**Assessment of Heterosis in Indian Mustard [*Brassica juncea* (L.)] Cross Combinations for Yield and Attributing Traits**

**Abstract**

Indian mustard [*Brassica juncea* (L.)] is a pivotal oilseed crop group, extensively cultivated worldwide for edible oil and livestock feed. Worldwide, it is the third most ranked oilseed in terms of consumption after palm oil and soybean. However, productivity remains below potential due to an array of biotic and abiotic stresses coupled with a narrow genetic base, highlighting the need for broadening genetic diversity and exploiting heterosis to develop superior cultivar (s). The present study was undertaken to evaluate heterosis for seed yield and attributing traits among 20 diverse cross combinations of Indian mustard, made during *Rabi*, 2024 and assessed along with zonal (Maya) and national (Kranti) checks at Research Farm Zonal Agricultural Research Station, Morena, RVSKVV, Gwalior during *Rabi*, 2025. Significant variability was observed for yield and component traits, with seed yield ranging from 1,078 kg/ha (Brijraj × Rukmini) to 3,343 kg/ha (Radhika × NPJ-253). Notably, cross combinations such as Radhika × NPJ-253, Rukmini × NPJ-253, and Brijraj × NPJ-253 exhibited high positive heterosis for yield and key traits like siliquae numbers, numbers of seeds per siliquae, seed weight, and earliness, indicating presence of strong hybrid vigour. Architectural traits such as increased branching and longer racemes in these crosses further reinforced their yield potential. These findings underscore the potential of targeted hybridization to overcome existing yield barriers. The identified superior crosses warrant multi-location testing to confirm stability and adaptability, offering promising avenues for enhancing mustard productivity and contributing to India’s edible oil self-reliance through robust breeding strategies.

**Keywords:** Indian mustard [*Brassica juncea* L.)], Heterosis, Hybrid performance, Plant architecture, Yield components

**1. Introduction**

Indian mustard [*Brassica juncea* (L.)] constitutes one of the most economically and nutritionally significant groups of oilseed crops cultivated across the globe (Rajpoot et al., 2020; Shivastava et al., 2023a; Anushree et al., 2025). It plays a pivotal role in meeting the growing demand for edible oils, serving as a major source of vegetable oil for human consumption as well as a valuable component of livestock feed (Tarar et al., 2021; Rajpoot et al., 2022; Shrivastav et al., 2023b;). Indian mustard (*Brassica juncea* L. Czern & Coss.) is a key oilseed crop of the Brassicaceae family, with a genome size of 922 Mb. It is an amphidiploid species (AABB, 2n=36) that originated from natural hybridization between *B. rapa* and *B. nigra*, followed by chromosome doubling (Verma et al., 2021; Singh et al., 2022; Kumar et al., 2022; Shrivastava et al., 2023c). The Brassicaceae family itself includes over 330 genera and 3,700 species distributed worldwide (Lietzow, 2021; Pippal et al., 2022). Six species of rapeseed-mustard are found in the Indian subcontinent, with Indian mustard (*Brassica juncea*) dominating cultivation (Barfa et al., 2017; Baghel et al., 2020). It occupies 75–80% of India’s rapeseed area due to its strong adaptation to local agro-climatic conditions (Shrivastava et al., 2023d; Nair, 2024). It is the third most important oilseed crop worldwide after palm and soybean, contributing about 12% to global edible oil production (Shrivastava et al., 2023e). In India, it supplies nearly 80% of the edible oil, with Rajasthan alone accounting for over 50% of the area and production. Other key producing states are Haryana, Uttar Pradesh, Madhya Pradesh and Gujarat (Kaur et al., 2019a; Shrivastav et al., 2024). This widespread cultivation underscores its integral role in the national agricultural economy and its contribution to the livelihoods of millions of smallholder farmers (Shyam et al., 2019; Bisht et al., 2020). The popularity of mustard cultivation in India can be attributed to its remarkable adaptability to diverse agro-climatic conditions (Shyam et al., 2020). Its resilience under low-input farming systems, combined with relatively modest fertilizer and water requirements, makes mustard an ideal crop for resource-constrained farmers (Shyam et al., 2021a; Kumari et al., 2024; Jain et al., 2024). Moreover, the ability of mustard to fit into varied cropping systems, such as being grown as a rabi (winter) crop following cereals like rice and pearl millet, enhances its importance in sustainable agricultural practices (Chapagain et al., 2018; Parihar et al., 2009; Shyam et al., 2021b).

Despite its critical economic and ecological roles, the productivity levels of rapeseed-mustard in India have remained considerably below the attainable potential (Shyam et al., 2021c). This yield gap is largely attributed to a combination of biotic and abiotic stresses (AICRP, 2012; Jat et al., 2019; Shyam et al., 2021d). The crop frequently suffers from diseases like white rust (*Albugo candida*), downy mildew, and Alternaria blight, as well as insect pests such as mustard aphids, which collectively impose severe constraints on yield (Jain et al., 2022; Shyam et al., 2022a; Sran et al., 2024). Additionally, abiotic factors including terminal heat stress, moisture scarcity during critical growth phases, and the sensitivity of mustard to saline or alkaline soils further restrict its productivity (Sangeetha & Siddaramaiah, 2007; Yadav et al., 2019; Shyam et al., 2022b; Kumawat et al., 2024). Another fundamental limitation is the relatively narrow genetic base of the cultivated mustard varieties, which restricts the scope for natural genetic gains through conventional selection. The reduced genetic diversity hampers the development of varieties with enhanced stress tolerance, yield potential, and quality attributes (Anushree et al., 2025; Kumar et al., 2024a; Shyam et al., 2022c; Shyam et al., 2022d).

Therefore, there is an urgent need to broaden the genetic base and explore advanced breeding strategies, such as heterosis breeding and interspecific hybridization, to overcome these constraints (Tripathi et al., 2015). Given this backdrop, the intensification of breeding efforts aimed to improve yield and stress resilience in mustard becomes imperative (Kumar et al., 2024b; Kumar et al., 2024c; Rout et al., 2025). This involves not only the systematic evaluation of diverse genotypes and hybrid combinations for yield and its component traits but also the incorporation of novel genetic resources to break the existing yield barriers. Such concerted efforts hold the promise of enhancing mustard productivity, thereby securing the livelihoods of farmers and contributing significantly to national edible oil self-sufficiency (Chaurasia & Bhajan, 2015; Katche et al., 2019; Sur et al., 2022; Qin et al., 2023). In this context, the present investigation was undertaken to evaluate the performance of 20 diverse cross combinations of Indian mustard, along with zonal and national checks, with the objective of assessing heterosis for seed yield and its contributing characters. The findings are expected to identify superior hybrid combinations and provide insights into the genetic architecture of key yield and physiological traits, thereby aiding in the formulation of effective breeding strategies for mustard improvement.

**2. Material & Methods**

The present investigation was carried out at the experimental farm of the Zonal Agricultural Research Station, Morena, Rajmata Vijayaraje Scindia, Agricultural University Gwalior, M.P., India during the *Rabi* 2024 and 2025, as part of the All India Coordinated Research Project (AICRP) on Rapeseed and Mustard, IIRMR, Bharatpur, India. During the 2024 season, 20 diverse cross combinations were manually made by hybridizing selected parental lines. These resultant F₁ hybrids were subsequently evaluated in the *Rabi* 2025 in RBD with three replications. The experiment was laid out with a spacing of 30 cm between rows and 10 cm between plants. Standard agronomic practices recommended for the region were adopted for crop management to ensure optimal growth conditions. Data on yield and yield-related traits were recorded from ten randomly selected plants from each genotype. The observations were statistically analysed following the methodologies described by Rai (1979) and Mahto and Haider (2004).

**3. Results**

The evaluation of 20 cross combinations of Indian mustard, along with the zonal check (Maya) and national check (Kranti), revealed considerable variability for seed yield, days to flower initiation, days to 50% flowering, days to physiological maturity, days to actual maturity, plant height, length of main raceme, numbers of secondary branches/ plant, numbers of siliquae/ plant, siliquae length, numbers of seeds /siliquae, single plant seed weight and test weight and presented in Table 1, Table 2, Table 3, Table 4 and Table 5. Seed yield among the hybrids ranged between 1,078 kgha-1 in the cross Brijraj × Rukmini to 3,343 kgha-1 in Radhika × NPJ-253. Remarkably, the cross Radhika × NPJ-253 exhibited the highest positive heterosis, 39.29% and 37.69% improvement over the zonal and national checks, respectively. This was followed by Rukmini × NPJ-253, which showed 21.25% heterosis over the zonal and 19.85% over the national check, while Brijraj × NPJ-253 also performed well, with heterosis values of 11.71% and 10.42%, correspondingly. In contrast, several crosses showed substantial negative heterosis for yield, with Brijraj × Rukmini demonstrating the lowest performance, -55.08% and –55.60% heterosis over the zonal and national checks, respectively.

For days to flower initiation, the cross combinations exhibited a range from 37 days in Rukmini × NPJ-253 to 47 days in Brijraj × PDZM-31 and PDZM-31 × Brijraj. Earliness, indicated by negative heterosis, was most pronounced in Rukmini × NPJ-253, with –7.5% and –5.13% heterosis over the zonal and national checks, respectively, followed by Radhika × NPJ-253 and Rukmini × Brijraj, which also flowered earlier than the checks. Conversely, crosses such as Brijraj × PDZM-31 and PDZM-31 × Brijraj exhibited delayed flowering, with heterosis reaching +17.5% and +20.51% over the zonal and national checks, respectively. A similar trend was also observed for days to 50% flowering, which varied from 46 days in cross combination Rukmini × NPJ-253 to 58 days in crosses involving PDZM-31 and Brijraj parents. The cross Rukmini × NPJ-253 again demonstrated the greatest earliness, recorded –6.12% and –8.0% heterosis over the zonal and national checks, respectively, while PDZM-31 × Brijraj exhibited the maximum delay in flowering with +18.37% and +16.0% heterosis.

Days to physiological maturity arrayed between 120 days in several crosses, including NPJ-253 × Rukmini, Brijraj × NPJ-253, Radhika × NPJ-253, Rukmini × NPJ-253, and PDZM-31 × NPJ-253, to 126 days in PDZM-31 × Rukmini. Compared to the checks, most of the hybrids showed earliness, with maximum negative heterosis observed in cross combination NPJ-253 × Rukmini, Radhika × NPJ-253, Rukmini × NPJ-253, and PDZM-31 × NPJ-253 (–6.25% over the zonal and –6.98% over the national check). Days to actual maturity followed a similar trend, varying from 128 to 134 days, where crosses such as NPJ-253 × Rukmini, Brijraj × NPJ-253, Radhika × NPJ-253, Rukmini × NPJ-253, and PDZM-31 × NPJ-253 matured earliest, exhibiting heterosis values up to –5.88% over zonal and –6.57% over national check.

Plant height among the hybrids ranged widely from 170.4 cm in Rukmini × NPJ-253 to as high as 329.4 cm in Brijraj × Radhika. Most crosses recorded reduced plant height relative to the checks, with Rukmini × NPJ-253 showed the greatest reduction, manifesting –9.41% heterosis over the zonal and –18.39% over the national check. However, some crosses like Brijraj × Radhika, Radhika × Brijraj, Radhika × PDZM-31, Rukmini × Brijraj, PDZM-31 × Brijraj, PDZM-31 × Radhika, and PDZM-31 × Rukmini exhibited enhanced plant height compared to the zonal check, with Brijraj × Radhika had the highest positive heterosis *i.e*., +75.12% over zonal and +57.76% over national check.

The length of main raceme ranged between 59.0 cm in Brijraj × Rukmini to 78.6 cm in Rukmini × NPJ-253. The cross Rukmini × NPJ-253 showed the highest positive heterosis, with improvements of +20.0% over the zonal check and +23.58% over the national check, closely tracked by Brijraj × NPJ-253 (+15.57% and +19.03%) and Radhika × NPJ-253 (+14.66% and +18.08%). In contrast, Brijraj × Rukmini chronicled negative heterosis, indicating shorter raceme length than both checks.

For the numbers of primary branches per plant, the hybrids exhibited values ranging from 4.1 in Rukmini × Brijraj to 7.5 in Rukmini × NPJ-253. The cross Rukmini × NPJ-253 was most outstanding, registering the highest heterosis of +66.67% over the zonal and +32.37% over the national check. Other notable crosses included Brijraj × NPJ-253 and Radhika × NPJ-253, which also recorded positive heterosis over both checks. However, several hybrids such as NPJ-253 × Radhika and Rukmini × Brijraj showed reductions, indicating fewer numbers of primary branches per plant compared to checks.

The numbers of secondary branches per plant varied from 4.2 in cross combination NPJ-253 × Radhika to 13.2 in Rukmini × NPJ-253. Again, Rukmini × NPJ-253 displayed remarkable superiority with heterosis values of +38.95% over the zonal and the national checks. Other hybrids such as Radhika × NPJ-253, Brijraj × NPJ-253, and PDZM-31 × Brijraj also recorded higher numbers of secondary branches per plant with positive heterosis over the both checks. Conversely, several cross combinations, including NPJ-253 × Radhika and Radhika × PDZM-31, displayed substantial negative heterosis, indicating fewer numbers of secondary branches per plant than the checks.

The numbers of siliquae per plant ranged from 138.1 in cross combination NPJ-253 × Radhika to a maximum of 365.1 in Rukmini × NPJ-253. This cross showed the highest positive heterosis, with improvements of +64.98% over the zonal check and +91.55% over the national check. Other promising crosses were Radhika × NPJ-253 (+61.09% and +91.76%), Brijraj × NPJ-253 (+59.78% and +85.52%), and Rukmini × Radhika (+59.38% and +85.05%). In contrast, cross combination NPJ-253 × Radhika exhibited considerable negative heterosis, indicating a reduction of –37.60% and –27.54% compared to the zonal and national checks, correspondingly.

Siliquae length varied from 3.9 cm in cross PDZM-31 × NPJ-253 to 5.0 cm in both cross combinations *viz*., Radhika × NPJ-253 and Rukmini × NPJ-253. The highest positive heterosis for this trait was recorded by these two crosses, with increases up to +21.95% over the zonal check and +25.0% over the national check. Most of the crosses showed modest positive heterosis, while a few crosses such as PDZM-31 × NPJ-253 and PDZM-31 × Rukmini recorded slight reductions compared to checks.

For numbers of seeds per siliquae, values ranged from 10.8 in NPJ-253 × Radhika to 17.1 in Rukmini × NPJ-253. The cross-combination Rukmini × NPJ-253 again demonstrated superiority with the highest positive heterosis, showing +32.56% over the zonal and +37.90% over the national check. Other crosses like Brijraj × NPJ-253, Radhika × NPJ-253, and PDZM-31 × Brijraj also exhibited positive heterosis, whereas crosses such as NPJ-253 × Radhika and Radhika × Rukmini displayed remarkable negative heterosis, indicating fewer seeds per siliquae compared to the checks.

Single plant seed weight ranged between 8.25 g in cross combination NPJ-253 × Brijraj, similar to the national check, to a maximum of 22.84 g in Radhika × NPJ-253. The cross-combination Radhika × NPJ-253 recorded the highest positive heterosis, showing improvements of +33.80% over the zonal check and +176.85% over the national check. This was followed by Rukmini × NPJ-253 (+17.22% and +142.55%), Brijraj × NPJ-253 (+16.99% and +142.06%), and PDZM-31 × Brijraj (+16.34% and +140.73%), all of them also displayed marked increases over the checks. In contrast, crosses like NPJ-253 × Brijraj and PDZM-31 × Radhika exhibited negative heterosis over the zonal check but still showed substantial improvement over the national check, highlighting the generally low baseline of the national check for this trait.

For test weight, values ranged between 4.02 g in cross combination PDZM-31 × Brijraj to 7.15 g in Radhika × NPJ-253. The cross-combination Radhika × NPJ-253 again stood out, showing the highest positive heterosis of +62.87% over the zonal and +54.43% over the national check. Other promising crosses comprised Rukmini × NPJ-253 (+45.56% and +38.01%), Brijraj × NPJ-253 (+41.0% over both checks), and NPJ-253 × Brijraj and NPJ-253 x Radhika (+29.16% and +22.46%). Interestingly, while most of the crosses demonstrated positive heterosis for test weight, a few hybrids such as PDZM-31 × Brijraj and Rukmini × PDZM-31 demonstrated reductions in heterosis compared to both of the checks.

**Table 1** **Heterosis of Indian mustard cross combinations for seed yield, days to flower initiation and days to 50% flowering over zonal (Maya) and national (Kranti) checks**

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| S. No. | Cross combination | Yield Kgha-1 | Heterosis over  Zonal check | Heterosis over  National  check | Days to flower initiation | Heterosis over  Zonal check | Heterosis  over  National  check | Days to 50% flowering | Heterosis over  Zonal check | Heterosis  over  National  check |
| 1 | NPJ-253 x Brijraj | 2359 | -1.71 | -2.84 | 44 | +10.0 | +12.82 | 55 | +12.24 | +10.0 |
| 2 | NPJ-253 x Radhika | 2260 | -5.83 | -6.92 | 40 | 0 | +2.56 | 50 | +2.04 | 0 |
| 3 | NPJ-253 x Rukmini | 2622 | +9.25 | +7.99 | 42 | +5.0 | +7.69 | 52 | +6.12 | +4.0 |
| 4 | NPJ-253 x PDZM-31 | 1704 | -29.00 | -29.82 | 44 | +10.0 | +12.82 | 56 | +14.29 | +12.0 |
| 5 | Brijraj x NPJ-253 | 2681 | +11.71 | +10.42 | 39 | -2.5 | 0 | 50 | +2.04 | 0 |
| 6 | Brijraj x Radhika | 1536 | -36.00 | -36.74 | 45 | +12.5 | +15.38 | 56 | +14.29 | +12.0 |
| 7 | Brijraj x Rukmini | 1078 | -55.08 | -55.60 | 45 | +12.5 | +15.38 | 56 | +14.29 | +12.0 |
| 8 | Brijraj x PDZM-31 | 1508 | -37.017 | -37.89 | 47 | +17.5 | +20.51 | 58 | +18.37 | +16.0 |
| 9 | Radhika x NPj-253 | 3343 | +39.29 | +37.69 | 38 | -5.0 | -2.56 | 49 | 0 | -2.0 |
| 10 | Radhika x Brijraj | 1896 | -21.00 | -21.91 | 46 | +15.0 | +17.95 | 57 | +16.33 | +14.0 |
| 11 | Radhika x Rukmini | 1919 | -20.04 | -20.96 | 42 | +5.0 | +7.69 | 52 | +6.12 | +4.0 |
| 12 | Radhika x PDZM-31 | 2054 | -14.42 | -15.40 | 43 | +7.5 | +10.26 | 54 | +10.20 | +8.0 |
| 13 | Rukmini x NPJ-253 | 2910 | +21.25 | +19.85 | 37 | -7.5 | -5.13 | 46 | -6.12 | -8.0 |
| 14 | Rukmini x Brijraj | 1733 | -27.79 | -28.62 | 39 | -2.5 | 0 | 49 | 0 | -2.0 |
| 15 | Rukmini x Radhika | 1378 | -42.58 | -43.25 | 39 | -2.5 | 0 | 50 | +2.04 | 0 |
| 16 | Rukmini x PDZM-31 | 2222 | -7.41 | -8.48 | 41 | +2.5 | +5.13 | 51 | +4.08 | -2.0 |
| 17 | PDZM-31 x NPJ-253 | 1954 | -18.58 | -19.52 | 43 | +7.5 | +10.26 | 54 | +10.20 | +8.0 |
| 18 | PDZM-31 x Brijraj | 1686 | -29.75 | -30.56 | 47 | +17.5 | +20.51 | 58 | +18.37 | +16.0 |
| 19 | PDZM-31x Radhika | 1903 | -20.71 | -21.62 | 46 | +15.0 | +17.95 | 56 | +14.29 | +12.0 |
| 20 | PDZM-31 x Rukmini | 2428 | +1.17 | 0.0 | 45 | +12.5 | +15.38 | 56 | +14.29 | +12.0 |
| 21 | Maya (ZC) | 2400 | - | - | 40 | - | - | 49 | - | - |
| 22 | Kranti (NC) | 2428 | - | - | 39 | - | - | 50 | - | - |

**Table 2 Heterosis of Indian mustard cross combinations for days to physiological maturity, days to actual maturity, and plant height over zonal (Maya) and national (Kranti) checks**

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| S. No. | Cross combination | Days to  Physiological  Maturity | Heterosis over  Zonal check | Heterosis  over  National  check | Days to  actual  maturity | Heterosis over  Zonal check | Heterosis  over  National  check | Plant height (cm) | Heterosis over  Zonal check | Heterosis  over  National  check |
| 1 | NPJ-253 x Brijraj | 125 | -2.34 | -3.10 | 133 | -2.21 | -2.92 | 184.3 | -2.02 | -11.73 |
| 2 | NPJ-253 x Radhika | 122 | -4.69 | -5.43 | 130 | -4.41 | -5.11 | 177.9 | -5.42 | -14.80 |
| 3 | NPJ-253 x Rukmini | 120 | -6.25 | -6.98 | 128 | -5.88 | -6.57 | 180.7 | -3.93 | -13.46 |
| 4 | NPJ-253 x PDZM-31 | 123 | -3.91 | -6.65 | 131 | -3.68 | -4.38 | 189.3 | +0.64 | -9.34 |
| 5 | Brijraj x NPJ-253 | 120 | -6.25 | -6.98 | 128 | -5.88 | -6.57 | 175.2 | -6.86 | -16.09 |
| 6 | Brijraj x Radhika | 124 | -3.13 | -3.88 | 132 | -2.94 | -3.65 | 329.4 | +75.12 | +57.76 |
| 7 | Brijraj x Rukmini | 123 | -3.91 | -6.65 | 131 | -3.68 | -4.38 | 191.3 | +1.70 | -8.38 |
| 8 | Brijraj x PDZM-31 | 121 | -5.47 | -6.20 | 129 | -5.15 | -5.84 | 182.9 | -2.76 | -12.40 |
| 9 | Radhika x NPj-253 | 120 | -6.25 | -6.98 | 128 | -5.88 | -6.57 | 174.5 | -7.23 | -16.43 |
| 10 | Radhika x Brijraj | 125 | -2.34 | -3.10 | 133 | -2.21 | -2.92 | 202.8 | +7.21 | -2.87 |
| 11 | Radhika x Rukmini | 122 | -4.69 | -5.43 | 130 | -4.41 | -5.11 | 186.4 | -0.90 | -10.73 |
| 12 | Radhika x PDZM-31 | 123 | -3.91 | -6.65 | 131 | -3.68 | -4.38 | 198.9 | +5.74 | -4.74 |
| 13 | Rukmini x NPJ-253 | 120 | -6.25 | -6.98 | 128 | -5.88 | -6.57 | 170.4 | -9.41 | -18.39 |
| 14 | Rukmini x Brijraj | 123 | -3.91 | -6.65 | 131 | 3.68 | -4.38 | 200.2 | +6.43 | -4.12 |
| 15 | Rukmini x Radhika | 122 | -4.69 | -5.43 | 130 | -4.41 | -5.11 | 184.4 | -1.97 | -11.69 |
| 16 | Rukmini x PDZM-31 | 121 | -5.47 | -6.20 | 129 | -5.15 | -5.84 | 193.6 | +2.92 | -7.28 |
| 17 | PDZM-31 x NPJ-253 | 120 | -6.25 | -6.98 | 128 | -5.88 | -6.57 | 187.0 | -0.58 | -10.44 |
| 18 | PDZM-31 x Brijraj | 123 | -3.91 | -6.65 | 131 | -3.68 | -4.38 | 194.4 | +3.35 | -6.90 |
| 19 | PDZM-31x Radhika | 122 | -4.69 | -5.43 | 129 | -5.15 | -5.84 | 201.3 | +7.02 | -3.59 |
| 20 | PDZM-31 x Rukmini | 126 | -1.56 | -2.33 | 134 | -1.47 | -2.19 | 200.9 | +6.80 | -3.78 |
| 21 | Maya (ZC) | 128 | - | - | 136 | - | - | 188.1 | - | - |
| 22 | Kranti (NC) | 129 | - | - | 137 | - | - | 208.8 | - | - |

**Table 3 Heterosis of Indian mustard cross combinations for length of main raceme, numbers of primary branches and secondary branches per plant over zonal (Maya) and national (Kranti) checks**

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| S. No. | Cross combination | Length of main raceme  (cm) | Heterosis over  Zonal check | Heterosis  over  National  check | Numbers of Primary branches/ plant | Heterosis over  Zonal check | Heterosis  over  National  check | Numbers of secondary branches/ plant | Heterosis over  Zonal check | Heterosis  over  National  check |
| 1 | NPJ-253 x Brijraj | 69.6 | +6.26 | +9.43 | 4.9 | +8.89 | -16.95 | 6.8 | -28.42 | -16.05 |
| 2 | NPJ-253 x Radhika | 66.7 | +1.83 | +4.87 | 4.3 | -4.44 | -27.12 | 4.2 | -55.79 | -48.15 |
| 3 | NPJ-253 x Rukmini | 67.6 | +3.21 | +6.29 | 5.7 | +26.67 | -3.39 | 8.9 | -6.32 | +9.88 |
| 4 | NPJ-253 x PDZM-31 | 70.7 | +7.94 | +11.16 | 5.5 | +22.22 | -6.78 | 8.9 | -6.32 | +9.88 |
| 5 | Brijraj x NPJ-253 | 75.7 | +15.57 | +19.03 | 6.3 | +40.0 | +6.78 | 11.3 | +18.95 | +39.51 |
| 6 | Brijraj x Radhika | 72.2 | +10.34 | +13.52 | 5.3 | +17.78 | -10.17 | 8.3 | -12.63 | +2.47 |
| 7 | Brijraj x Rukmini | 59.0 | -9.92 | -7.23 | 5.7 | +26.67 | -3.39 | 9.6 | +1.05 | +18.52 |
| 8 | Brijraj x PDZM-31 | 71.2 | +8.71 | +11.95 | 5.5 | +22.22 | -6.78 | 7.7 | -18.95 | -4.94 |
| 9 | Radhika x NPj-253 | 75.1 | +14.66 | +18.08 | 6.9 | +23.76 | +16.95 | 11.9 | +25.26 | +46.91 |
| 10 | Radhika x Brijraj | 65.2 | -0.46 | +2.52 | 5.5 | +22.22 | -6.78 | 7.6 | -20.0 | -6.17 |
| 11 | Radhika x Rukmini | 68.2 | +4.12 | +7.23 | 5.9 | +31.11 | 0 | 7.9 | -16.84 | -2.47 |
| 12 | Radhika x PDZM-31 | 73.5 | +12.21 | +15.57 | 4.8 | +6.67 | -18.64 | 5.3 | -44.21 | -34.57 |
| 13 | Rukmini x NPJ-253 | 78.6 | +20.0 | +23.58 | 7.5 | 66.67 | +32.37 | 13.2 | +38.95 | +62.96 |
| 14 | Rukmini x Brijraj | 70.9 | +8.24 | +11.48 | 4.1 | -8.89 | -30.51 | 6.3 | -33.68 | -22.22 |
| 15 | Rukmini x Radhika | 74.3 | +13.44 | +16.82 | 5.9 | +31.11 | 0 | 11.1 | +16.84 | +37.04 |
| 16 | Rukmini x PDZM-31 | 71.3 | +8.85 | +12.11 | 5.5 | +22.22 | -6.78 | 5.1 | -46.32 | -37.04 |
| 17 | PDZM-31 x NPJ-253 | 72.5 | +10.69 | +13.99 | 5.3 | +17.78 | -16.17 | 6.9 | -27.37 | -14.81 |
| 18 | PDZM-31 x Brijraj | 69.5 | +6.11 | +9.28 | 5.8 | +28.89 | -1.69 | 11.3 | +18.95 | +39.51 |
| 19 | PDZM-31x Radhika | 71.4 | +9.01 | +12.26 | 4.9 | +8.89 | -16.95 | 8.0 | -15.79 | -1.23 |
| 20 | PDZM-31 x Rukmini | 65.6 | +0.15 | +3.14 | 4.7 | +4.44 | -20.34 | 6.7 | -29.47 | -17.28 |
| 21 | Maya (ZC) | 65.5 | - | - | 4.5 | - | - | 9.5 | - | - |
| 22 | Kranti (NC) | 63.6 | - | - | 5.9 | - | - | 8.1 | - | - |

**Table 4 Heterosis of Indian mustard cross combinations for numbers of siliquae per plant, siliqua length, and numbers of seeds per siliquae over zonal (Maya) and national (Kranti) checks**

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| S. No. | Cross combination | Numbers of  siliquae/ plant | Heterosis over  Zonal check | Heterosis  over  National  check | Siliquae length (cm) | Heterosis over  Zonal check | Heterosis  over  National  check | Numbers of seeds /siliquae | Heterosis over  Zonal check | Heterosis  over  National  check |
| 1 | NPJ-253 x Brijraj | 271.7 | +22.77 | +42.55 | 4.5 | +9.76Z | +12.50 | 12.4 | -3.88 | 0 |
| 2 | NPJ-253 x Radhika | 138.1 | -37.60 | -27.54 | 4.8 | +17.07 | +20.0 | 10.8 | -16.28 | -12.90 |
| 3 | NPJ-253 x Rukmini | 252.3 | +14.01 | +32.37 | 4.4 | +7.32 | +10.0 | 13.2 | +2.33 | +6.45 |
| 4 | NPJ-253 x PDZM-31 | 324.9 | +46.81 | +70.46 | 4.2 | +2.44 | +5.0 | 11.5 | -10.85 | -7.26 |
| 5 | Brijraj x NPJ-253 | 353.6 | +59.78 | +85.52 | 4.8 | +17.07 | +20.0 | 14.3 | +10.85 | +15.32 |
| 6 | Brijraj x Radhika | 300.0 | +35.56 | +57.40 | 4.3 | +4.88 | +7.50 | 12.8 | -0.78 | +3.23 |
| 7 | Brijraj x Rukmini | 273.8 | +23.72 | +43.65 | 4.3 | +4.88 | +7.50 | 11.5 | -10.85 | -7.26 |
| 8 | Brijraj x PDZM-31 | 288.9 | +30.55 | +51.57 | 4.3 | +4.88 | 7.50 | 12.9 | 0 | +4.03 |
| 9 | Radhika x NPj-253 | 356.5 | +61.09 | 91.76 | 5.0 | +21.95 | +25.0 | 13.8 | +6.98 | +11.29 |
| 10 | Radhika x Brijraj | 258.7 | +16.90 | +35.73 | 4.5 | +9.76 | +12.50 | 11.6 | -10.08 | -6.45 |
| 11 | Radhika x Rukmini | 237.2 | +7.18 | +24.45 | 4.1 | 0 | +2.50 | 11.7 | -9.30 | -5.65 |
| 12 | Radhika x PDZM-31 | 200.9 | -9.22 | +5.40 | 4.3 | +4.88 | +7.50 | 12.3 | -4.65 | -0.81 |
| 13 | Rukmini x NPJ-253 | 365.1 | +64.98 | +91.55 | 5.0 | +21.95 | +25.0 | 17.1 | +32.56 | +37.90 |
| 14 | Rukmini x Brijraj | 213.8 | -3.39 | +12.17 | 4.3 | +4.88 | +7.50 | 11.8 | -8.53 | -4.84 |
| 15 | Rukmini x Radhika | 352.7 | +59.38 | +85.05 | 4.6 | +12.20 | +15.0 | 11.9 | -7.75 | -4.03 |
| 16 | Rukmini x PDZM-31 | 298.6 | +34.93 | +56.66 | 4.1 | 0 | +2.50 | 13.1 | +1.55 | +5.65 |
| 17 | PDZM-31 x NPJ-253 | 264.4 | +19.48 | +38.72 | 3.9 | -4.88 | -2.50 | 12.1 | -6.20 | -2.42 |
| 18 | PDZM-31 x Brijraj | 208.0 | -6.01 | +9.13 | 4.5 | +9.76 | +12.50 | 13.3 | +3.10 | +7.26 |
| 19 | PDZM-31x Radhika | 266.7 | +20.52 | +39.93 | 4.4 | +7.32 | +10.0 | 11.8 | -8.55 | -4.84 |
| 20 | PDZM-31 x Rukmini | 240.2 | +8.54 | +26.02 | 4.0 | -2.44 | 0 | 13.1 | +1.55 | +5.65 |
| 21 | Maya (ZC) | 221.3 | - | - | 4.1 | - | - | 12.9 | - | - |
| 22 | Kranti (NC) | 190.6 | - | - | 4.0 | - | - | 12.4 | - | - |

**Table 5 Heterosis of Indian mustard cross combinations for single plant seed weight and test weight (1000-seed weight) over zonal (Maya) and national (Kranti) checks**

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| S. No. | Cross combination | Single plant  seed weight (g) | Heterosis over  Zonal check | Heterosis  over  National  check | Test weight (g) (1000-seeds) | Heterosis over  Zonal check | Heterosis  over  National  check |
| 1 | NPJ-253 x Brijraj | 8.25 | -51.67 | 0 | 5.67 | +29.16 | +22.46 |
| 2 | NPJ-253 x Radhika | 11.04 | -35.33 | +33.81 | 5.67 | +29.16 | +22.46 |
| 3 | NPJ-253 x Rukmini | 17.28 | +1.23 | +109.45 | 5.29 | +20.64 | +14.25 |
| 4 | NPJ-253 x PDZM-31 | 18.10 | +6.03 | +119.39 | 5.09 | +15.94 | +9.93 |
| 5 | Brijraj x NPJ-253 | 19.97 | +16.99 | +142.06 | 6.19 | +41.0 | +41.0 |
| 6 | Brijraj x Radhika | 13.40 | -21.50 | +62.42 | 4.93 | +12.30 | +6.48 |
| 7 | Brijraj x Rukmini | 15.87 | -7.03 | +92.36 | 5.58 | +27.11 | +20.52 |
| 8 | Brijraj x PDZM-31 | 14.22 | -16.70 | +72.36 | 5.30 | +20.73 | +14.47 |
| 9 | Radhika x NPj-253 | 22.84 | +33.80 | +176.85 | 7.15 | +62.87 | +54.43 |
| 10 | Radhika x Brijraj | 16.25 | -4.80 | +96.97 | 5.00 | +13.90 | +7.99 |
| 11 | Radhika x Rukmini | 17.19 | +0.70 | +108.36 | 5.67 | +29.16 | +22.46 |
| 12 | Radhika x PDZM-31 | 12.51 | -26.71 | +51.64 | 4.64 | +5.69 | +0.22 |
| 13 | Rukmini x NPJ-253 | 20.01 | +17.22 | +142.55 | 6.39 | +45.56 | +38.01 |
| 14 | Rukmini x Brijraj | 14.34 | -15.99 | +73.82 | 5.16 | +17.54 | +11.45 |
| 15 | Rukmini x Radhika | 14.45 | -15.35 | +75.15 | 5.54 | +26.20 | +19.65 |
| 16 | Rukmini x PDZM-31 | 19.97 | +16.99 | +142.06 | 4.39 | 0 | -5.18 |
| 17 | PDZM-31 x NPJ-253 | 13.79 | -19.21 | +67.15 | 4.68 | +6.61 | +1.08 |
| 18 | PDZM-31 x Brijraj | 19.86 | +16.34 | 140.73 | 4.02 | -8.29 | -13.17 |
| 19 | PDZM-31x Radhika | 15.44 | -9.55 | +87.15 | 4.85 | +10.48 | +4.75 |
| 20 | PDZM-31 x Rukmini | 18.69 | +9.49 | +126.55 | 4.40 | +0.23 | -4.97 |
| 21 | Maya (ZC) | 17.07 | - | - | 4.39 | - | - |
| 22 | Kranti (NC) | 8.25 | - | - | 4.63 | - | - |

**4. Discussion**

The present investigation revealed substantial genetic variability among the 20 Indian mustard cross combinations evaluated for yield and related agronomic traits, demonstrating significant opportunities for crop improvement through hybridization. The consistent expression of positive heterosis for seed yield and its components in crosses such as Radhika × NPJ-253, Rukmini × NPJ-253, and Brijraj × NPJ-253 suggests the effectiveness of these parental combinations in exploiting genetic complementarities (Snehi et al., 2019; Rout et al., 2025). These crosses not only exhibited the highest seed yields also gave superior performance for key yield-attributing traits such as numbers of siliquae per plant, numbers of seeds per siliquae, single plant seed weight, and test weight, indicating that heterosis for yield in these cross combinations is largely underpinned by enhancements in sink capacity and seed development (Kaur et al., 2019a; Saroj et al., 2021; Kumar et al., 2024c). The observation of pronounced earliness in crosses like Rukmini × NPJ-253 and Radhika × NPJ-253, as evidenced by significant negative heterosis for days to flowering and maturity, is of particular agronomic value, facilitating crop diversification and escape from terminal stresses. As earlier suggested by Surin et al. (2018) and Kaur et al. (2019b). Meanwhile, the tendency of certain crosses involving PDZM-31 and Brijraj to flowering and maturity later recommends their potential utility in longer season environments where extended growth duration may contribute to higher biomass accumulation (Singh et al., 2014; Bagade et al., 2024). Plant stature varied widely among the cross combinations, with most crosses exhibiting reduced plant height compared to checks, a desirable trait for minimizing lodging though some, remarkably Brijraj × Radhika, displayed substantial increases, which may still be advantageous in dual-purpose systems aimed at grain and fodder production (Shah et al., 2019; Limbalkar et al., 2021; Mathur et al., 2022). Moreover, Rukmini × NPJ-253 excelled in architectural traits such as numbers of primary and secondary branches per plant and raceme length, highlighting its potential for developing robust ideotypes capable of sustaining heavier reproductive loads (Gideon et al., 2015; Saroj et al., 2021; Aragi et al., 2023). The study also underscored the role of additive and non-additive genetic effects, with differential expressions of heterosis across traits indicating complex inheritance patterns. Overall, the superior performance of crosses involving NPJ-253, particularly with Rukmini and Radhika, highlights their strong combining ability and suitability for further breeding (Meena et al., 2015; Priyamedha et al., 2018; Margam & Chakraborty, 2024; Rout et al., 2025). Similar studies have also been conducted by Tripathi et al. (2015), Aakanksha et al. (2021), Mandal et al. (2022), Singh et al. (2022), Kumar et al. (2024c) and Gupta et al. (2024) for various traits of Indian mustard. These findings advocate for advancing such promising hybrids for testing in multi-location trials to validate their stability and performance, while also serving as valuable parental sources for generating genetically diverse and high-yielding lines in Indian mustard improvement programmes.

**Conclusion**

The present investigation highlighted the substantial scope for genetic enhancement in Indian mustard through heterosis breeding. The evaluation of 20 diverse cross combinations, along with zonal and national checks, revealed remarkable variability for seed yield and its attributing traits, underscoring the effectiveness of strategic hybridization in tapping genetic complementarities. Among the crosses, combinations such as Radhika × NPJ-253, Rukmini × NPJ-253, and Brijraj × NPJ-253 consistently demonstrated superior performance across multiple yield-contributing traits, including numbers of siliquae per plant, numbers of seeds per siliquae, seed weight, and test weight, coupled with desirable earliness in flowering and maturity. The pronounced positive heterosis observed in these crosses points to the potential of exploiting both additive and non-additive gene actions to achieve significant yield gains. Furthermore, the improvement in plant architectural traits like increased branching and raceme length in main crosses suggests avenues for developing robust ideotypes capable of sustaining higher reproductive loads under varying agro-ecological conditions. These findings advocate for the advancement of identified superior crosses to test in multi-locations to validate their yield stability and adaptability. Ultimately, the investigation reinforces the importance of broadening the genetic base and utilizing heterosis breeding as a pivotal strategy for breaking existing yield plateaus in Indian mustard. This will not only enhance farm-level productivity even also contribute substantially to securing India’s edible oil requirements and strengthening the livelihoods of mustard-growing communities.

**Disclaimer (Artificial Intelligence)**

Author(s) hereby declare that No generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

**Competing Interests**

Authors have declared that no competing interests exist.

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