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|Research Article|

Quantitative Genetic Perspectives on Hybrid Vigour and Inbreeding Depression for Yield Grain Quality and Biofortification Traits in Rice *(Oryza sativa L.)*

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Abstract- Hybrid vigour plays an important role in enhancing productivity and nutritional quality in rice breeding programmes. The present study was conducted to assess the extent of heterosis, heterobeltiosis and inbreeding depression for yield, grain quality and micronutrient traits in the rice cross 'Swarna × Madhukar'. The experimental material consisted of P_1, P_2, F_1 and F_2 generations evaluated during kharif under irrigated conditions. Significant positive heterosis over both mid parent and better parent was observed for productive tillers per plant, plant height, grain yield per plant and iron content. Productive tillers per plant expressed the highest mid-parent heterosis (62.26%) and heterobeltiosis (52.21%) accompanied by substantial inbreeding depression (25.90%), suggesting the importance of dominance and over-dominance effects in the inheritance of this trait. Grain yield per plant also exhibited high positive heterosis over mid parent (34.07%) and better parent (8.50%) with considerable inbreeding depression (32.39%), indicating substantial contribution of non-additive genetic interactions toward yield expression. Iron content recorded positive heterotic response over both parental values, reflecting the possibility of improving grain nutritional quality through hybridization. In contrast, traits such as panicle length, kernel length and length/breadth ratio exhibited comparatively low heterosis and low inbreeding depression, suggesting relatively greater involvement of additive genetic effects. The results revealed that both additive and non-additive genetic components contributed to the inheritance of the studied traits. The cross 'Swarna × Madhukar' demonstrated considerable potential for exploitation in heterosis breeding and rice biofortification programmes.

Keywords: Rice, hybrid vigour, heterobeltiosis, inbreeding depression, grain quality, micronutrients, biofortification

Introduction

Rice (Oryza sativa L.; 2n = 24), belonging to the family Poaceae, is one of the most extensively cultivated cereal crops and serves as a major source of food and energy for a large proportion of the global population. The crop plays a crucial role in ensuring food and nutritional security, particularly in Asian countries where it constitutes a major dietary component (Muthayya et al., 2014).

Globally, rice is cultivated over approximately 165 million hectares with annual production exceeding 750 million tonnes, thereby contributing substantially to global caloric intake and agricultural economies (GRiSP, 2013). In India, rice cultivation is closely associated with rural livelihoods, employment generation and socioeconomic stability. Owing to continuous population growth, shrinking cultivable land, climate variability and changing consumer preferences, there is increasing demand for development of high-yielding rice cultivars possessing superior grain quality and enhanced nutritional value (Khush, 2013). Rice also serves as an important source of carbohydrates, proteins, minerals and vitamins for millions of people in developing countries, emphasizing its central role in nutritional security and sustainable agriculture (Muthayya et al., 2014; Shahidullah et al., 2009). Conventional breeding approaches contributed substantially toward enhancement of rice productivity during the Green Revolution era; however, the rate of yield improvement has gradually slowed in recent decades. Under such circumstances, exploitation of heterosis has emerged as an effective strategy for overcoming the existing yield plateau and improving productivity potential in rice. Hybrid rice technology has demonstrated considerable success in enhancing grain yield through utilization of favourable dominance interactions and genetic complementation between genetically diverse parental lines (Virmani Kumar, 2004). The magnitude of heterosis largely depends upon the genetic divergence of parental genotypes and the nature of gene action governing economically important traits (Falconer Mackay, 1996). Consequently, heterosis breeding has become an important component of modern rice improvement programmes aimed at achieving higher productivity and stability under diverse agro-climatic conditions. Estimation of heterosis, heterobeltiosis and inbreeding depression provides valuable insight into the inheritance pattern of quantitative traits and assists breeders in formulating suitable breeding strategies. Traits exhibiting high heterosis coupled with high inbreeding depression are generally associated with non-additive genetic interactions and are more amenable to hybrid breeding approaches. In contrast, traits exhibiting relatively low inbreeding depression are likely to possess greater additive genetic control and may be effectively improved through selection in segregating generations (Falconer Mackay, 1996). Several earlier investigations have reported substantial heterosis for grain yield, productive tillers, panicle length, filled grains and other yield-contributing traits in rice hybrids (Alam et al., 2004; Pandya Tripathi, 2006; Seyoum et al., 2012). Positive heterotic responses for grain yield and its associated traits have also been reported by Rahimi et al. (2010), Hasan et al. (2012) indicating the importance of dominance effects in the inheritance of these economically important characters. Apart from grain yield, grain quality has become an equally important breeding objective because of its direct influence on consumer preference, cooking quality, milling recovery, market value and export potential. Grain quality traits such as kernel length, kernel breadth and length/breadth ratio largely determine the commercial acceptability of rice varieties and hybrids. Improvement in grain quality is therefore essential for meeting consumer demand and enhancing the economic value of rice cultivars. Significant heterotic responses for grain quality traits have been reported by Raju et al. (2003), Sanjeevkumar et al. (2010) and Babu et al. (2012) indicating the possibility of improving grain appearance and cooking quality through hybridization. Simultaneously, micronutrient malnutrition, particularly deficiencies of iron and zinc, has emerged as a serious public health concern in many developing countries where rice constitutes the principal staple food. Hidden hunger resulting from inadequate micronutrient intake affects millions of people worldwide, especially women and children. Therefore, biofortification of rice with elevated iron and zinc concentration has gained considerable importance as a sustainable and cost-effective strategy for improving nutritional security (Bouis Welch, 2010). Recent advances in rice biofortification research have demonstrated the feasibility of developing nutritionally enriched rice cultivars with improved grain micronutrient concentration. However, simultaneous improvement of grain yield, grain quality and micronutrient concentration remains a major challenge because of complex genetic relationships and possible trade-offs among these traits . Although several studies have independently reported heterosis for yield and grain quality traits, information regarding simultaneous inheritance of yield, grain quality and micronutrient traits in nutritionally important rice crosses remains limited. Therefore, the present investigation involving the rice cross 'Swarna × Madhukar' was undertaken to estimate the magnitude of heterosis, heterobeltiosis and inbreeding depression for yield, grain quality and micronutrient traits and to understand the nature of gene action governing these characters for their effective utilization in rice improvement programmes.

Materials and Methods

The experiment was conducted during the kharif season at the Directorate of Rice Research (DRR), ICRISAT, Patancheru, Hyderabad, Telangana under irrigated conditions. The experimental location lies at 17.53°N latitude and 78.16°E longitude with an altitude of 545 m above mean sea level. The region experiences semi-arid tropical climatic conditions. The experimental material consisted of the rice cross 'Swarna × Madhukar'. Swarna is a popular high-yielding variety known for its adaptability and stable performance, whereas Madhukar possesses desirable grain quality and nutritional attributes. Crosses were made through clipping and hand emasculation techniques to generate F_1 seed, and the F_2 population was subsequently raised through selfing of F_1 plants. The parental lines along with F_1 and F_2 generations were evaluated in a randomized block design with two replications. Each entry was transplanted in 3 m rows maintaining a spacing of 20 × 10 cm between rows and plants, respectively. Recommended

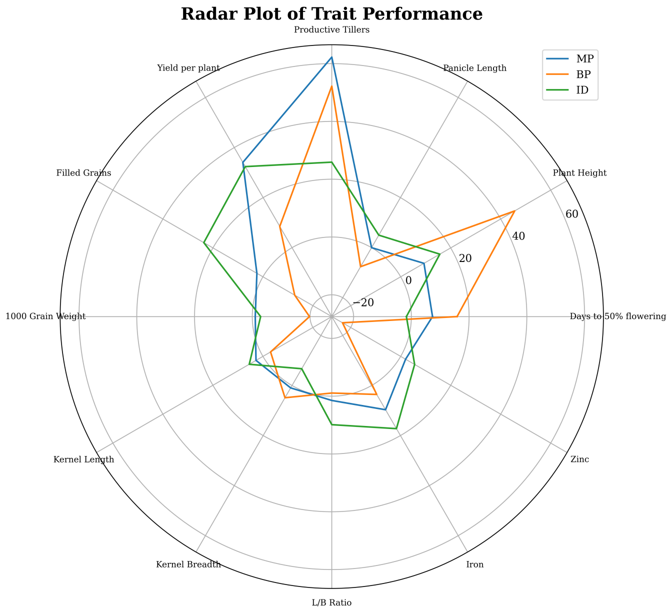

Fig. 1. Radar Visualization of Yield, Quality and Micronutrient Traits

agronomic practices and crop protection measures were followed uniformly throughout the crop growth period. Data were recorded on five randomly selected plants in each replication 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. Iron and zinc concentrations were estimated using Energy Dispersive X-ray Fluorescence (EDXRF) spectrometry. Heterosis over mid parent, heterobeltiosis over better parent and inbreeding depression were estimated following the methods suggested by Turner (1953), Hayes et al. (1956) and Wynne et al. (1970), respectively. Significance of heterotic effects was tested using standard 't' tests.

Results and Discussion

Days to 50 %Flowering

Days to 50 per cent flowering exhibited significant positive heterosis over both mid parent (7.34%) and better parent (15.84%), whereas inbreeding depression was negligible and negative (-1.71%). The positive heterotic response indicated delayed flowering behaviour in the F_1 generation compared with the parental lines. The low magnitude of inbreeding depression suggested relatively greater additive genetic influence together with partial contribution of dominance effects in the inheritance of this trait.

Plant Height

Plant height recorded significant positive heterosis over both mid parent (9.31%) and better parent (45.60%) along with appreciable inbreeding depression (15.66%). The substantial heterobeltiosis observed for this trait reflected strong hybrid vigour for vegetative growth and biomass accumulation. High heterosis associated with considerable inbreeding depression suggested substantial contribution of non-additive genetic interactions in the inheritance of plant height. Increased plant stature may contribute toward enhanced vegetative growth and photosynthetic surface area; however, excessive plant height may also increase susceptibility to lodging under intensive cultivation conditions. Comparable positive heterosis for plant height in rice was reported by Ananda Kumar and Sreeranga Swamy (1986), Verma et al. (2004) and Saravanan et al. (2006).

Panicle Length

Panicle length exhibited negligible mid-parent heterosis (0.00%) and negative heterobeltiosis (-7.60%) with comparatively low inbreeding depression (5.00%). The relatively low magnitude of heterosis and inbreeding depression suggested comparatively greater contribution of additive genetic effects in the inheritance of this trait. Panicle length is an important yield-contributing character influencing spikelet-bearing capacity and grain production. The comparatively stable expression of this trait across generations suggested that improvement through selection in segregating populations may be effective. Similar observations were reported by Pandya and Tripathi (2006).

Productive Tillers per Plant

Productive tillers per plant exhibited remarkably high positive heterosis over both mid parent (62.26%) and better parent (52.21%) coupled with substantial inbreeding depression (25.90%). The superior tillering ability observed in the F_1 generation reflected strong hybrid vigour for this character. Productive tillers directly influence panicle density, sink strength and overall assimilate partitioning efficiency in rice. High heterosis associated with substantial inbreeding depression suggested the importance of dominance and over-dominance effects governing this trait. The reduction observed in the F_2 generation may be attributed to segregation and breakdown of favourable gene combinations present in the F_1 hybrid. Comparable findings were reported by Ganeshan et al. (1997) and Gourishankar et al. (2010).

Grain Yield per Plant

Grain yield per plant recorded substantial positive heterosis over both mid parent (34.07%) and better parent (8.50%) together with high inbreeding depression (32.39%). The superior performance of the F_1 hybrid indicated favourable genetic interactions contributing toward enhanced grain productivity. Grain yield is governed by complex interactions among tillering ability, assimilate translocation, grain filling efficiency and source–sink balance. The simultaneous occurrence of high heterosis and substantial inbreeding depression suggested a major contribution of non-additive gene effects and indicated that exploitation through heterosis breeding may be more effective than direct selection in segregating generations. Similar positive heterosis for grain yield in rice was reported by Alam et al. (2004), Borah and Barman (2010) and Gourishankar et al. (2010).

Filled Grains per Panicle

Filled grains per panicle exhibited low positive mid-parent heterosis (2.41%) and negative heterobeltiosis (-12.71%) but recorded considerable inbreeding depression (23.64%). Although the trait did not exhibit appreciable heterotic superiority, the relatively high magnitude of inbreeding depression suggested the involvement of dominance effects and epistatic interactions. Reduction in grain filling efficiency in the segregating generation may have resulted from disruption of favourable gene combinations present in the F_1 hybrid. Similar observations regarding inheritance of filled grains per panicle were reported by Ganeshan et al. (1997).

1000-Grain Weight

The trait 1000-grain weight exhibited slight negative heterosis over both mid parent (-1.03%) and better parent (-19.83%) along with negligible negative inbreeding depression (-2.90%). The comparatively low magnitude of heterosis and inbreeding depression indicated relatively stable inheritance of grain weight across generations. Grain weight is an important yield-contributing trait influencing both productivity and market value. The comparatively stable inheritance of this trait suggested relatively greater additive genetic influence.

Kernel Length

Kernel length exhibited positive mid-parent heterosis (2.77%) but negative heterobeltiosis (-3.06%) associated with low inbreeding depression (5.47%). The low heterotic response and comparatively stable inheritance suggested relatively greater involvement of additive gene effects. Kernel length is an important grain quality parameter influencing consumer preference and market acceptability. The low magnitude of inbreeding depression indicated that effective improvement through selection in advanced generations may be possible. Similar observations regarding grain quality traits in rice were reported by Raju et al. (2003).

Kernel Breadth

Kernel breadth recorded slight positive heterosis over both mid parent (0.95%) and better parent (4.88%) together with negative inbreeding depression (-6.71%). The relatively low heterotic response observed for this trait indicated limited hybrid superiority. Kernel breadth contributes significantly toward grain appearance and cooking quality. The negative inbreeding depression suggested comparatively stable inheritance and possible fixation of favourable alleles in segregating generations.

Length/Breadth Ratio

Length/breadth ratio exhibited low positive mid-parent heterosis (1.48%) and slight negative heterobeltiosis (-1.09%) coupled with comparatively low inbreeding depression (9.86%). The results suggested relatively greater involvement of additive and additive × additive genetic interactions in controlling grain shape. Length/breadth ratio is an important determinant of grain appearance quality and market preference in rice. The comparatively low inbreeding depression indicated stable inheritance and greater scope for improvement through selection. Similar findings for grain quality traits were reported by Sanjeevkumar et al. (2010).

Iron Content

Iron content recorded significant positive heterosis over both mid parent (9.68%) and better parent (3.56%) accompanied by appreciable inbreeding depression (17.23%). The positive heterotic response observed for iron concentration indicated partial dominance effects governing micronutrient accumulation in rice grains. Improvement of grain iron concentration is an important objective in rice biofortification programmes aimed at alleviating micronutrient malnutrition. Iron accumulation in rice grains involves nutrient uptake, translocation and remobilization processes during grain development. The moderate inbreeding depression suggested involvement of both additive and non-additive gene effects in controlling iron accumulation. Comparable findings regarding rice biofortification were reported.

Zinc Content

Zinc content exhibited low positive mid-parent heterosis (1.96%) but significant negative heterobeltiosis (-23.27%) together with moderate inbreeding depression (5.58%). The negative heterobeltiosis indicated limited hybrid superiority for zinc accumulation in the present cross. Zinc accumulation in rice grains is governed by complex physiological and genetic mechanisms involving nutrient uptake, translocation and deposition within grain tissues. The moderate inbreeding depression suggested involvement of both additive and non-additive gene effects in the inheritance of this trait. Similar observations regarding zinc inheritance and biofortification in rice were reported.

Table 1. Estimates of heterosis, heterobeltiosis and inbreeding depression in the cross ‘Swarna X Madhukar’

S.No.	**Character**	**Heterosis percent over**		**Inbreeding Depression**
		MP	**BP**	
1	Days to 50% flowering	7.34**	15.84**	-1.71
2	Plant Height	9.31*	45.60**	15.66**
3	Panicle Length	0.00**	-7.60**	5.0**
4	Productive Tillers	62.26**	52.21**	25.901**
5	Yield per plant	34.07**	8.50**	32.39**
6	Filled Grains	2.41	-12.71	23.64**
7	1000 Grain Weight	-1.03	-19.83**	-2.90
8	Kernel Length	2.77**	-3.06**	5.47**
9	Kernel Breadth	0.95**	4.88**	-6.71**
10	Length/Breadth Ratio	1.48**	-1.09**	9.86**
11	Iron	9.68**	3.56**	17.23**
12	Zinc	1.96	-23.27**	5.58**

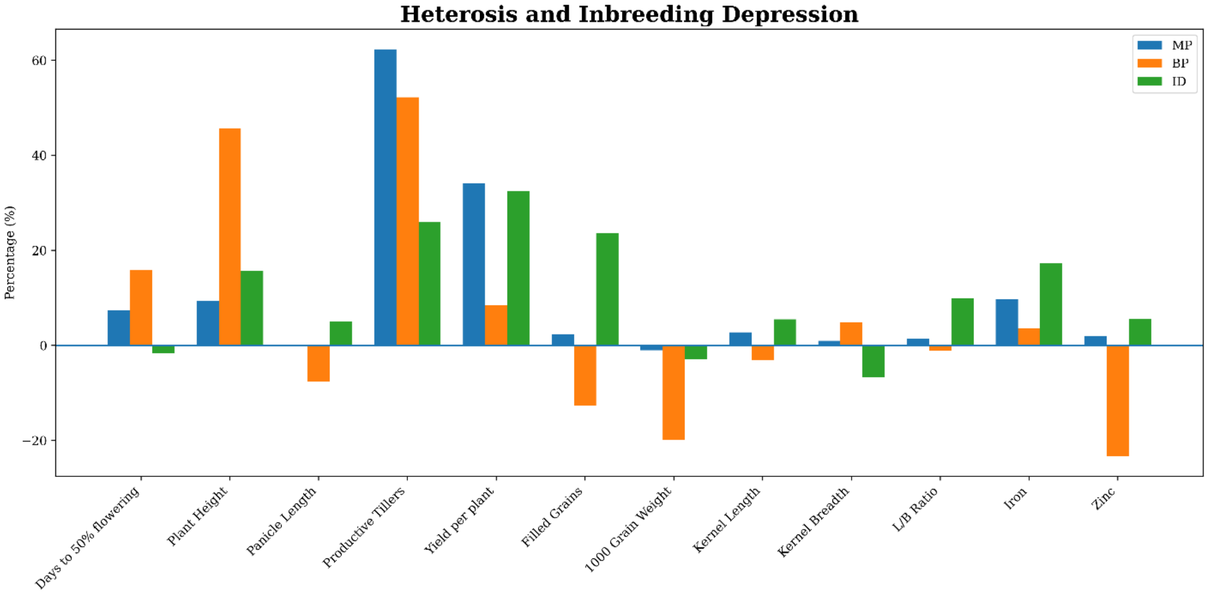

Fig. 2. Graphical Representation of Heterotic Response and Inbreeding Depression in Rice

Conclusion

The present investigation revealed considerable heterotic potential in the rice cross 'Swarna × Madhukar' for several agronomic, yield and nutritional traits. Productive tillers per plant, grain yield per plant and plant height exhibited substantial positive heterosis associated with appreciable inbreeding depression, indicating the importance of non-additive genetic interactions and the suitability of these traits for exploitation through heterosis breeding. In contrast, traits such as panicle length, kernel length and length/breadth ratio exhibited relatively low heterosis and lower inbreeding depression, suggesting comparatively greater additive genetic control and the possibility of effective improvement through selection in segregating generations. Iron content exhibited positive heterotic response over both parental values, highlighting the usefulness of the cross for rice biofortification programmes. Overall, the cross 'Swarna × Madhukar' may serve as a promising genetic resource for development of high-yielding rice hybrids possessing improved grain quality and enhanced nutritional value.

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