levels of these micronutrients need to be further studied for their stability across environments. Zinc content was not associated with grain yield and grain size, while iron content was negatively associated with grain yield, but only in 50% of the trials. Therefore, this subject merits further study as it has a direct bearing on the effectiveness of simultaneous selections for higher grain yield and higher level of iron content. Predominantly additive gene action for both Fe and Zn contents implies that to breed hybrids with higher levels of Fe and Zn would entail breeding these traits into both parental lines, the effectiveness of which can be enhanced with the application of marker-assisted selection and gene deployment. Consistently positive and highly significant correlation between the Fe and Zn contents showed that simultaneous selection for both micronutrients will be highly effective. The EDXRF extensively validated and found as a rapid and cost-effective screening technique with high level of precision can be effectively used to enhance the breeding efficiency for both micronutrients.

Table 4 Correlation among energy-dispersion X-ray fluorescence (EDXRF), inductively coupled plasma optical emission spectrometry (ICP-OES) and near-infrared reflectance spectrometry (NIRS) estimates for grain iron (Fe) and zinc (Zn) content in various trials of pearl millet, Patancheru

Material	Season/year	No. of entries	Correlation coefficient (<i>r</i>) between			
			ICP-OES versus EDXRF		ICP-OES versus NIRS	
			Fe	Zn	Fe	Zn
Designated B-lines	Summer 2009	98	0.95**	0.98**	0.75**	0.52**
ICMV 221 S ₁ progenies	Summer 2009	146	0.90**	0.93**	0.53**	0.35**
AIMP 92901 S ₁ progenies	Rainy 2009	215	0.92**	0.95**	0.41**	0.41**
ICMR 312 S ₁ progenies	Rainy 2009	260	0.91**	0.92**	0.34**	0.40**
Hybrid trial-1	Rainy 2010	44	0.94**	0.89**	0.58**	0.48**
Hybrid trial-2	Rainy 2010	40	0.93**	0.96**	0.49**	0.43**
Hybrid trial-3	Rainy 2010	32	0.91**	0.92**	0.50**	0.43*
Hybrid trial-4	Rainy 2010	34	0.94**	0.88**	0.52**	0.24

*, **, significant at $P \leq 0.05$ and $P \leq 0.01$ probability level, respectively.

Acknowledgements

Funding support from the HarvestPlus Challenge Program of the Consultative Group on International Agricultural Research is gratefully acknowledged.

References

- Andrews D.J., Kumar K.A. (1992) Pearl millet for food, feed and forage. *Advances in Agronomy*, **48**, 89–139.
- Arunachalam V. (1974) The fallacy behind the use of a modified line \times tester design. *Indian Journal of Genetics and Plant Breeding*, **34**, 280–287.
- Ashok Kumar A., Reddy B.V.S., Ramaiah B., Sanjana Reddy P., Sahrawat K.L., Upadhyaya H.D. (2009) Genetic variability and plant character association of grain Fe and Zn in selected core collection accessions of sorghum germplasm and breeding lines. *Journal of SAT Agricultural Research*, **7**, 1–4.
- Bouis H.E., Hotz C., McClafferty B., Meenakshi J.V., Pfeiffer W.H. (2011) Biofortification: a new tool to reduce micronutrient malnutrition. *Food and Nutrition Bulletin*, **32** (Suppl 1), 31S–40S.
- Brkić I., Šimić D., Zdumić Z., Jambrović A., Ledenčan T., Kovačević V., Kadar I. (2003) Combining abilities of Corn-Belt inbred lines of maize for mineral content in grain. *Maydica*, **48**, 293–297.
- Chakraborti M., Hossain F., Kumar R., Gupta H.S., Prasanna B.M. (2009) Genetic evaluation of grain yield and kernel micronutrients traits in maize. *Pusa AgriScience*, **32**, 11–16.
- Chakraborti M., Prasanna B.M., Singh A.M., Hossain F. (2010) Generation mean analysis of kernel iron and zinc concentrations in maize (*Zea mays*). *Indian Journal of Agricultural Sciences*, **80**, 956–959.
- Collins V.P., Cantor A.H., Pescatore A.J., Straw M.L., Ford M.J. (1997) Pearl millet in layer diets enhances egg yolk n-3 fatty acids. *Poultry Science*, **76**, 326–330.
- Dahlberg J.A., Wilson J.P., Snyder T. (2004) Sorghum and pearl millet: health foods and industrial products in developed countries. In: *Alternative Uses of Sorghum and Pearl Millet in Asia*. Proceedings of the Expert Meeting, pp. 42–59, ICRISAT, Patancheru, Andhra Pradesh, India, 1–4 July 2003. CFC Technical Paper No. 34.
- Doesthale Y.G., Devara S., Rao S., Belavady B. (1979) Effect of milling on mineral and trace element composition of raw and parboiled rice. *Journal of the Science of Food and Agriculture*, **30**, 40–46.
- Gomez K.A., Gomez A.A. (1984) *Statistical Procedures for Agricultural Research*. John Wiley & Sons, New York, p. 680.
- Gupta S.K., Velu G., Rai K.N., Sumalini K. (2009) Association of grain iron and zinc content with grain yield and other traits in pearl millet (*Pennisetum glaucum* (L.) R.Br.). *Crop Improvement*, **36**, 4–7.
- Jambunathan R., Subramanian V. (1988) Grain quality and utilization in sorghum and pearl millet. In: *Biotechnology in Tropical Crop Improvement* eds de Wet J.M.J., Preston T.A. pp. 133–139, ICRISAT, Patancheru, India.
- Kabir K.A., Haque M., Hossain M.A., Dipti S.S., Tetens I. (2003) Breeding for iron-dense rice in Bangladesh. In: *Rice Science: Innovations and Impact for Livelihood* ed Mew T.W. pp. 397–402, International Rice Research Institute, Metro Manila.
- Kempthorne O. (1957) *An Introduction to Genetic Statistics*. John Wiley and Sons, New York.
- Long J.K., Banziger M., Smith M.E. (2004) Diallel analysis of grain iron and zinc density in southern African-adapted maize inbreds. *Crop Science*, **44**, 2019–2026.
- Ma G. (2007) Iron and zinc deficiencies in China: existing problems and possible solutions, PhD thesis, Wageningen University, the Netherlands.
- Maziya-Dixon B., Kling J.G., Menakshi A., Dixon A. (2000) Genetic variation in total carotene, iron, and zinc contents of maize and cassava genotypes. *Food and Nutrition Bulletin*, **21**, 419–422.

- Monasterio I., Graham R.D. (2000) Breeding for trace minerals in wheat. *Food and Nutrition Bulletin*, **21**, 392–396.
- Morgounov A., Gomez-Becerra H.F., Abugalieva A., Dzhunusova M., Yessimbekova M., Muminjanov H., Zelenskiy Y., Ozturk L., Cakmak I. (2007) Iron and zinc grain density in common wheat grown in Central Asia. *Euphytica*, **155**, 193–203.
- Paltridge N.G., Palmer L.J., Milham P.J., Guild G.E., Stangoulis J.C.R. (2012) Energy-dispersive X-ray fluorescence analysis of zinc and iron concentration in rice and pearl millet grains. *Plant and Soil*, (in press), doi:10.1007/s11104-011-1104-4.
- Parthasarathy Rao P., Birthal P.S., Reddy B.V.S., Rai K.N., Ramesh S. (2006) Diagnostics of sorghum and pearl millet grains-based nutrition in India. *International Sorghum and Millets Newsletter*, **47**, 93–96.
- Peleg Z., Saranga Y., Yazici A., Fahima T., Ozturk L., Cakmak I. (2008) Grain zinc, iron and protein concentrations and zinc efficiency in wild emmer wheat under contrasting irrigation regimes. *Plant and Soil*, **306**, 57–67.
- Reddy B.V.S., Ramesh S., Longvah T. (2005) Prospects of breeding for micronutrients and β -carotene-dense sorghums. *International Sorghum and Millets Newsletter*, **46**, 10–14.
- Sehgal S., Kawatra A., Singh G. (2004) Recent advances in pearl millet and sorghum processing and food product development. In: *Alternative Uses of Sorghum and Pearl Millet in Asia*. Proceedings of the Expert Meeting. pp. 60–92, ICRISAT, Patancheru, Andhra Pradesh, India.
- Stein A.J. (2010) Global impacts of human mineral malnutrition. *Plant and Soil*, **335**, 133–154.
- Stein A.J., Qaim M., Meenakshi J.V., Nestel P., Sachdev H.P.S., Bhutta Z.A. (2007) Biofortification, an agricultural micronutrient intervention: its potential impact and cost-effectiveness. In: *Consequences and control of micronutrient deficiencies: science, policy, and programs*. 16–18 April, Istanbul, Turkey.
- Velu G., Bhattacharjee R., Rai K.N., Sahrawat K.L. (2008a) A simple and rapid screening method for grain zinc content in pearl millet. *Journal of SAT Agricultural Research*, **6**, 1–4.
- Velu G., Kulkarni V.N., Rai K.N., Muralidharan V., Longvah T., Sahrawat K.L., Raveendran T.S. (2006) A rapid method for screening grain iron content in pearl millet. *International Sorghum and Millets Newsletter*, **47**, 158–161.
- Velu G., Monasterio I., Singh R.P., Payne T. (2011a) Variation for grain micronutrients in wheat core collections accession of diverse origin. *Asian Journal of Crop Science*, **3**, 43–48.
- Velu G., Rai K.N., Muralidharan V., Kulkarni V.N., Longvah T., Raveendran T.S. (2007) Prospects of breeding biofortified pearl millet with high grain iron and zinc contents. *Plant Breeding*, **126**, 182–185.
- Velu G., Rai K.N., Muralidharan V., Longvah T., Crossa J. (2011b) Gene effects and heterosis for grain iron and zinc density in pearl millet (*Pennisetum glaucum* (L.) R. Br.). *Euphytica*, **180**, 251–259.
- Velu G., Rai K.N., Sahrawat K.L., Sumalini K. (2008b) Variability for grain iron and zinc content in pearl millet hybrids. *Journal of SAT Agricultural Research*, **6**, 1–4.
- Wheal M.S., Fowles T.O., Palmer L.T. (2011) A cost-effective acid digestion method using closed polypropylene tubes for inductively coupled plasma optical emission spectrometry (ICP-OES) analysis of plant essential elements. *Analytical Methods*, **3**, 2854–2863.
- White P.J., Broadley M.R. (2009) Biofortification of crops with seven mineral elements often lacking in human diets -iron, zinc, copper, calcium, magnesium, selenium and iodine. *New Phytologist*, **182**, 49–84.
- WHO. (2002) *The World Health Report: Reducing Risks, Promoting Healthy Life*. World Health Organization, Geneva, pp. 1–168.
- Zhang M.W., Guo B.J., Peng Z.M. (2004) Genetic effects on Fe, Zn, Mn and P contents in *Indica* black pericarp rice and their genetic correlations with grain characteristics. *Euphytica*, **135**, 315–323.