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|Research Article|

Genetic Dissection of Heterotic Expression and Inbreeding Depression for Yield, Grain Quality and Micronutrient Enhancement in Rice *(Oryza sativa L.)*

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Abstract- Exploitation of heterosis has become an effective strategy for improving grain yield, grain quality, and nutritional traits in rice. The present investigation was undertaken to estimate heterosis, heterobeltiosis, and inbreeding depression for yield, grain quality, and micronutrient traits in the rice cross ‘Rpbio-226 × Jalmagna’. The experimental material comprising P_1, P_2, F_1, and F_2 generations was evaluated during kharif under irrigated conditions in a randomized block design with two replications. Observations were recorded for days to 50 per cent flowering, plant height, panicle length, productive tillers per plant, filled grains per panicle, grain yield per plant, 1000-grain weight, kernel length, kernel breadth, length/breadth ratio, iron content, and zinc content. Significant positive heterosis over both mid parent and better parent was observed for grain yield per plant, panicle length, and length/breadth ratio. Grain yield per plant recorded high positive heterosis over mid parent (31.75%) and better parent (23.07%) coupled with high inbreeding depression (31.17%), indicating the predominance of non-additive gene action and over-dominance effects. Length/breadth ratio exhibited remarkably high heterobeltiosis (65.70%), reflecting substantial improvement in grain appearance quality. Panicle length exhibited positive heterosis associated with comparatively low inbreeding depression, suggesting the involvement of additive gene effects. Kernel breadth recorded significant negative heterosis, contributing toward desirable slender grain type preferred by consumers. Iron and zinc contents exhibited negative heterotic responses, indicating the complexity involved in simultaneously improving grain yield and micronutrient concentration.The study revealed the importance of both additive and non-additive gene actions in controlling different agronomic, grain quality, and micronutrient traits. The cross ‘Rpbio-226 × Jalmagna’ demonstrated substantial heterotic potential for grain yield and grain quality traits and may serve as a valuable genetic resource for developing superior rice hybrids with improved productivity and consumer-preferred grain characteristics.

Keywords: Rice, heterosis, heterobeltiosis, inbreeding depression, grain quality, iron, zinc, biofortification

Introduction

Rice (Oryza sativa L.) is one of the most important cereal crops cultivated worldwide and constitutes the staple food for more than half of the global population, particularly in Asian countries where rice forms the foundation of food and nutritional security (Gross and Zhao, 2014). Globally, rice is cultivated over approximately 165 million hectares with an annual production exceeding 750 million tonnes, thereby contributing significantly to agricultural economies and livelihood security in developing nations. In India, rice plays a crucial role in food security, nutrition, employment generation, and rural livelihoods. Rapid population growth, urbanization, climate change, shrinking cultivable land, and declining water resources have created an urgent need for developing rice varieties possessing higher yield potential along with superior grain quality and nutritional value (Khush, 2013). Future rice improvement programmes must therefore focus not only on productivity enhancement but also on improving nutritional quality to address emerging health challenges. Micronutrient malnutrition, commonly referred to as "hidden hunger," affects billions of people worldwide, particularly in developing countries where cereal-based diets predominate (Cakmak, 2002; White and Broadley, 2009). Iron and zinc deficiencies are among the most widespread nutritional disorders and are associated with anemia, impaired immunity, reduced growth, and cognitive disorders (WHO, 2002; Stein, 2010). Since rice is consumed as a staple food by a large section of the population, enhancement of grain iron and zinc concentration through biofortification has gained considerable importance. However, simultaneous improvement of grain yield and micronutrient concentration remains difficult because of complex inheritance patterns and the negative association often observed between productivity and nutrient accumulation. Exploitation of heterosis has emerged as one of the most effective approaches for increasing rice productivity and breaking the yield ceiling of semi-dwarf rice cultivars. Commercial hybrid rice technology has demonstrated yield advantages of nearly 20–25 per cent over conventional inbred varieties (Peng and Virmani, 1991). The magnitude of heterosis largely depends upon the degree of genetic divergence between parental lines and the nature of gene action governing the traits (Onyia et al., 2012). Estimation of heterosis and inbreeding depression provides valuable information regarding the relative importance of additive and non-additive gene effects and helps breeders formulate appropriate breeding strategies for crop improvement (Falconer and Mackay, 1996). Several earlier investigations reported substantial heterosis for productive tillers, panicle length, grain yield, and test weight in rice hybrids, indicating the importance of dominance and over-dominance effects in controlling these traits (Ananda Kumar and Sreeranga Swamy, 1986; Ganeshan et al., 1997; Gourishankar et al., 2010). Similarly, grain quality parameters such as kernel length, kernel breadth, and length/breadth ratio are important determinants of market acceptability and consumer preference. Significant heterosis for grain quality traits has also been documented by Raju et al. (2003) and Sanjeevkumar et al. (2010), suggesting the possibility of simultaneous improvement of productivity and grain quality through heterosis breeding. Despite considerable progress in rice heterosis breeding, limited information is available regarding the simultaneous inheritance of yield, grain quality, and micronutrient traits through heterosis and inbreeding depression analysis in biofortified rice crosses. Therefore, the present investigation was undertaken in the rice cross 'Rpbio-226 × Jalmagna' with the following objectives of estimating heterosis and heterobeltiosis for yield, grain quality, and micronutrient traits, assessment of the extent of inbreeding depression in the F_2 generation, understanding the nature of gene action governing different characters and identification of promising breeding approaches for developing superior rice hybrids combining high yield, desirable grain quality, and improved nutritional value.

Materials and Methods

The present investigation was carried out at the Directorate of Rice Research (DRR), ICRISAT, Patancheru, Hyderabad, Telangana during the kharif season under irrigated conditions. The experimental site is situated at 17.53°N latitude and 78.16°E longitude with an altitude of 545 m above mean sea level. The climate of the region is semi-arid tropical with moderate rainfall during the cropping season. The experimental material consisted of the rice cross 'Rpbio-226 × Jalmagna'. Rpbio-226 (Improved Samba Mahsuri) is a high-yielding semi-dwarf rice cultivar possessing superior grain quality, whereas Jalmagna is a traditional genotype known for relatively higher iron and zinc contents. Hybridization between the parental lines was carried out through clipping and hand emasculation-pollination techniques to obtain F_1 seeds. The F_2 generation was subsequently developed through selfing of F_1 plants. The experimental material comprising P_1, P_2, F_1, and F_2 generations was evaluated in a randomized block design with two replications. Each entry was transplanted in rows of 3 m length with a spacing of 20 cm between rows and 10 cm between plants. Recommended agronomic practices and necessary plant protection measures were followed uniformly throughout the crop growth period. Observations were recorded on five randomly selected plants from each replication for days to 50 per cent flowering, plant height (cm), panicle length (cm), productive tillers per plant, filled grains per panicle, grain yield per plant (g), 1000-grain weight (g), kernel length (mm), kernel breadth (mm), length/breadth ratio, iron content, and zinc content. Grain iron and zinc concentrations were estimated using Energy Dispersive X-ray Fluorescence (EDXRF) spectrometry. Mid-parent heterosis, better-parent heterosis (heterobeltiosis), and inbreeding depression were estimated following the methods suggested by Turner

(1953), Hayes et al. (1956), and Wynne et al. (1970), respectively. The significance of heterotic effects was tested using 't' tests as described by Wynne et al. (1970). Statistical analyses were carried out following standard biometrical procedures.

Results

Heterosis and Inbreeding Depression for Flowering and Plant Architecture Traits

Days to 50 per cent flowering exhibited significant negative mid-parent heterosis (-4.60%), whereas heterobeltiosis was non-significant (-0.91%). The F_2 generation showed negligible inbreeding depression (0.28%), suggesting relatively lower influence of dominance effects and partial involvement of additive gene action. Plant height recorded positive heterosis over both mid parent and better parent with highly significant heterobeltiosis (49.91%) and considerable inbreeding depression (22.20%). The high magnitude of heterosis coupled with substantial inbreeding depression indicated the predominance of dominance and over-dominance gene effects controlling this trait. Panicle length exhibited significant positive heterosis over both mid parent (4.86%) and better parent (3.72%) along with comparatively low inbreeding depression (7.23%). The results suggested the involvement of additive and additive × additive gene interactions governing this trait.

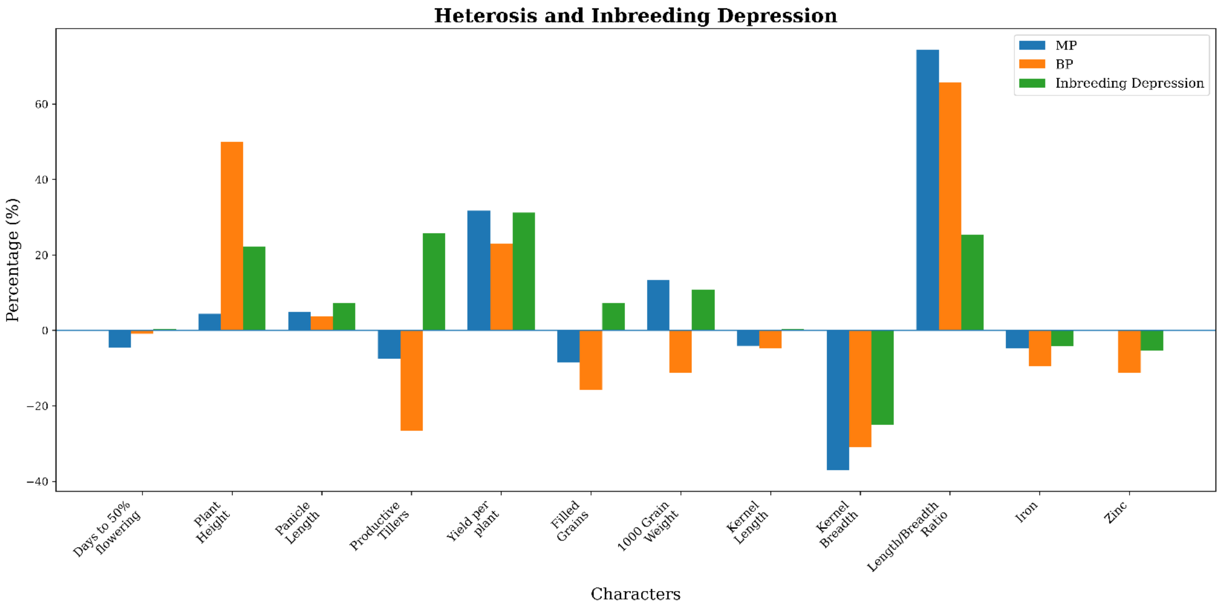

Fig. 1. Heterosis and Inbreeding Depression for Yield and Quality Traits in Rice

Heterosis for Yield and Yield-Contributing Traits

Productive tillers per plant exhibited significant negative heterosis over both mid parent (-7.48%) and better parent (-26.57%) coupled with high inbreeding depression (25.71%). The substantial inbreeding depression indicated the importance of non-additive gene effects and epistatic interactions controlling tiller production. Grain yield per plant recorded highly significant positive heterosis over mid parent (31.75%) and better parent (23.07%) along with very high inbreeding depression (31.17%). The high heterotic response demonstrated marked superiority of the F_1 hybrid over both parents for grain productivity. Filled grains per panicle exhibited negative heterosis over both parental values with comparatively low inbreeding depression (7.28%). The results suggested relatively greater involvement of additive gene effects for this trait. The trait 1000-grain weight exhibited significant positive mid-parent heterosis (13.31%) but negative heterobeltiosis (-11.29%) with moderate inbreeding depression (10.74%). The results indicated partial involvement of dominance effects governing grain weight inheritance.

Heterosis for Grain Quality Traits

Kernel length exhibited significant negative heterosis over both mid parent (-4.06%) and better parent (-4.81%) with negligible inbreeding depression (0.27%), indicating relatively stable inheritance across generations. Kernel breadth recorded highly significant negative heterosis over both mid parent (-37.10%) and better parent (-30.85%) accompanied by negative inbreeding depression (-25.06%). Negative heterosis for kernel breadth is considered desirable because slender grains are generally preferred by consumers. Length/breadth ratio exhibited remarkably high positive heterosis over mid parent (74.39%) and better parent (65.70%) coupled with high inbreeding depression (25.31%). The substantial heterotic response indicated marked improvement in grain appearance quality in the F_1 hybrid.

Heterosis for Micronutrient Traits

Iron content exhibited significant negative heterosis over both mid parent (-4.77%) and better parent (-9.41%) with low negative inbreeding depression (-4.23%). Similarly, zinc content exhibited negligible mid-parent heterosis (0.08%) but significant negative heterobeltiosis (-11.21%) along with low negative inbreeding depression (-5.26%). The negative heterotic responses observed for iron and zinc contents indicated the complexity involved in simultaneously improving grain yield and micronutrient concentration.

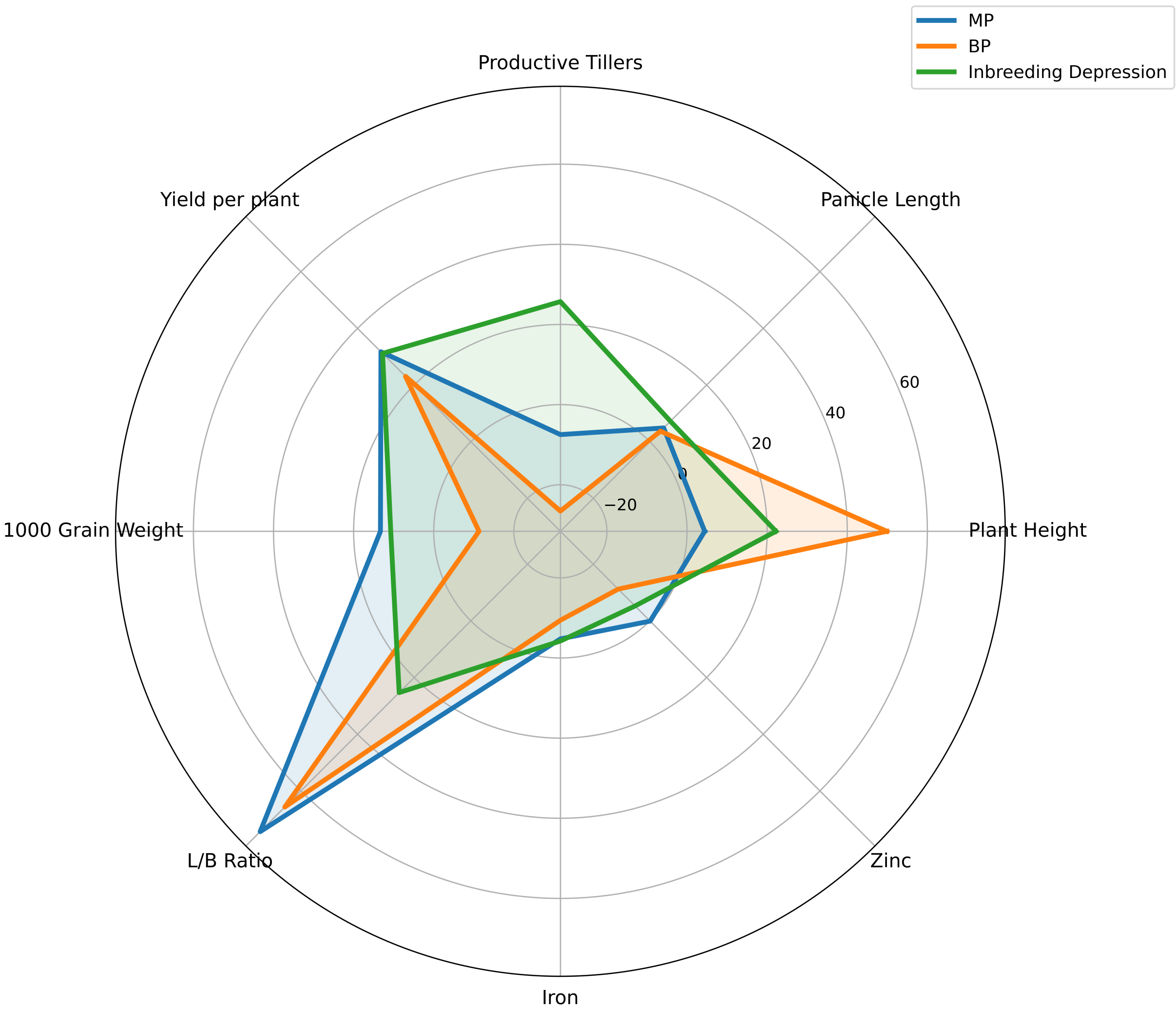

Fig. 2. Radar diagram of heterosis, heterobeltiosis and inbreeding depression in the rice cross ‘Rpbio-226 × Jalmagna’.

Table 1. Estimates of heterosis, heterobeltiosis and inbreeding depression in the cross 'Rpbio-226 X Jalmagna'

S.No.	Character	Heterosis percent over		Inbreeding Depression
		MP	BP	
1	Days to 50% flowering	-4.60**	-0.91	0.28
2	Plant Height	4.41	49.91**	22.20**
3	Panicle Length	4.86**	3.72**	7.23**
4	Productive Tillers	-7.48**	-26.57**	25.71**
5	Yield per plant	31.75**	23.07**	31.17**
6	Filled Grains	-8.48	-15.86	7.28
7	1000 Grain Weight	13.31**	-11.29**	10.74*
8	Kernel Length	-4.06**	-4.81**	0.27**
9	Kernel Breadth	-37.10**	-30.85**	-25.06**
10	Length/Breadth Ratio	74.39**	65.70**	25.31**
11	Iron	-4.77**	-9.41**	-4.23**
12	Zinc	0.08	-11.21**	-5.26**

Discussion

The present investigation revealed substantial heterotic variation among agronomic, grain quality, and micronutrient traits, indicating the involvement of diverse genetic mechanisms governing their inheritance. Traits exhibiting high heterosis coupled with high inbreeding depression are generally considered to be predominantly controlled by non-additive gene action and over-dominance effects, whereas traits showing low inbreeding depression are often governed by additive gene effects (Falconer and Mackay, 1996). The significant negative heterosis observed for days to 50 per cent flowering indicated the possibility of developing early-duration hybrids suitable for intensive cropping systems and climate-resilient agriculture. Earliness enables efficient utilization of available resources and escape from terminal drought conditions. Similar desirable negative heterosis for flowering duration was reported earlier by Rashid et al. (2017) and Kumari and Senapati (2019). The high heterotic response observed for plant height and grain yield per plant may be attributed to favorable dominance interactions governing photosynthetic efficiency, assimilate partitioning, sink strength, and spikelet fertility. Grain yield is a complex quantitative trait influenced by several interrelated component characters and environmental factors. The simultaneous occurrence of high heterosis and high inbreeding depression for grain yield indicated predominance of over-dominance effects and suggested that exploitation through hybrid breeding would be more effective than direct selection in segregating generations. Similar findings were reported by Alam et al. (2004), Borah and Barman (2010), and Gourishankar et al. (2010). Panicle length exhibited positive heterosis associated with comparatively low inbreeding depression, suggesting the involvement of additive and additive × additive gene interactions. Longer panicles generally possess greater spikelet-bearing capacity and contribute positively toward grain productivity. Similar results were also reported by Elsy (1997), Bharathi (1998), and Pandya and Tripathi (2006). The substantial improvement observed in length/breadth ratio resulted mainly from marked reduction in kernel breadth while maintaining adequate kernel length. Grain shape and appearance quality are among the most important determinants of consumer preference and market acceptability in rice. The high heterotic response observed for length/breadth ratio indicated the possibility of improving grain quality through heterosis breeding. Similar findings were reported by Raju et al. (2003) and Sanjeevkumar et al. (2010). The negative heterotic responses observed for iron and zinc contents may be attributed to dilution effects associated with increased biomass accumulation and grain yield. Micronutrient accumulation in rice grains is quantitatively inherited and influenced by complex physiological mechanisms including uptake efficiency, translocation, and deposition within endosperm tissues. Similar negative associations between productivity and micronutrient concentration were reported. These findings suggest that specialized breeding approaches such as recurrent selection, genomic selection, and marker-assisted breeding may be required for simultaneous improvement of grain yield and micronutrient density.

Breeding Implications

The present study demonstrated that grain yield per plant and length/breadth ratio are predominantly governed by non-additive gene action and therefore can be effectively exploited through heterosis breeding programmes. Panicle length exhibited relatively greater additive gene effects, suggesting that selection in segregating generations may be effective for improving this trait. The desirable reduction in kernel breadth indicated the possibility of improving grain appearance quality and consumer preference through appropriate parental combinations. However, the negative heterotic responses observed for iron and zinc contents highlighted the complexity involved in combining high productivity with enhanced nutritional quality. Integration of conventional breeding approaches with molecular breeding and biofortification strategies may therefore be necessary for developing nutritionally superior rice cultivars.

Conclusion

The present investigation on the rice cross 'Rpbio-226 × Jalmagna' revealed considerable heterotic potential for important agronomic and grain quality traits. Significant positive heterosis was observed for grain yield per plant, panicle length, and length/breadth ratio, indicating the usefulness of this cross for improving productivity and grain appearance quality in rice. Grain yield per plant and length/breadth ratio exhibited high heterosis coupled with high inbreeding depression, indicating the predominance of non-additive gene action and over-dominance effects. These traits can therefore be effectively exploited through heterosis breeding programmes. In contrast, panicle length exhibited comparatively low inbreeding depression despite positive heterosis, suggesting the involvement of additive gene effects and the possibility of effective selection in segregating generations. Kernel breadth exhibited desirable negative heterosis contributing toward slender grain type preferred by consumers. However, iron and zinc contents showed negative heterotic responses, indicating the existence of an inverse relationship between productivity and micronutrient concentration. Overall, the study demonstrated the potential of integrating heterosis breeding with biofortification approaches for developing superior rice hybrids possessing high yield potential, desirable grain quality, and improved nutritional characteristics.

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