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Evaluation of single cross Quality Protein Maize (QPM) hybrids for kernel iron and zinc concentrations

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Abstract

This study was carried out to ascertain the potential of Quality Protein Maize (QPM) genotypes for attaining desirable kernel iron (Fe) and zinc (Zn) concentrations. Forty two QPM hybrids generated out of seven inbreds varied significantly for kernel Fe and Zn concentrations, and grain yield at both Hyderabad and Delhi locations during 2007-2008. Considering both the micronutrient traits, DQPM-3 × DQPM-2 (Fe=38.46 mg/kg; Zn=39.92 mg/kg) at Hyderabad; and DQPM-7 × DQPM-3 (Fe=30.06 mg/kg; Zn=30.69 mg/kg) at Delhi were identified as the most promising cross combinations. Reciprocal effects for both the micronutrient traits were observed in some of the cross combination. The study revealed the influence of environment in determining the kernel micronutrient traits. Despite the presence of 'dilution effect', superior QPM hybrids with enriched kernel Fe and Zn concentrations were identified in the study. Kernel Fe and Zn concentrations were positively correlated, while no significant associations were found between either of the micronutrients with grain yield, suggesting the possibility of simultaneous improvement of both the kernel micronutrients without negatively impacting grain yield in the QPM hybrids.

Key words: Maize, biofortification, kernel micronutrient, iron, zinc, QPM

Introduction

Micronutrient malnutrition, often called 'hidden hunger', is one of the alarming problems in the developing world [1]. In India, about 230 million people are estimated to be undernourished, accounting for more than 27% of the world's undernourished population [2]. Iron (Fe) deficiency anemia (the most common nutritional disorder) affects 4-5 billion of people worldwide, with more than two billion people in the developing countries. Fe related deficiencies also affect cognitive development, growth, reproductive performance and work productivity [3]. Zinc (Zn) deficiency leads to anorexia, depression, impaired growth and development, altered reproductive biology, gastro-intestinal problems and impaired immunity; it is estimated that about 49 per cent of world population is affected by the Zn deficiency [4, 5].

Measures such as medical supplements and fortification of food products have been attempted in several countries for decades to ameliorate 'hidden hunger' [6, 7]. However, these measures have been only partly successful primarily due to lack of effective distribution system and purchasing power of the poor [8]. Micronutrient-enriched or biofortified maize could potentially serve as a cost-effective and sustainable approach to alleviate micronutrient deficiencies [3, 9]. Available data indicate that the genes necessary for micronutrient enrichment traits are available in the genomes of major staple food crops like rice, wheat and maize, which could allow substantial increase in kernel Fe and Zn concentrations without any negative impact on the grain yield [10]. Biofortified maize holds considerable significance worldwide, including countries like India where a significant proportion (~25%) of maize produced is used for human consumption [11].

In the QPM genotypes, the *opaque2* (*o2*) mutation alters the amino acid profile and composition of the endosperm protein, resulting in 2-3-fold increase in levels of lysine and tryptophan in comparison with non-QPM genotypes [12]. Besides the obvious advantage

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of better protein quality, QPM genotypes were reported to show higher concentration of kernel micronutrients, especially Zn [13-17]. Therefore, the present study was aimed at analyzing the kernel Fe and Zn concentrations along with grain yield among the QPM genotypes.

Materials and methods

A set of seven QPM inbred lines, varying for both kernel Fe and Zn concentrations, were crossed in all possible combinations including the reciprocals, at the IARI Experimental Farm, during monsoon season (*kharif*), 2007. The QPM inbred lines were developed from diverse populations at the Directorate of Maize Research, New Delhi and have been designated here as DQPM-1 to DQPM-7 (Table 1).

The experimental materials, comprising of seven parental lines, 42 cross combinations and one commercial QPM check (HQPM-1) were evaluated at two locations: (i) Maize Winter Nursery, Hyderabad (17°22'N, 78°28'E, 489 masl) during winter season (*rabi*) 2007-08, and (ii) IARI Experimental Farm, New Delhi (28°40'N, 77°12'E, 218 masl) during monsoon (*Kharif*) season 2008. Soil Fe and Zn concentrations at both the experimental sites were estimated at 0-15 cm and 15-30 cm depths, using the standard procedure [18]. The genotypes were planted in randomized complete block design with two replications per entry and one row per replication, with a plant-to-plant spacing of 20 cm and row-to-row spacing of 75 cm. Standard agronomic practices were followed for raising and maintenance of the plants. Five random plants from each row were selfed, while the rest of the plants in each row were allowed to open-pollinate. In each plot, a uniform plant stand of 20 plants was maintained by thinning. For measuring the grain yield per plot (kg), ears from five open-pollinated plants in each plot were sampled, excluding the border plants.

The control-pollinated ears harvested from the plots were used for micronutrient analysis following the protocol suggested by HarvestPlus (www.harvestplus.org/content/cropsampling-protocols-micronutrient-analysis). After kernel maturation and plant dry down, ears with the husk were hand-harvested and dried under clean shade to lower the grain moisture content to 14%. The individual ears were hand-shelled and triplicate grain samples from each ear were collected by the quartering method. The grain samples were dried in an oven for 48h at 60°C and ground into a fine powder using an aluminum mill. Kernel Fe and Zn concentrations were determined by open-air digestion with 9:4 di-acid (HNO_3: $HClO_4$), followed by atomic absorption spectrometry (AAS) method using ECIL AAS. The basic protocol described for multi element analysis [19], with some modifications [18], was followed for estimation of kernel Fe and Zn concentrations. The average F_1 values over replications were used for the estimation of heterosis expressed in percentage over better parent and standard commercial check.

Results and discussion

ANOVA for kernel Fe and Zn concentrations, and grain yield among the experimental crosses and their parents is presented in Table 2. Hybrids varied significantly for kernel Fe and Zn concentrations, and grain yield at both Hyderabad and Delhi locations, suggesting the possibility of selection of promising cross combination

Table 1. Pedigree details of the QPM inbred lines and check used in the study and their mean values for kernel Fe, Zn concentrations and grain yield.

Inbreds	Pedigree/ Source Population	IRON		ZINC		YLD	
		Hyd	Delhi	Hyd	Delhi	Hyd	Delhi
DQPM-1	DMRQPM-28 (Derived from Shakti-1)	18.83	17.73	30.77	31.38	1.00	0.97
DQPM-2	SO/SN Composite (ABP) SN CCB-f-f-#-#-#	17.22	23.14	22.35	36.65	1.75	1.23
DQPM-3	SO/SN Composite (P) ABP 25% -f-f-#-#-#	26.49	20.08	30.44	32.08	2.07	1.02
DQPM-4	DMRQPM Synthetic- Set I inbred line -#-#	22.10	19.94	23.09	33.13	1.31	1.13
DQPM-5	DMRQPM Synthetic- Set II inbred line -#-#	20.57	30.81	29.16	49.14	2.17	1.04
DQPM-6	DMRQPM Synthetic- Set III inbred line-#-#	22.54	19.34	28.85	36.32	1.86	1.16
DQPM-7	DMRQPM Synthetic- Set IV inbred line -#-#	19.44	29.75	26.97	35.67	1.57	1.30
HQPM-1	HKI-193-1 × HKI-163	18.16	10.52	29.67	27.61	2.60	1.91

YLD: Grain yield (kg per plot); IRON: Kernel Fe concentration (mg/kg); ZINC: Kernel Zn concentration (mg/kg). Hyd: Hyderabad *rabi* 2007-08; Delhi: Delhi *kharif* 2008.

Table 2. ANOVA of kernel Fe, Zn concentrations and grain yield among single cross hybrids and parents

Sources of variation	df	Mean sum of squares					
		IRON		ZINC		YLD	
		Hyd	Delhi	Hyd	Delhi	Hyd	Delhi
Replicates	1	4.00	7.50	0.07	0.08	0.06	0.001
Genotypes	48	38.10**	43.67**	28.02**	96.30**	0.26**	0.12**
Parents	6	18.50	55.19**	23.36	72.50**	0.35**	0.03*
Hybrids	41	39.50**	42.33**	28.96**	96.50**	0.20**	0.13**
Parent vs hybrids	1	100.76**	30.71*	17.61**	231.72**	2.21**	0.32**
F_1's	20	26.92**	36.78**	13.27	126.34**	0.17**	0.12**
Reciprocals	20	50.60**	43.80**	45.32**	70.52**	0.24**	0.13**
F_1vs reciprocals	1	67.13**	124.02**	15.50	18.36*	0.01	0.24**
Error	48	8.62	7.00	12.70	4.04	0.02	0.01
Total	97	23.17	25.15	20.15	49.65	0.14	0.06

*Significant at P = 0.05; **Significant at P = 0.01; YLD: Grain yield (kg per plot); IRON: Kernel Fe concentration (mg/kg); ZINC: Kernel Zn concentration (mg/kg). Hyd: Hyderabad *rabi* 2007-08; Delhi: Delhi *kharif* 2008.

for the target traits. Significant variation due to parents vs. hybrids was recorded for kernel Fe and Zn concentrations and grain yield at both the locations. This indicated that effects of genomic constitution among the cross combinations were quite different from their parental inbreds in terms of determining the potential of kernel micronutrients and grain yield. Significant differences for kernel Fe concentration among the direct vs. reciprocal crosses were observed at both locations, while for kernel Zn concentration and grain yield, such differences were significant only at Delhi location. This indicated the importance of choice of female parents and effects of environments in determining kernel micronutrients and grain yield.

Kernel Fe concentration among the inbred parents varied from 17.22-26.49 mg/kg (mean = 21.03 mg/kg) and 17.73-30.81 mg/kg (mean = 22.97 mg/kg) at Hyderabad and Delhi, respectively (Table 1). In case of kernel Zn concentration, range of 22.35-30.77 mg/kg (mean = 27.38 mg/kg) was observed at Hyderabad, while at Delhi it varied from 31.38-49.14 mg/kg with a mean of 36.34 mg/kg. Taking into consideration of both the micronutrients across locations, inbred lines such as DQPM-5 (Fe=25.69 mg/kg; Zn=39.15 mg/kg), DQPM-7 (Fe=24.60 mg/kg; Zn=31.32 mg/kg) and DQPM-3 (Fe=23.29 mg/kg; Zn=31.26 mg/kg) were identified as promising.

In case of hybrids, kernel Fe and Zn concentrations varied from 12.02-38.46 mg/kg and 17.57-47.62 mg/kg, respectively across locations (Table 3). Hybrids such as DQPM-3 × DQPM-2 (38.46 mg/kg), DQPM-3 × DQPM-1 (29.70 mg/kg), DQPM-6 × DQPM-3 (29.31 mg/kg), DQPM-2 × DQPM-6 (29.27 mg/kg) and DQPM-7 × DQPM-4 (29.08 mg/kg) at Hyderabad and DQPM-7 × DQPM-3 (30.06 mg/kg) at Delhi were identified as promising for kernel Fe concentration. In case of kernel Zn concentration, DQPM-3 × DQPM-2 (39.92 mg/kg) was found to be promising at Hyderabad, while eight cross combinations [DQPM-2 × DQPM-4 (47.62 mg/kg), DQPM-1 × DQPM-4 (45.02 mg/kg), DQPM-1 × DQPM-3 (44.91 mg/kg), DQPM-1 × DQPM-7 (44.08 mg/kg), DQPM-7 × DQPM-5 (43.66 mg/kg), DQPM-7 × DQPM-4 (43.56 mg/kg), DQPM-7 × DQPM-1 (42.18 mg/kg) and DQPM-7 × DQPM-2 (41.59 mg/kg)] were observed to be promising at Delhi location.

It is important to note that the highest yielding experimental hybrids displayed significantly low concentration of micronutrients. However, the study led to the identification of some of the cross combinations having high grain yield with reasonably higher concentration of kernel micronutrients. Crosses such as DQPM-4 × DQPM-1 (grain yield=2.49 kg/plot and Zn=32.56 mg/kg), DQPM-4 × DQPM-5 (grain yield=2.35 kg/plot and Zn=32.03 mg/kg) and DQPM-3 × DQPM-4 (grain yield=2.28 kg/plot and Zn=30.71 mg/kg), DQPM-7 × DQPM-5 (grain yield=2.15 kg/plot and Zn=32.19 mg/kg) and DQPM-3 × DQPM-1 (grain yield=2.08 kg/plot and Zn=34.08 mg/kg) at Hyderabad; and DQPM-3

× DQPM-7 (grain yield=1.97 kg/plot and Zn=31.04 mg/kg), DQPM-7 × DQPM-6 (grain yield=1.95 kg/plot and Zn=33.48 mg/kg), at Delhi were identified as promising for both grain yield and kernel Zn (Table 3). In case of kernel Fe, DQPM-2 × DQPM-6 (grain yield=2.16 kg/plot and Fe=29.27 mg/kg) and DQPM-1 × DQPM-3 (grain yield=2.08 kg/plot and Fe=29.70 mg/kg) at Hyderabad were the promising ones, while no such combinations could be observed at Delhi.

The study revealed positive correlation between kernel Fe and Zn concentration (r = 0.64 at Hyderabad and r = 0.43 at Delhi). Some researchers [9, 20-22] also reported such positive correlation earlier. However, none of the kernel micronutrient traits displayed any significant correlation with grain yield (grain yield vs. kernel Fe concentration: r = 0.01 and 0.13 at Hyderabad and Delhi respectively; grain yield vs. kernel Zn concentration: r = 0.06 and 0.02 at Hyderabad and Delhi respectively), suggesting the scope of simultaneous improvement of both the micronutrients without negatively impacting grain yield in the QPM hybrids.

Reciprocal effects were observed in some of the hybrid combinations for kernel Fe and Zn concentrations at both the locations. In case of kernel Fe, DQPM-1 × DQPM-3 (12.02 mg/kg in F_1 and 29.70 mg/kg in RF_1) and DQPM-2 × DQPM-3 (22.67 mg/kg in F_1 and 38.46 in RF_1) at Hyderabad and; DQPM-2 × DQPM-6 (14.01 mg/kg in F_1 and 26.77 mg/kg in RF_1) and DQPM-1 × DQPM-2 (14.07 in F_1 and 24.51 in RF_1) at Delhi are the examples of some of the crosses that exhibited reciprocal effects (Table 3). For kernel Zn, among the experimental hybrids that showed reciprocal effects, DQPM-1 × DQPM-3 (44.91 mg/kg in F_1 and 27.73 mg/kg in RF_1), DQPM-2 × DQPM-4 (47.62 mg/kg in F_1 and 25.49 mg/kg in RF_1), DQPM-2 × DQPM-7 (24.53 mg/kg in F_1 and 41.59 in RF_1) and DQPM-4 × DQPM-7 (17.57 mg/kg in F_1 and 43.56 mg/kg in RF_1) at Delhi were the prominent. Similar trend was also observed in some of the experimental hybrids at Hyderabad. Reciprocal effect, in the given context, could be due to (i) effects of cytoplasm alone or in combination with nuclear genome, and (ii) for kernel related traits in particular, this could be potentially due to the dosage effect. This highlights the importance of proper choice of female and male parents in identifying potential biofortified maize hybrids, especially for kernel micronutrient traits.

Some cross combinations (e.g. DQPM-5 × DQPM-7 for kernel Zn) also exhibited reciprocal effects at Delhi, but not at Hyderabad, while some crosses (e.g., DQPM-3 × DQPM-4 for kernel Fe) exhibited the reverse trend (Table 3). This indicated the potential role of environment in determining the reciprocal effects for both kernel Fe and Zn concentrations. Besides, in some cases, a particular cross combination performed differentially at two locations for both the micronutrients. For example, DQPM-1 × DQPM-3 (12.02 mg/kg at Hyderabad and 23.30 mg/kg at Delhi) and DQPM-2 × DQPM-6 (29.27 mg/kg at Hyderabad and 14.01 mg/kg at Delhi) exhibited the influence of environment on kernel Fe concentration. Similarly, crosses such as DQPM-1 × DQPM-3 (21.96 mg/kg at Hyderabad and 44.91 mg/kg at Delhi) and DQPM-2 × DQPM-3 (39.92 mg/kg at Hyderabad and 26.80 mg/kg at Delhi) showed differential behaviour for kernel Zn concentration under two different environments. The effect of locations on kernel micronutrients in maize has been reported earlier [8, 23].

Micronutrient concentration is affected by various factors such as soil type, soil fertility, interactions among nutrients, other environmental factors and crop genotype [13, 24, 25]. Soil analysis at Hyderabad indicated Fe concentration of 4.76 mg/kg (0-15 cm depth) and 4.70 mg/kg (15-30 cm depth), while the soil Zn concentrations were 0.76 mg/kg and 0.71 mg/kg at 0-15 cm and 15-30 cm depth, respectively. At Delhi, Fe concentration at 0-15 cm soil depth was 4.93 mg/kg and at 15-30 cm depth it was 4.85 mg/kg, while the Zn concentrations at the same depth level were 0.85 mg/kg and 0.78 mg/kg, respectively. This indicated that status of soil at both the locations was more or less of similar nature in terms of Fe and Zn concentrations. Thus, the difference in kernel micronutrients observed in the same set of genotypes grown at two locations, could be attributed to other soil factors, crop growth duration, season and microclimatic effects, besides genotype x environment interactions.

Heterosis for kernel micronutrient traits and grain yield in various experimental hybrids were estimated and presented in Table 4. In case of kernel Fe and Zn concentrations, only heterosis over better parent (heterobeltiosis) was considered, as the commercial check (HQPM-1) displayed relatively lower concentration of kernel Fe (18.16 mg/kg at Hyderabad; 10.52 mg/kg at Delhi) and moderate kernel Zn concentrations (29.67 mg/kg at Hyderabad; 27.61 mg/kg at Delhi). However, for grain yield, standard heterosis was estimated, as HQPM-1 is regarded as a popular commercial QPM variety in India due to its yield performance. In case of kernel Fe concentration, heterosis over the better parent varied from –54.62-

Table 3. Mean values for kernel Fe and Zn concentrations and grain yield in the experimental crosses.

Crosses	Kernel Fe concentration				Kernel Zn concentration				Grain Yield			
	Hyderabad 07-08		Delhi 08		Hyderabad 07-08		Delhi 08		Hyderabad 07-08		Delhi 08	
	F_1	RF_1	F_1	RF_1	F_1	RF_1	F_1	RF_1	F_1	RF_1	F_1	RF_1
P_1 x P_2	19.63	27.17	14.07	24.51	26.59	29.84	31.17	26.57	1.89	1.89	0.98	0.99
P_1 x P_3	12.02	29.70	23.30	14.97	21.96	34.08	44.91	27.73	2.13	2.08	0.99	1.31
P_1 x P_4	23.06	25.22	16.50	14.75	24.03	32.56	45.02	32.72	1.89	2.49	0.88	1.08
P_1 x P_5	23.80	17.84	22.24	19.00	29.85	25.00	33.55	33.26	2.18	2.51	1.29	1.50
P_1 x P_6	20.41	18.18	17.11	14.72	29.88	29.61	29.89	26.33	2.46	1.92	1.21	1.09
P_1 x P_7	19.34	25.28	27.93	27.93	29.13	32.92	44.08	42.18	2.04	1.75	1.33	1.55
P_2 x P_3	22.67	38.46	15.95	25.38	30.56	39.92	29.47	26.8	1.45	1.69	1.18	0.91
P_2 x P_4	26.17	22.63	26.77	24.87	30.95	20.26	47.62	25.49	1.87	1.99	1.50	1.72
P_2 x P_5	20.54	25.54	18.67	16.93	29.38	28.68	31.05	26.70	2.22	2.12	1.15	1.46
P_2 x P_6	29.27	27.33	14.01	26.77	29.85	27.98	29.19	36.15	2.16	2.12	1.22	1.44
P_2 x P_7	26.57	24.93	27.39	24.12	29.41	24.58	24.53	41.59	1.98	2.53	0.87	1.63
P_3 x P_4	27.08	14.62	25.61	25.40	30.71	21.68	27.37	30.43	2.28	2.48	1.04	1.23
P_3 x P_5	25.38	25.19	20.36	25.72	31.3	27.83	25.16	33.37	1.76	1.89	1.22	1.14
P_3 x P_6	22.1	29.31	16.91	23.06	30.94	30.06	22.21	26.49	1.91	1.66	1.21	1.23
P_3 x P_7	21.58	23.49	19.23	30.06	29.15	26.49	31.04	30.69	2.46	2.97	1.97	1.43
P_4 x P_5	22.58	22.54	21.03	23.07	32.03	20.81	24.33	30.06	2.35	1.57	1.39	1.54
P_4 x P_6	25.34	20.02	21.54	18.11	26.49	23.19	33.21	33.16	2.61	2.03	1.27	1.19
P_4 x P_7	23.16	29.08	17.33	27.74	29.2	28.97	17.57	43.56	2.09	1.93	1.18	1.17
P_5 x P_6	21.55	23.97	19.66	18.40	29.96	28.31	33.26	30.22	2.04	1.96	1.29	1.41
P_5 x P_7	26.41	27.80	22.30	25.35	31.76	32.19	28.70	43.66	1.99	2.15	1.47	1.16
P_6 x P_7	24.96	22.88	15.37	25.45	26.20	26.34	27.70	33.48	2.62	2.20	1.27	1.95
SE±	0.80	1.10	0.94	1.03	0.56	1.04	1.74	1.30	0.06	0.08	0.05	0.06

P_1=DQPM-1, P_2= DQPM-2, P_3=DQPM-3, P_4=DQPM-4, P_5= DQPM-5, P_6= DQPM-6, P_7= DQPM-7, F_1: Direct cross; RF_1: Reciprocal cross.

45.19% at Hyderabad, while at Delhi, the range was -48.34-27.54% (Table 4). At Hyderabad, DQPM-3 × DQPM-2 (45.19%) was found to be the best combination, followed by DQPM-2 × DQPM-1 (44.29%), DQPM-2 × DQPM-7 (36.75%), DQPM-7 × DQPM-5 (35.15%), DQPM-7 × DQPM-4 (31.58%) and DQPM-2 × DQPM-6 (29.86%). Only two experimental hybrids showed significant negative heterobeltiosis at Hyderabad, while majority of the experimental hybrids displayed significant negative heterobeltiosis at Delhi. DQPM-3 × DQPM-4 (27.54%) and DQPM-4 × DQPM-3 (26.49%) could be identified as the most promising with significant positive better parent heterosis at Delhi.

Heterobeltiosis values for kernel Zn concentrations varied from –28.63-34.04% and –50.74 –39.99% at Hyderabad and Delhi, respectively. Two cross combinations revealed significant positive better-parent heterosis [DQPM-2 × DQPM-4 (34.04%) and DQPM-3 × DQPM-2 (31.14%)], while one experimental hybrid [DQPM-1 × DQPM-3 (-28.63%)] displayed significant negative heterobeltiosis at Hyderabad (Table 4). Seven experimental hybrids with significant positive heterobeltiosis were also identified at Delhi. DQPM-2 × DQPM-4 displayed significant positive better-parent heterosis at both Hyderabad and Delhi. Similar to kernel Fe, significant negative better parent heterosis for kernel Zn concentration were observed at Delhi for majority of the cross combinations.

Analysis of standard heterosis of grain yield over the QPM check (HQPM-1), revealed DQPM-7 × DQPM-3 (14.23%) as the most promising experimental hybrid at Hyderabad, while none of the experimental hybrids

Table 4. Heterosis for kernel Fe and Zn concentrations and grain yield in the experimental crosses.

Crosses	Heterobeltiosis/ Better Parent Heterosis								Standard Heterosis (over HQPM1)			
	Kernel Fe concentration				Kernel Zn concentration				Grain Yield			
	Hyderabad 07-08		Delhi 08		Hyderabad 07-08		Delhi 08		Hyderabad 07-08		Delhi 08	
	F_1	RF_1	F_1	RF_1	F_1	RF_1	F_1	RF_1	F_1	RF_1	F_1	RF_1
$P_1 \times P_2$	4.25	44.29**	-39.20**	5.92	-13.58	-3.02	-14.95**	-27.50**	-27.31**	-27.31**	-48.69**	-48.17**
$P_1 \times P_3$	-54.62**	12.12	16.04	-25.45	-28.63*	10.76	39.99**	-13.56*	-18.08**	-20.00**	-48.17**	-31.41**
$P_1 \times P_4$	4.34	14.12	-17.25	-26.03	-21.90	5.82	35.89**	-1.24	-27.31**	-4.23	-53.93**	-43.46**
$P_1 \times P_5$	15.70	-13.27	-27.82**	-38.33**	-2.99	-18.75	-31.73**	-32.32**	-16.15**	-3.46	-32.46**	-21.47**
$P_1 \times P_6$	-9.45	-19.34	-11.53	-23.89	-2.89	-3.77	-18.38**	-28.10**	-5.38	-26.15**	-36.65**	-42.93**
$P_1 \times P_7$	-0.46	30.11	-6.12	-6.12	-5.33	6.99	23.58**	18.25**	-21.54**	-32.69**	-30.37**	-18.85**
$P_2 \times P_3$	-14.42	45.19**	-31.07**	9.68	0.39	31.14*	-19.59**	-26.88**	-44.23**	-35.00**	-38.22**	-52.36**
$P_2 \times P_4$	18.42	2.40	15.69	7.48	34.04*	-12.26	29.93**	-30.45**	-28.08**	-23.46**	-21.47**	-9.95
$P_2 \times P_5$	-0.15	24.16	-39.40**	-45.05**	0.79	-1.61	-36.81**	-45.67**	-14.62**	-18.46**	-39.79**	-23.56**
$P_2 \times P_6$	29.86*	21.25	-39.46**	15.69	3.47	-3.02	-20.35**	-1.36	-16.92**	-18.46**	-36.13**	-24.61**
$P_2 \times P_7$	36.75*	28.31	-7.93	-18.92*	9.05	-8.86	-33.07**	13.48*	-23.85**	-2.69	-54.45**	-14.66**
$P_3 \times P_4$	2.23	-44.81**	27.54*	26.49*	0.89	-28.78	-17.39**	-8.15	-12.31*	-4.62	-45.55**	-35.60**
$P_3 \times P_5$	-4.19	-4.91	-33.92**	-16.52	2.83	-8.57	-48.80**	-32.09**	-32.31**	-27.31**	-36.13**	-40.31**
$P_3 \times P_6$	-16.57	10.65	-15.79	14.84	1.64	-1.25	-38.85**	-27.06**	-26.54**	-36.15**	-36.65**	-35.60**
$P_3 \times P_7$	-18.54	-11.33	-35.36**	1.04	-4.24	-12.98	-12.98*	-13.96**	-5.38	14.23*	3.14	-25.13**
$P_4 \times P_5$	2.17	1.99	-31.74**	-25.12**	9.88	-28.61	-50.49**	-38.83**	-9.62	-39.62**	-27.23**	-19.37**
$P_4 \times P_6$	12.42	-11.18	8.02	-9.18	-8.18	-19.62	-8.56	-8.70	0.38	-21.92**	-33.51**	-37.70**
$P_4 \times P_7$	4.80	31.58*	-41.75**	-6.76	8.27	7.42	-50.74**	22.12**	-19.62**	-25.77**	-38.22**	-38.74**
$P_5 \times P_6$	-4.39	6.34	-36.19**	-40.28**	2.78	-2.88	-32.32**	-38.50**	-21.54**	-24.62**	-32.46**	-26.18**
$P_5 \times P_7$	28.39	35.15*	-27.62**	-17.72*	8.95	10.43	-41.60**	-11.15*	-23.46**	-17.31**	-23.04**	-39.27**
$P_6 \times P_7$	10.74	1.51	-48.34**	-14.45	-9.19	-8.70	-23.73**	-7.82	0.77	-15.38**	-33.51**	2.09
SE±	2.94	2.61	3.56	1.99	0.14	0.10						

P_1=DQPM-1, P_2=DQPM-2, P_3=DQPM-3, P_4=DQPM-4, P_5=DQPM-5, P_6=DQPM-6, P_7=DQPM-7; F_1: Direct cross; RF_1: Reciprocal cross *Significant at P = 0.05; **Significant at P = 0.01

could perform significantly better than the check at Delhi (Table 4). The low magnitude of heterosis for grain yield could be due to relatively narrow genetic base of the DQPM lines. Molecular diversity analysis of selected QPM inbred lines developed in India also supports this observation [26]. This also suggests the need for genetic enhancement, development of broad-based QPM pools and isolation of QPM inbred lines with desirable attributes as well as combining ability, besides conversion of elite non-QPM inbreds to QPM versions through molecular marker-assisted selection [27].

Several researchers reported significantly lower kernel Fe and Zn concentrations in non-QPM hybrids as compared to their parents [28, 29]. The lower level of heterosis in terms of concentration of micronutrients could be attributed to the 'dilution effect' in hybrids. Fe and Zn concentrations are higher in the aleurone layer and lower in the endosperm of maize [30]. Micronutrient concentration in the flour samples is therefore highly influenced by kernel size. As the aleurone layer is a single layer surrounding the starchy endosperm, the ratio of surface area of aleurone cell layer and endosperm volume is higher for the kernels of lower endosperm volume. Thus, increased Fe and Zn concentrations in flour may lead to selection for smaller kernel size, leading to lower 100-kernel weight and consequently grain yield. Despite dilution effect, QPM hybrids have revealed considerable potential particularly in Zn biofortification programmes unlike the non-QPM hybrids. The apparent homeostasis for kernel Zn concentration of the QPM inbreds and hybrids may be possibly attributed to the pleiotropic effect of *opaque2* allele or its close linkage with genes responsible for accumulation of higher Zn [13, 17].

In summary, the study reports the potential for exploiting heterosis for enhancing kernel micronutrient concentrations of QPM genotypes. In spite of dilution effects, superior QPM hybrids with enriched micronutrients particularly kernel Zn concentration, could be identified. The study also found that kernel Fe and Zn concentrations were positively correlated and with no adverse correlation with grain yield, suggesting the possibility of simultaneous improvement of both the target traits in high yielding genotypes.

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