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Heterosis Analysis for Yield and Resistance to Yellow Stem Borer (*Scirpophaga incertulas* Wlk.) in F_1 Progenies Derived from Six Crosses of Rice (*Oryza sativa* L.)

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ABSTRACT

Heterosis breeding has been a successful strategy for improving yield and insect pest resistance in rice. This study evaluated heterosis for yield and resistance to the yellow stem borer (*Scirpophaga incertulas* Wlk.) in F_1 progenies from six rice crosses. Five diverse parents, including high-yielding varieties (ADT 43, ADT 45, ASD 16) as females and yellow stem borer resistant varieties (TKM 6, ASD 12) as males, were used to generate the F_1 progenies. The parents and F_1 progenies were screened for yellow stem borer resistance under screenhouse conditions by artificial infestation with larva reared in laboratory. Quantitative traits like plant height, total number of tillers, number of productive tillers, panicle length, thousand grain weight, grains per panicle and grain yield per plant were evaluated for yield performance. The F_1 progenies from ADT 43 × TKM 6, ADT 45 × TKM 6, ASD 16 × TKM 6 and ASD 16 × ASD 12 exhibited highly resistant status, while ADT 43 × ASD 12 and ADT 45 × ASD 12 showed resistance status to yellow stem borer. Estimation of heterosis revealed significant positive mid-parent, better-parent and useful heterosis for traits like tiller number, productive tillers, panicle length, grains per panicle and grain yield per plant in most crosses. The study identified promising heterotic rice hybrids combining high yield potential and yellow stem borer resistance, which can contribute to sustainable pest management strategies. The development of resistant varieties provides an environmentally-friendly approach to pest management, reducing excessive pesticide use and enhancing rice productivity for food security.

Keywords Rice, Heterosis, Yellow stem borer, Yield, Resistance.

INTRODUCTION

Rice (*Oryza sativa* L.) is a critically important cereal crop that serves as a staple food for more than half

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of the world's population (Ricepedia 2023, Shai Prasanna *et al*. 2023). It is a primary source of calories and provides essential nutrients, making it a crucial component of food security, particularly in developing countries. The cultivation of rice has a long and rich history, dating back thousands of years, and it has played a significant role in shaping the cultural and economic landscape of many societies. The importance of rice in agriculture cannot be overstated. It is cultivated on approximately 167 million hectares worldwide, accounting for nearly 11% of the total arable land (FAOSTAT 2023). Rice production is a major economic activity, providing employment and income for millions of farmers and supporting entire agricultural communities. Furthermore, rice cultivation plays a vital role in maintaining ecological balance and preserving biodiversity in many regions (Rehman *et al.* 2022). Globally, rice production has experienced significant growth over the past few decades, driven by factors such as improved agricultural practices, the development of high-yielding varieties and increased adoption of modern technologies (Oladosu *et al.* 2020). According to the food and agriculture organization (FAOSTAT 2023), the global production of paddy rice reached 783.5 million tons in 2021, with Asia being the leading producer, contributing approximately 90% of the world's total rice production. India, being one of the largest producers and consumers of rice, plays a crucial role in the global rice market. The country produced approximately 129.7 million tons of rice in the 2022-2023 crop year, making it the second-largest producer after China (USDA 2023). Rice cultivation in India spans across diverse agro-climatic regions, from the northern Himalayan foothills to the southern peninsular regions and it is an integral part of the country's cultural and agricultural heritage (Mohanty *et al.* 2017). Despite the impressive production levels, the demand for rice continues to rise due to population growth and changing dietary preferences (Samal *et al.* 2018). Consequently, there is a pressing need to address challenges such as climate change, water scarcity and the sustainable intensification of rice production systems to meet the growing demand while minimizing environmental impacts (Kumar *et al.* 2021, Prasad *et al.* 2017, Nawaz *et al.* 2022). The study of heterosis, or hybrid vigor, in rice holds significant importance for improving yield potential and enhancing resistance against insect pests like the yellow stem borer (YSB). Heterosis breeding has been a successful strategy for increasing crop productivity and developing superior cultivars with desirable traits. Hybrid rice technology, which exploits heterosis, has revolutionized rice production globally. Heterosis breeding has been instrumental in breaking the yield plateau and achieving significant yield advantages over conventional inbred varieties (Jing and Yang 2012). Several studies have reported heterosis for yield-related traits such as grain number, grain weight, and overall grain yield in rice hybrids (Gaballah *et al.* 2022, Wang *et al.* 2024). The exploitation of heterosis allows breeders to develop high-yielding hybrid rice cultivars that can contribute to meeting the increasing global demand for food. The yellow stem borer (*Scirpophaga incertulas* Walker) is a major insect pest that causes significant yield losses in rice cultivation (Pathak and Khan 1994). Developing rice cultivars with resistance to YSB is crucial for sustainable and eco-friendly pest management (Hajjar *et al.* 2023). YSB resistant inheritance and QTL studies have revealed the potential for improving YSB resistance through hybrid breeding (Gokulan *et al.* 2023). Hybridization can combine favorable alleles from diverse parental lines, resulting in superior YSB resistance in the hybrid progeny. Heterosis for YSB resistance traits, such as reduced dead heart and white ear heads, has been reported in several rice hybrids (Horgan *et al.* 2024, Singh *et al*. 2020). By combining high yield potential and YSB resistance through heterosis breeding, researchers aim to develop rice hybrids that can simultaneously address the challenges of food security and sustainable pest management.

MATERIALS AND METHODS

Parental material

Five rice genotypes were selected as parental materials. The high yielding rice varieties namely, ADT 43, ADT 45, ASD 16 were used as a female parent and yellow stem borer resistant varieties namely TKM 6, ASD 12 were used as male parental source. The details of the parents used are presented in a Table 1.

Hybridization between male and female parents

The crossing procedures were conducted at the green-

Table 1. Details of the parents used in the crosses.

Particulars varieties	Parentage	Duration (Days)	Average yield (kg/ha)	Grain type	1000 grain weight (g)	Habit
ADT 43	IR 50/White Ponni	110	5900	Medium slender	15.5	Semi dwarf
ADT 45	IR 50/ADT 37	110	6100	Medium slender	17.5	Semi dwarf, erect
ASD 16	ADT 31/CO 39	110 - 115	5600	Short bold	24.2	Semi dwarf, erect
TKM 6	GEB 24/CO 18	115 - 120	5500	Fine slender	14.8	Tall, erect
ASD 12	GEB 24/PTB 15 (Natural cross)	165	4500	Medium slender	13.6	Moderately tall

house of the Plant Breeding Farm, Department of Genetics and Plant Breeding, Faculty of Agriculture, Annamalai University using the hybridization protocol given by Jennings *et al.* (1979). The emerging panicles in a rice plant were chosen for emasculation in the female parents early in the morning. The pollen was collected from the male parent's healthy panicles by placing the panicles in a pot with 50 degrees celsius hot water to induce opening of the spikelets. The opened panicles of male parent were gently shaked over emasculated panicles of the female parent. The F_1 seeds were harvested from 30 days after pollination and stored in a 4°C temperature.

Screening for YSB resistance in F_1 plant progenies under screenhouse

The F_1 plants were raised in pots of inside the screenhouse. The yellow stem borer egg mass was collected from the field and allow previously collected egg masses to hatch in rearing jars. Infest the test plants of F_1 seeds with newly hatched larvae (10 larvae/hill) at 14 days after transplanting. Using a fine camel hair brush, place the larvae on the youngest leaf or auricles of one tiller. The parents and susceptible checks were also grown in along with F_1 plants and details of the susceptible checks were given in Table 2.

Evaluation for yield and its components using quantitative traits

The seedlings were transplanted into pot filled with fertile soil. Completely Randomized Design (CRD) with two replications were utilized for the purpose of study. Biometrical data such as plant height (PH, in cm), total number of tillers per plant (TNT), number of productive tillers per plant (NPT), panicle length (PL in cm), thousand grain weight (TGW in g) and grain yield per plant (GYP in g) were collected and analyzed.

Statistical calculations for heterosis and D value of YSB

Heterosis were expressed as a greatest or lowest in the performance of F_1 generation on comparing with their parents. The calculations were based on the differences from Relative heterosis (RH) and Heterobeltiosis (HB) and Useful heterosis (superior over standard commercial check variety, UB). Here the high yielding variety ADT 45 is recognized as standard commercial check variety.

$$\text{Relative heterosis} = \frac{F_1 - MP}{MP} \times 100$$

Table 2. Details of the susceptible checks used for yellow stem borer resistance.

Particulars	Parentage	Duration (Days)	Average yield (kg/ha)	Grain type	1000 grain weight (g)	Habit
TN 1	Dwarf -chow-wu-gen/Tsai-yuan-chunj	120 - 125	4000	Short bold	14.2	Semi dwarf
IR 8	Peta/Dee-gee-woo-gen	130	4564	Medium bold	30.3	Dwarf

Table 3. Standard evaluation system for scoring yellow stem borer resistance in rice.

Scale	Percent damage of White Ear Head (WEH)	D value	Resistant status
0	No damage	No damage	Highly Resistant (HR)
1	1 - 5%	1 - 10%	Resistant (R)
3	6 - 10%	11 - 25%	Moderately Resistant (MR)
5	11 - 15%	26 - 40%	Moderately Susceptible (MS)
7	16 - 25%	41-60%	Susceptible (S)
9	26% and above	61-100%	Highly Susceptible (HS)

$$\text{Heterobeltiosis} = \frac{F_1 - BP}{BP} \times 100$$

$$\text{Useful heterosis} = \frac{F_1 - CC}{CC} \times 100$$

Whereas,

MP - Mid-parental value

BP - Better parent value

CC – Commercial check variety value

Observations on the incidence of yellow stem borer in terms white ear at reproductive stage were recorded at 70 – 75 days after transplanting (DAT). All the F_1 plants were examined for recording the incidence of yellow stem borer infection and the per cent white ear damage of YSB was calculated using the per cent white ear calculation formula, based on the damage rating scale, the status was determined by following IRRI's Standard Evaluation System (SES) for yellow stem borer (IRRI 2013). This SES for YSB was presented in Table 3. The D value calculations were adopted from studies of Prasanna and Joshi (2024).

$$\text{\% of white ear} = \frac{\text{Number of damaged tillers (white ear)}}{\text{Total number of tillers}} \times 100$$

Percentage of white ears was converted D value,

$$\text{D value (\%)} = \frac{\text{Per cent white ear in } F_1 \text{ progenies}}{\text{Per cent white ear in susceptible checks}} \times 100$$

RESULTS AND DISCUSSION

Screening for YSB resistance in F_1 plant progenies of six crosses

The screening provides information about the resistance status of different rice genotypes against the yellow stem borer (YSB) insect pest. The parents include five different rice varieties viz., ADT 43, ADT 45, ASD 16, TKM 6 and ASD 12. The "D value (%)" which represents the percentage of damage caused by YSB and the resistant status was given based on the scale and D value. The female parents ADT 43 (51.39%), ASD 16 (46.82%) are classified as susceptible and ADT 45 (62.11%) classified as highly susceptible, while the male parents TKM 6 and ASD 12 are classified as highly resistant, with no damage observed. The susceptible checks shown

Table 4. Resistant status to YSB for parents, F_1 progenies of crosses and susceptible checks.

Parents	D value (%)	Scale	Resistant status
ADT 43	51.39	7	Susceptible
ADT 45	62.11	9	Highly susceptible
ASD 16	46.82	7	Susceptible
TKM 6	No damage	0	Highly resistant
ASD 12	No damage	0	Highly resistant
F_1 progenies of crosses	D value (%)	Scale	Resistant status
ADT 43×TKM 6	No damage	0	Highly resistant
ADT 43×ASD 12	6.70	1	Resistant
ADT 45×TKM 6	No damage	0	Highly resistant
ADT 45×ASD 12	8.17	1	Resistant
ASD 16×TKM 6	No damage	0	Highly resistant
ASD 16×ASD 12	No damage	0	Highly resistant
Susceptible checks	D value (%)	Scale	Resistant status
TN 1	81.12	9	Highly susceptible
IR 8	69.43	9	Highly susceptible

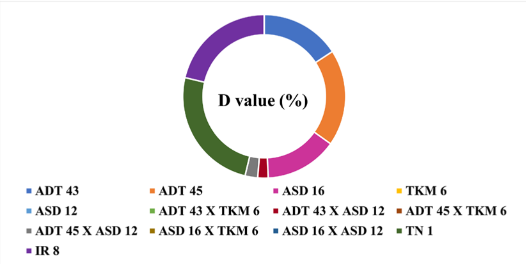

Fig. 1. D value (%) representation for parents, F_1 progenies and susceptible checks.

highly susceptible status to YSB with the D value of 81.12% (TN 1) and 69.43% (IR 8), respectively. The F_1 progenies of cross ADT 43 × TKM 6, ADT 45 × TKM 6, ASD 16 × TKM 6 and ASD 16 × ASD 12 performed highly resistant status to the YSB with no damage (0%). The crosses ADT 43 × ASD 12 and ADT 45 × ASD 12 showed resistant status with the D value of 6.70% and 8.17%, respectively (Table 4 and Fig. 1). It is observed that, the larva tends to move towards susceptible checks and female parents from F_1 progenies of all crosses. The feeding preference status of larva tends towards susceptible check varieties followed by female parental varieties and crosses ADT 43 × ASD 12, ADT 45 × ASD 12 and all other four crosses. Similar screening procedure for yellow stem borer in rice was studied by Justin and Preetha (2014), Prasad *et al.* (2015), Joshi *et al.* (2019), Reuolin *et al.* (2019), Sudha Rani *et al.* (2020), Nalla *et al.* (2020), Rakesh *et al.* (2021), Sampathkumar *et al.* (2022), Prasanna and Joshi (2024).

Mean performance evaluation between parents and F_1 progenies of six crosses

For the trait plant height, the crosses ADT 43 × TKM 6 and ADT 43 × ASD 12 have slightly higher PH than their parent ADT 43, but lower than the taller parents TKM 6 and ASD 12. The crosses ADT 45 × TKM 6 and ADT 45 × ASD 12 have higher PH than both parents, likely exhibiting hybrid vigor and the crosses ASD 16 × TKM 6 and ASD 16 × ASD 12 have PH values in between their respective parents. For the traits total number of tillers, number of productive tillers and grain yield per plant, all F_1 crosses have higher values compared to their parents, indicating hybrid vigor for these traits. For the trait panicle length, the crosses involving ADT 43 and ADT 45 have PL values in between their respective parents and the crosses ASD 16 × TKM 6 and ASD 16 × ASD 12 have higher PL than both parents, exhibiting hybrid vigor. For the trait thousand grain weight, most F_1 crosses have TGW values similar to or slightly lower than their female parent, except for ASD 16 × TKM 6 which has a lower TGW than both parents. For the trait number of grains per panicle, the crosses involving ADT 43 have similar NGP values as their

Table 5. Mean performance of parents and F_1 progenies of all six crosses. Whereas, PH – Plant height, TNT – Total number of tillers, NPT – Number of productive tillers, PL – Panicle length, TGW – Thousand grain weight, NGP – Number of grains per panicle and GYP – Grain yield per plant.

Genotypes parents	Biometrical traits observed						
	PH	TNT	NPT	PL	TGW	NGP	GYP
ADT 43	77.56	18.13	15.73	21.89	15.73	160.93	39.92
ADT 45	79.54	20.13	18.87	21.26	17.54	197.67	65.51
ASD 16	96.47	21.80	20.80	24.46	24.55	204.67	84.56
TKM 6	119.40	12.07	10.13	13.25	14.01	124.60	17.58
ASD 12	107.29	13.07	11.67	12.15	13.70	102.67	16.44
F_1 progenies of crosses	PH	TNT	NPT	PL	TGW	NGP	GYP
ADT 43 × TKM 6	78.08	23.65	21.60	21.25	15.36	158.47	52.58
ADT 43 × ASD 12	76.28	20.66	19.10	17.63	16.01	160.67	49.12
ADT 45 × TKM 6	87.56	19.46	17.97	24.31	17.21	199.62	61.83
ADT 45 × ASD 12	88.52	20.63	19.13	25.18	17.15	205.55	67.33
ASD 16 × TKM 6	95.46	20.35	19.03	25.75	23.09	194.79	85.68
ASD 16 × ASD 12	99.87	19.27	17.88	23.24	23.70	200.03	84.66

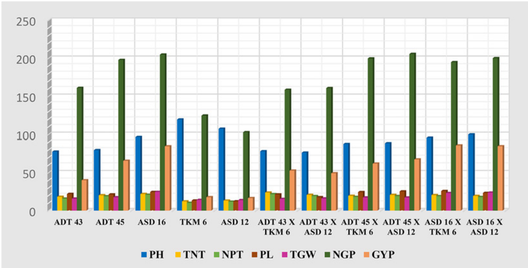

Fig. 2. Mean performance of parents and F_1 progenies of all six crosses of rice.

parents and the other crosses have NGP values slightly lower than their higher parent (Table 5 and Fig. 2).

Estimation of various heterosis for F_1 progenies of all six crosses of rice

Heterosis refers to the phenomenon where the hybrid progeny exhibits superior performance compared to its parents for certain traits. Table 5 and Fig. 3 provides the details on mid-parent heterosis (Relative heterosis), better parent heterosis (Heterobeltiosis) and economic heterosis (useful heterosis). Positive heterosis values indicate that the F_1 progeny exhibited better performance than the mid parent or better parent or standard commercial check variety for that particular trait, while negative values indicate poorer performance compared to the parents. The Table 6 provides the detailed view on various heterosis estimation for F_1 progenies. On evaluation of relative heterosis the trait plant height shows negative RH values indicate that the F_1 progenies were shorter than the taller parent, ranging from -2.19% (ASD 16 × TKM 6) to -23.31% (ADT 43 × ASD 12). The trait total number of tillers and number of productive tillers displays positive RH values indicate that the F_1 progenies had more tillers than the parent with the higher number of tillers, ranging from 10.52% (ASD 16 × ASD 12) to 56.62% (ADT 43 × TKM 6) for TNT and 10.13% (ASD 16 × ASD 12) to 67.05% (ADT 43 × TKM 6) for NPT, respectively. The trait panicle length observed for positive RH values indicate that the F_1 progenies had longer panicles than the parent with the longer panicles, ranging from 2.17% (ADT 43 × ASD 12) to 54.15% (ASD 16 × TKM 6). The trait thousand grain weight provides both positive and negative RH values, indicating that some F_1 progenies had higher RH for all the crosses except cross ADT 45 × TKM 6 thousand grain weight than the better parent, ranging from -10.74% (ADT 45 × TKM 6) to

Table 6. Various heterosis value estimation for observed biometrical traits in F_1 progenies of six crosses. Whereas, HET – Heterosis, RH – Relative heterosis, HB – Heterobeltiosis, UH - Useful heterosis, PH – Plant height, TNT – Total number of tillers, NPT – Number of productive tillers, PL – Panicle length, TGW – Thousand grain weight, NGP – Number of grains per panicle and GYP – Grain yield per plant.

F_1 progenies of crosses	HET	PH	TNT	NPT	PL	TGW	NGP	GYP
ADT 43 ×TKM 6	RH	-20.71	56.62	67.05	20.94	3.30	11.00	82.89
	HB	-34.61	30.45	37.32	2.92	-2.35	-1.53	31.71
	UH	-1.84	17.49	14.47	-0.05	-12.43	-19.83	-19.74
ADT 43 × ASD 12	RH	-23.31	28.32	31.72	2.17	1.49	0.29	18.23
	HB	-28.90	13.95	21.42	19.46	1.78	-0.16	23.05
	UH	-4.10	2.63	1.22	-17.07	-8.72	-18.72	-25.02
ADT 45 × TKM 6	RH	-18.88	14.91	16.20	28.93	-10.74	21.25	36.73
	HB	-26.67	3.33	4.77	14.35	-1.88	0.99	6.59
	UH	10.08	-3.33	-4.77	14.35	-1.88	0.99	6.59
ADT 45 × ASD 12	RH	-5.26	32.24	39.64	47.94	16.55	55.96	138.93
	HB	-18.39	2.48	1.38	18.44	-2.22	3.99	2.78
	UH	10.08	2.48	1.38	18.44	-2.22	3.99	2.78
ASD 16 × TKM 6	RH	-2.19	22.59	24.62	54.15	47.82	29.71	109.10
	HB	-20.05	6.65	8.51	5.27	-5.95	-4.83	1.32
	UH	20.02	1.09	0.85	21.12	31.64	-1.46	30.79
ASD 16 × ASD 12	RH	-1.97	10.52	10.13	26.96	23.92	30.17	67.64
	HB	-6.92	11.61	14.04	4.99	3.46	-2.27	0.12
	UH	25.56	-4.27	-5.25	9.31	35.12	1.19	29.23

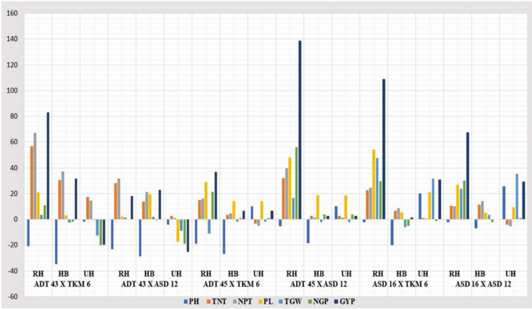

Fig. 3. Various heterosis estimation for all six crosses of rice.

47.82% (ASD 16 × TKM 6). For the traits, number of grains per panicle and grain yield per plant positive RH values indicate that the F_1 progenies had more grains per panicle and higher yield than the parents, ranging from 0.29% (ADT 43 × ASD 12) to 55.96% (ADT 45 × ASD 12) for NGP and 18.23% (ADT 43 × ASD 12) to 138.93% (ADT 45 × ASD 12) for GYP, respectively.

The heterobeltiosis estimation reveals that the trait plant height shows negative HB values indicate shorter plant height in F_1 compared to the better parents ranges from -34.61% (ADT 43 × TKM 6) to -6.92% (ASD 16 × ASD 12). For the trait total number of tillers, positive HB for most crosses, indicating more tillers than the better parent which ranges from 2.48% (ADT 45 × ASD 12) to 30.45% (ADT 43 × TKM 6). The trait number of productive tillers shows positive HB for all the six crosses, indicating more productive tillers than the better parent that ranges from 1.38% (ADT 45 × ASD 12) to 37.32% (ADT 43 × TKM 6). The trait panicle length displays positive HB for all crosses, indicating longer panicles than the better parent which ranges from 2.92% (ADT 43 × TKM 6) to 19.46% (ADT 43 × ASD 12). The trait thousand grain weight and number of grains per panicle, both positive and negative HB values were observed which ranges from -5.95% (ASD 16 × TKM 6) to 3.46% (ASD 16 × ASD 12) for TGW and -4.83% (ASD 16 × TKM 6) to 3.99% (ADT 45 ×ASD 12) for NGP, respectively. The trait grain yield per plant exhibits positive HB value observed for all the crosses i.e., grain yield which is higher than better parents and ranges from 0.12% (ASD 16 × ASD 12) to 31.71% (ADT 43 × TKM 6).

The useful heterosis was given by Meredith and Bridge (1972) which is also called as economic heterosis. The trait plant height both positive and negative UH observed which ranges from -1.84% (ADT 43 × TKM 6) to 25.56% (ASD 16 × ASD 12). The trait total number of tillers and number of productive tillers displayed both positive and negative UH observed that ranges from -3.33% (ADT 45 × TKM 6) to 17.49% (ADT 43 × TKM 6) for TNT and -5.25% (ASD 16 × ASD 12) to 14.47% (ADT 43 × TKM 6) for NPT, respectively. The trait panicle length shows positive UH for most crosses, indicating longer panicles than standard variety except cross ADT 43 × TKM 6 and ADT 43 × ASD 12 which ranges from -0.05% (ADT 43 × TKM 6) to 21.12% (ASD 16 × TKM 6).The trait thousand grain weight and number of grains per panicle exhibited both positive and negative UH observed which ranges from -12.43% (ADT 43 × TKM 6) to 35.12% (ASD 16 × ASD 12) for TGW and -19.83% (ADT 43 × TKM 6) to 3.99% (ADT 45 × ASD 12) for NGP, respectively. The trait grain yield per plant shows positive UH for most crosses, indicating higher yield than standard variety except for ADT 43 × TKM 6 and ADT 43 × ASD 12 and yield ranges from -25.02% (ADT 43 × ASD 12) to 30.79% (ASD 16 × TKM 6). Similar studies were conducted by Virmani *et al.* (1982), Rahimi *et al.* (2010), Devi *et al*. (2014), Ahmad *et al.* (2023), Lingaiah *et al*. (2023), Wang *et al.* (2024).

CONCLUSION

The screening and identifying resistant rice F_1 plant is a crucial strategy for combating the destructive yellow stem borer pest. By utilizing conventional breeding methods along with modern biotechnological tools like marker-assisted selection, researchers can efficiently pinpoint genes conferring resistance and introgress them into high-yielding rice cultivars. The development of resistant varieties provides an environmentally-friendly and sustainable approach to pest management, reducing the need for excessive pesticide applications. Not only does this mitigate the risks to human health and the environment posed by chemical control methods, but it also enhances rice productivity and ensures food security for farming communities afflicted by this voracious insect pest. Furthermore, the durability of resistance can be prolonged through gene pyramiding and the judicious deployment of major resistance genes. As such, the screening and development of yellow stem borer-resistant rice should be a top priority for rice research programs worldwide to safeguard this globally important cereal crop against emerging insect biotypes and secure future rice yields. The F_1 progenies generally show hybrid vigor (higher values than parents) for traits like TNT, NPT and GYP, while exhibiting values in between or slightly lower than the better parent for traits like PH, PL, TGW and NGP. The heterosis estimation allows for identifying crosses that exhibit significant heterosis for specific traits, which can be beneficial for breeding programs aiming to develop superior hybrid varieties. In summary, the crosses generally exhibited positive heterosis (hybrid vigor) for traits like TNT, NPT, PL, NGP and GYP, with varying degrees of positive and negative heterosis for traits like PH and TGW. The magnitude of heterosis varied across crosses and traits, with some crosses showing substantial heterosis for certain traits compared to others.

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