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Genetic Potential Evaluation of Some Maize (*Zea mays* L.) Genotypes in Terai Region of West Bengal

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***Short Title**: Evaluation of genetic potential of maize*

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An investigation was carried out in University farm of Uttarbanga Krishi Viswavidyalaya to evaluate genetic potential of 37 genotypes of maize in the two seasons Kharif (2024-25) and Rabi (2024-25). From the Analysis of Variance (ANOVA), the results confirmed significant genetic variability among the genotypes for all 16 characters studied where 6 characters were taken as DUS characters. Traits like Yield (Y), Grain Dry Weight (GDW), Anthesis-Silking Interval (ASI), and Moisture % (MP) showed high genotypic coefficient of variation (GCV), high heritability (>60%), and high genetic advance. Conversely, traits like Days to Harvesting (DH) showed low heritability and genetic advance, suggesting they are heavily influenced by the environment and less suitable for direct selection. Traits like Yield, grain dry weight, anthesis silking interval, leaf width, moisture percentage showed high genotypic coefficient of variation, high heritability and high genetic advance against mean, because of which these characters can be taken as important morphological characters for future crop improvement program.

***Key words**: Genetic Potential, GCV, PCV, Heritability, Genetic advance against mean, DUS characters*

Introduction

Introduction: Maize (*Zea mays* L.) is a significant multiuse cereal crop in many tropical countries and practically all the countries in Asia which also includes Thailand, Philippines, Vietnam and Indonesia. As per production, Maize ranks first in world production (868 million tons) followed by wheat (691 million tons) and Rice (461 million tons), (FAO, 2016). A relative study of various traits specially those associated with the yield, is useful for the plant breeder to select breeding materials through minor traits to initiate efficient breeding program. Different parameters like estimated means, genotypic-phenotypic variances, heritability and genetic advance are important to select the superior genotypes and to determine the efficiency of a breeding program (Sujiprihati *et al.*, 2003). Moreover, a very careful investigation of the factors that contribute maximum towards the yield need to be fulfilled before following any ambitious programme on maize (Quayyum, 2002). Due to complex nature of grain yield, a better understanding of the components that contribute to higher yields should play an important role in improving the selection process. In view of the evaluation of 37 genotypes, the objective of the experiment was planned so that, the genotypes would be evaluated for genetic potential in quantitative parameters during the kharif and rabi season in 2024-25 in terai region of West Bengal.

Materials and methods

This experiment was carried out in 2024-2025 at the Instructional farm field, Uttar Banga Krishi Vishwavidyalaya, Pundibari, Cooch Behar, West Bengal, India, located at 26.34‘ N latitude, 89.45‘ E longitude, and 48 meters above mean Sea level. The study site has a humid, sub-tropical climate with average temperatures.

Crop management and field experiments :

All the genotypes were grown with 60 cm row to row distance and 20 cm plant to plant distance, the plot size is 4m x 3m with three replication (According to AICRP MAIZE guidelines). Maize Genotypes were sown during the kharif season (July 2024) and rabi season (December 2024) by using randomized complete block design (RCBD) with three replications and maintained according to the package of practices recommended by (AICRP Maize). Thirteen exotic lines

and twenty-four native lines were among the thirty-seven Maize Genotypes that were chosen as experimental materials for the study. List of 37 genotypes was given in the Table-1. 16 quantitative characters were chosen for evaluation of genetic potential of 37 genotypes in this investigation (Table-2)

Results and Discussion

Analysis of Variance (Combined)

The Analysis of Variance (ANOVA) was conducted for all 16 quantitative characters. The results, as summarized in **(Table No. 3 a)** and **(Table No. 3b),** reveals the significance of the all the quantitative characters. This is a critical finding, as it confirms the existence of substantial and statistically significant genetic differences among the 37 genotypes. Significance of these characters in all 37 genotypes would suggest for consideration of all characters in selection process taking 37 genotypes in future crop improvement programme. This inherent variability is the fundamental prerequisite for any successful crop improvement program, as it provides the raw material for selection.

GCV, PCV, heritability and Genetic advance against mean studies

In germination (%), trait exhibited low GCV (6.62%) and PCV (6.80%) with high heritability (94.77%), and moderate genetic advance (13.27%) (Table-4) suggested that as the overall genetic gain was medium, selection could be done for crop improvement in future. Iqbal *et al.,* (2014), his study reported similar results where he found high heritability but a very low genetic advance for germination percentage under normal conditions, indicated direct selection would have limited potential for this trait. **In plant height**, showed moderate GCV (12.67%) and PCV (13.54%). The combination of high heritability (87.51%) and a high genetic advance (24.41%) was found to be indicative of predominant additive gene action. This conclusion is strongly supported by Matin *et al.,* (2017), where they reported high GCV and PCV, high heritability in his experiments and concluded it was controlled by additive gene effects. **In 50% pollen shade** low GCV (5.56%) and PCV (5.75%) suggested limited genetic variation for this trait with high heritability (93.29%) with the moderate genetic advance (11.06%) implied this character cannot be taken for a future crop improvement program. This is consistent with findings by Kumar *et al.,* (2014) where their findings in their experiment similarly supported this outcome. **In 50% silking,** showed low GCV (5.58%) and PCV (5.76%) with high heritability (93.72%) and moderate genetic advance (11.12%) indicated this selection for this trait would be moderately effective. Kumar *et al.,*(2020) also reported low GCV and PCV for days to 50% silking, along with high heritability but low genetic advance in their experiments. **In Anthesis Silking Interval** (ASI), this trait displayed very high GCV (35.20%) and PCV (35.50%) combined with extremely high heritability (98.28%) and a very high genetic advance (71.87%), strongly suggested ASI governed by additive gene effects and could be taken to crop improvement programme through direct selection. Mishra *et al.,*(2023), also reported high GCV, high heritability, and high genetic advance for Anthesis Silking Interval, in their experiment. **In 75% dry husk**, this trait showed very low GCV (2.71%) and PCV (3.13%) with high heritability (75.17%), though genetic advance was very low (4.84%), indicating that environmental factors significantly influence this trait, limiting the effectiveness of simple selection. Jagadev *et al.,*(2021), also reported very low PCV and GCV and a low genetic advance for days to 75% dry husk, suggesting limited scope for improvement through direct selection.

In Ear Ht from ground, moderate GCV (16.85%) and PCV (16.95%) were observed with very high heritability (98.85%) and high genetic advance (34.51%) which indicated strong genetic control, making selection for a desired ear height highly effective. These findings are strongly supported by Nzuve *et al.,*(2014), who reported high heritability and high genotypic variance for ear height in their experiment, suggesting the influence of additive gene action and that the trait could be taken for future crop improvement programme.

TABLE 1. List of 37 Maize genotypes along with their place of collection

S. No	Genotype	Source/ Institute	Country
1	IML-187	IIMR, Ludhiana	India
2	CML-451	CIMMYT, Mexico	USA
3	HKI-484-5	HAU, Hisar	India
4	CML-556	CIMMYT, Mexico	USA
5	CML-425	CIMMYT, Mexico	USA
6	KDM-895-A	SKUAST-K	India
7	KDM-340-A	SKUAST-K	India
8	CML-141	CIMMYT, Mexico	USA
9	CML-72	CIMMYT, Mexico	USA
10	CML-208	CIMMYT, Mexico	USA
11	KML-225	PJTSAU, Hyderabad	India
12	V-351	VPKAS, Almora	India
13	CML-139	CIMMYT, Mexico	USA
14	NGB-17096-1	Nordic GeneBank	Sweden
15	DML-134-2	IIMR, Ludhiana	India
16	CML-474	CIMMYT, Mexico	USA
17	DQL-784(o)-4-1	IIMR, Ludhiana	India
18	CML-117	CIMMYT, Mexico	USA
19	CML-545	CIMMYT, Mexico	USA
20	DML-1018	IIMR, Ludhiana	India
21	DMR-E-63	IIMR, Ludhiana	India
22	CML-338	CIMMYT, Mexico	USA
23	CML-128	CIMMYT, Mexico	USA
24	LM-12	PAU, Ludhiana	India
25	HKI-488-RG	HAU, Hisar	India
26	C-6	SKUAST-K	India
27	LR-1	SKUAST-K	India
28	LR-2	SKUAST-K	India
29	LR-5	SKUAST-K	India
30	SMC-3	SKUAST-K	India
31	LR-3	SKUAST-K	India
32	LR-4	SKUAST-K	India
33	KDM-33	SKUAST-K	India
34	SMC-7	SKUAST-K	India
35	C-15	SKUAST-K	India
36	SKG-2	SKUAST-K	India
37	SMC-4	SKUAST-K	India

HAU: Choudary Charan Singh Haryana Agricultural University.
SKUAST-K: Sher-e-Kashmir University of Agricultural Sciences and Technology-Kashmir.
PJTSAU: Professor Jayashankar Telangana State Agricultural University.
VPKAS: Vivekananda Parvatiya Krishi Anusandhan Sansthan.
PAU: Punjab Agricultural University.
IIMR: Indian Institute of Maize Research.; CIMMYT: International Maize and Wheat Improvement Centre.

Table 2. List of Quantitative characters of Maize taken for investigation

DUS Quantitative Characters			
S. No.	**Part**	**Character**	**Description / Unit**
1	Stem	Plant height (PH)	cm
2	Tassel	50% pollen shed (FPS)	Days
3	Ear	50% silking (FS)	Days
4	Cob	Length without husk (CL)	cm
5	Tassel	Tassel length (TL)	Centimeters (cm)
6	Stem	Ear height from ground (EHG)	Centimeters (cm)
		Other Quantitative Characters	
7	Seed	Germination % (GP)	Percentage (%)
8	Ear	Anthesis-Silking Interval (ASI)	Days
9	Ear	Days to 75% dry husk (DSDH)	Days
10	General	Days to harvesting (DH)	Days
11	Cob	Cob weight (CW)	Grams (g)
12	Kernel	Grain wet weight (GWW)	Grams (g)
13	Kernel	Grain dry weight (GDW)	Grams (g)
14	Kernel	Shelling % (SP)	Percentage (%)
15	Kernel	Moisture % (MP)	Percentage (%)
16	General	Yield (Y)	Kilograms per hectare (kg/ha)

In Tassel length, moderate GCV (13.37%) and PCV (13.72%) were recorded. High heritability (94.89%) and a high genetic advance (26.83%) suggested that selection for this trait would be effective for a crop improvement program. This is supported by Rahman (2004), who also reported high heritability coupled with high genetic gain for tassel length, indicating the presence of additive gene effects and making it a vital character in selection for grain yield improvement.

In Days to Harvesting, very low GCV (1.26%) and PCV (2.21%), with low heritability (32.40%) and a very low genetic advance (1.48%)**,** indicated that this trait was strongly influenced by the environment and had very limited potential for improvement through direct selection. Studies by Effendy *et al.,*(2018) also reported a low GCV for days to harvesting in their experiment, suggesting that direct selection for this trait would be challenging for crop improvement programme. In **Cob length**, moderate GCV (11.90%) and PCV (12.43%) with high heritability (91.79%) and a high genetic advance (23.50%) were recorded**.** This indicated that selection for increased cob length would be effective for a crop improvement program. Kumar *et al.,*(2020), who reported high heritability with high genetic advance for cob length, indicating the action of additive gene action and suggested emphasis should be given to this character during selection.

In Cob wt moderate GCV (18.99%) and PCV (19.99%) with high heritability (90.24%) and a high genetic advance (37.17%) were observed. This character would make this a key yield component that would respond very well to selection. This is supported by Mishra *et al.,*(2023), who also similarly reported high heritability and high genetic advance for cob

TABLE 3. a) Analysis of variance (ANOVA) for 16 quantitative characters in Maize (Combined) (Kharif and rabi)

Source	Df	GP	PH	FPS	FS	ASI	DSDH	EHG	TL
Season	1	176409.32***	37873.51***	94775.61***	77972.65***	42445.53***	1142791.66**	77195.7***	9084.16***
Genotypes	36	3848.26***	2928.99**	2159.68***	2267.99***	17038.69***	1878.31***	50942.06**	4613.81**
Replication (with in environment)	4	5.77	0.576	5.662	6.514	3.111	572.026	20.598	3.206
G × S	36	2858.59***	1471***	620.5***	621.24***	4966.51***	1177.194***	17038.77***	1979.07***
Error(combined)	144	144	144	144	144	144	144	642.991	267.503

TABLE 3. b) **(Contd) Analysis of variance for 16 quantitative characters in Maize (Combined) (Kharif and rabi)**

Source	Df	DH	CL	CW	GWW	GDW	SP	MP	Y
Season	1	24801.88***	9746.52***	28628.79***	5478.28***	4260.47***	18797.51***	206.288	2915.74***
Genotypes	36	182.045***	1871.08***	9248.108**	4222.68***	5223.42***	1450.9***	3064.43***	798.183***
Replication (with in environment)	4	182.144	3.427	3.701	18.97	6.612	46.793	546.9	465.791
G × S	36	108.447***	1314.22***	9143.825***	3468.51***	3368.31***	190.17***	2004.49***	67.741***
Error (combined)	144	144	144	144	144	144	144	37.7	144

*****, **,* Significant at 0.05%, 1% and 5% levels of probability, respectively.**

Abbreviations: GP= Germination %, **PH**= Plant height (cm), **FPS**= 50% pollen shed, **FS**= 50% silking, **ASI**= Anthesis-Silking Interval (Days), **DSDH**= Days to 75% dry husk, **EHG**= Ear height from ground (cm), **TL**= Tassel length (cm), **DH**= Days to harvesting, **CL**= Cob length (cm), **CW**= Cob weight (g), **GWW**= Grain wet weight (g), **GDW**= Grain dry weight (g), **SP**= Shelling %, **MP**= Moisture %, **Y**= Yield (kg/ha).**DUS Quantitative Characters**

weight, indicated that the trait was governed by additive gene action and that selection could be done. **In Grain Wet wt**, high GCV (21.92%) and PCV (23.02%) indicated significant genetic variation. High heritability (90.73%) and a high genetic advance (43.02%) showed that this trait would be very responsive to selection. This is supported by Bello *et al.,*(2012), who reported high GCV, high heritability, and high genetic advance for the number of grains per ear, indicating that the parameter was primarily controlled by additive gene effects and that effective selection is possible in their experiment. **In Grain dry wt**, high GCV (27.12%) and PCV (28.04%) with high heritability (93.58%) and high genetic advance (54.05%) were observed**.** In this parameter, direct selection for this trait would be highly effective for a future crop improvement program. This is strongly supported by Magar *et al.,*(2021), who reported very high heritability and high genetic advance for 1000-grain weight in their experiment., indicating that selection for this trait would be highly effective in future.

In Shelling (%) low GCV (6.77%) and PCV (7.04%) suggested limited genetic variation. Despite high heritability (92.61%), the moderate genetic advance (13.43%) this character implied that selection gains would be modest for crop improvement programme. This is in support with Sukumar *et al.,*(2020), who reported medium heritability and low genetic advance for shelling percentage, indicating that non-additive gene action is predominant and direct selection would be less effective.

In Moisture (%), high GCV (21.70%) and PCV (21.80%) were recorded**.** Extremely high heritability (99.09%) and a high genetic advance (44.49%) indicate that moisture content is under strong genetic control and can be effectively selected for future crop improvement programme. This is supported by Khan and Saleem (2006), who reported high heritability estimated for dry matter content (a related trait), indicating that selection would be effective. The ability to select for this trait is economically important as it can reduce post-harvest drying costs.

In Grain yield, high GCV (20.72%) and PCV (21.92%) indicated substantial genetic variation for yield. This, combined with high heritability (89.36%) and a high genetic advance (40.36%)**,** confirms that

Table 4. Analysis of Phenotypic and genotypic coefficient of variation, heritability, genetic advance and genetic gain for 16 characters in Maize

Characters	Grand Mean	Range		GCV (%)	PCV (%)	Heritability (%)	Genetic gain (%)
		Max	Mean				
GP	80.52	92.13	65.75	6.62	6.8	94.77	13.27
PH	192.23	255.13	142.33	12.67	13.54	87.51	24.41
FPS	67.53	77.13	59.9	5.56	5.75	93.29	11.06
FS	67.5	77.33	60	5.58	5.76	93.72	11.12
ASI	2.23	4.4	1.18	35.2	35.5	98.28	71.87
DSDH	106.04	112.5	100.03	2.71	3.13	75.17	4.84
EHG	90.96	133.15	63.59	16.85	16.95	98.85	34.51
TL	34.26	49.7	27.37	13.37	13.72	94.89	26.83
DH	131.12	140.67	124.33	1.26	2.21	32.4	1.48
CL	12.7	16.12	8.07	11.9	12.43	91.79	23.5
KR	12.73	14.83	10.67	9.35	10.05	86.49	17.91
GWW	77.73	115.75	50.54	21.92	23.02	90.73	43.02
GDW	66.07	107.3	39.4	27.12	28.04	93.58	54.05
SP	86.6	97	66.65	6.77	7.04	92.61	13.43
MP	17.33	24.57	11.13	21.7	21.8	99.09	44.49
Y	5550.15	8275.85	3845.13	20.72	21.92	89.36	40.36

Abbreviations: GP= Germination %, **PH**= Plant height (cm), **FPS**= 50% pollen shed, **FS**= 50% silking, **ASI**= Anthesis-Silking Interval (Days), **DSDH**= Days to 75% dry husk, **EHG**= Ear height from ground (cm), **TL**= Tassel length (cm), **DH**= Days to harvesting, **CL**= Cob length (cm), **CW**= Cob weight (g), **GWW**= Grain wet weight (g), **GDW**= Grain dry weight (g), **SP**= Shelling %, **MP**= Moisture %, **Y**= Yield (kg/ha)

yield is highly heritable and governed by additive gene effects. This makes direct phenotypic selection for yield a highly effective and promising strategy for improving productivity in this maize germplasm. This conclusion is supported by Magar *et al.,* (2021), who also reported high GCV, high heritability, and high genetic advance for grain yield, concluding that these conditions are best for effective selection.

Conclusion

The detailed analysis confirms that significant genetic variability exists across the 37 maize genotypes for all 16 traits. The most promising traits for achieving significant genetic gains through direct selection are those that simultaneously exhibit high GCV, high heritability, and high genetic advance. Based on these results, future breeding efforts should prioritize selection for Yield (Y), Grain Dry Weight (GDW), Anthesis-Silking Interval (ASI), Grain Wet Weight (GWW), Cob Weight (CW), and Moisture % (MP). These traits are predominantly controlled by additive genes, show minimal environmental influence, and possessed ample variability, making them suitable characters for effective development of improved maize varieties in future course of crop improvement programme.

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Interactive Effects of Nitrogen Split Scheduling and Silicon Nutrition on Yield Attributes, Productivity and Associated Insect Pest Incidence of Rice (Oryza sativa L.)

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Abstract

A field experiment was conducted during the kharif season of 2022-23 Puratangram village, Galsi-I Block, Purba Bardhaman district, West Bengal, to evaluate the effect of nitrogen split scheduling and silicon nutrition on yield attributes, productivity and insect pest incidence in rice (*Oryza sativa* L.). The experiment was laid out in a factorial randomized block design . The nitrogen treatments consisted of N1 (50% basal + 25% at active tillering + 25% at panicle initiation), N2 (25% basal + 50% at active tillering + 25% at panicle initiation) and N3 (25% basal + 25% at active tillering + 50% at panicle initiation). Silicon treatments consisted of S0 (no silicon application), S1 (Basal application of calcium silicate @ 500 kg ha^{-1} before transplanting), S2 (Foliar spray of soluble silicic acid @ 4 mL L^{-1} at maximum tillering and booting) and S3 (Calcium silicate @ 250 kg ha^{-1} as basal + soluble silicic acid @ 4 mL L^{-1} as a foliar spray at booting).

Nitrogen split scheduling significantly influenced yield attributes and productivity. Application of nitrogen according to N3 recorded the highest number of filled grains panicle{ ¹ (132.05), test weight (23.42 g), grain yield (5.21 t ha^{-1}) and straw yield (6.60 t ha^{-1}), whereas N2 produced the maximum effective tillers (361.78 m^{-2}) and panicle length (27.69 cm). Among silicon treatments, basal application of calcium silicate (S1) recorded the highest grain yield (5.02 t ha^{-1}), while differences in other yield attributes were not significant. The interaction between nitrogen scheduling and silicon nutrition significantly influenced effective tillers, filled grains $panicle^{-1}$, test weight, grain yield and straw yield.

Nitrogen scheduling also affected insect pest incidence. Stem borer damage, expressed as dead heart (4.53%) and white ear (6.37%), was highest under N2, whereas hopper damage was greater under N3. Silicon application did not significantly reduce stem borer or hopper incidence, although combined soil and foliar application showed comparatively lower pest infestation. The results indicate that application of 25% nitrogen as basal, 25% at active tillering and 50% at panicle initiation, together with basal application of calcium silicate, improved grain productivity and provided a suitable nutrient management strategy for rice under the agro-climatic conditions of eastern India.

Key words: *Nitrogen split application, Silicon fertilization, Grain productivity, Stem borer*

Introduction

Rice (*Oryza sativa* L.) is the staple food for more than half of the global population and plays a critical role in food and nutritional security. Globally, rice is cultivated on about 165 million hectares with an annual production exceeding 780 million tonnes (Abeysekara & Rathnayake, 2024). India occupies the largest area under rice cultivation and contributes substantially to global rice production (Mahajan *et al*., 2017). Despite significant advances in varietal improvement and crop management, achieving sustainable rice productivity remains a challenge due to increasing biotic stresses, particularly insect pests (Iqbal *et al*., 2023).

Among the insect pests affecting rice, stem borer (*Scirpophaga incertulas*) and hopper complexes,

including brown planthopper (*Nilaparvata lugens*), white-backed planthopper (*Sogatella furcifera*), and green leafhopper (*Nephotettix* spp.), are among the most destructive pests in Asian rice ecosystems. Stem borer larvae cause characteristic dead hearts during the vegetative stage and white ears during the reproductive stage, leading to substantial yield losses (Bhatt *et al*., 2018). Similarly, hopper infestation causes direct damage through phloem sap extraction, resulting in chlorosis, stunted growth, reduced photosynthetic activity, hopper burn, and severe yield decline. In addition, leafhoppers serve as vectors of viral diseases, further aggravating production losses. Under severe infestations, yield losses due to stem borers and hopper outbreaks may exceed 30–60%, depending on crop stage and environmental conditions (Muralidharan & Pasalu, 2006).

Nitrogen fertilization is indispensable for maximizing rice productivity because of its crucial role in chlorophyll synthesis, tillering, leaf area development, and grain formation. However, excessive or improperly timed nitrogen application has frequently been associated with increased incidence of stem borers and hopper pests (Sarkar, 2021). Nitrogen-rich plants contain higher concentrations of soluble amino acids and nitrogenous compounds that improve host suitability for insect feeding and reproduction (Rashid *et al*., 2017). Luxuriant vegetative growth induced by high early nitrogen application creates a humid and dense canopy microclimate that favors hopper multiplication and stem borer survival. Consequently, nitrogen management is increasingly recognized not only as a productivity-enhancing practice but also as a critical determinant of pest dynamics in rice ecosystems (Saroj *et al*., 2025).

Nitrogen split scheduling offers an opportunity to improve nitrogen use efficiency while reducing pest-favourable crop conditions. By synchronizing nitrogen supply with crop demand at basal, active tillering, and panicle initiation stages, nutrient availability can be optimized without promoting excessive early vegetative growth (Hu *et al*., 2024). Appropriate redistribution of nitrogen application may therefore reduce pest susceptibility while maintaining adequate nutrient supply for yield formation. Nevertheless, information regarding the influence of different nitrogen splitting patterns on hopper and stem borer incidence remains limited (Tiwari, 2016).

Silicon (Si) is considered a beneficial element for rice and has attracted considerable attention because of its role in enhancing plant resistance against insect pests. Rice is a silicon accumulator capable of depositing substantial quantities of silica in epidermal tissues (Meharg & Meharg, 2015). Silicon deposition forms a silica-cellulose layer that increases tissue hardness and acts as a mechanical barrier against insect feeding and penetration. In stem borer-infested rice, increased silica accumulation strengthens stem tissues and reduces larval penetration and feeding damage. Similarly, silicon-mediated strengthening of leaf and stem tissues reduces hopper feeding efficiency and negatively affects survival, development, and fecundity (Yang *et al*., 2017).

Beyond its physical effects, silicon also activates biochemical defense mechanisms by stimulating the production of phenolic compounds, lignin, defense-related enzymes, and antioxidant systems. These responses enhance plant tolerance and resistance to insect attack (Hassan *et al*., 2024). Previous studies have demonstrated that silicon application significantly reduces stem borer infestation, dead heart formation, leaf folder damage, and hopper populations while improving crop growth and yield (Sakr, 2017). Silicon supplementation has also been reported to offset the pest-enhancing effects of nitrogen fertilization by strengthening host plant defences and reducing insect preference. Rice plants supplied with both nitrogen and silicon exhibited lower pest incidence and superior grain yield compared with plants receiving nitrogen alone (Malav & Ramani, 2015).

Apart from its role in pest management, silicon contributes to enhanced crop productivity through improved photosynthetic efficiency, erect leaf architecture, nutrient uptake, lodging resistance, and grain filling (Kovács *et al*., 2022). Likewise, optimized nitrogen scheduling improves nutrient use efficiency and ensures sustained nutrient availability during critical growth stages. Therefore, integrating nitrogen split scheduling with silicon nutrition may provide a dual advantage by simultaneously suppressing stem borer and hopper infestations while enhancing crop growth and yield (Dash, 2021).

Materials and Methods

The field experiment was conducted during the kharif season of 2022–23 at Puratangram village, Galsi-I Block, Purba Bardhaman district, West Bengal, India (23.3149° N latitude and 87.6163° E longitude). The field experiment was conducted in sandy clay loam to clay loam textured soils of rice growing areas. The nature of soil was acidic to neutral and pH ranged from 6.32 to 7.20. The soluble salts content was low to high and mean value was 0.43 ds m^{-1}. The available nitrogen, phosphorus, potassium and sulphur ranged from medium to high.

The experiment was laid out in a Factorial Randomized Block Design (FRBD) with three replications. The treatments comprised three nitrogen split schedules and four silicon application regimes, resulting in twelve treatment combinations. The nitrogen treatments consisted of N1 (50% basal + 25% at active tillering + 25% at panicle initiation), N2 (25% basal + 50% at active tillering + 25% at panicle initiation) and N3 (25% basal + 25% at active tillering + 50% at panicle initiation). Silicon treatments consisted of S0 (no silicon application), S1 (Basal application of calcium silicate @ 500 kg ha^{-1} before transplanting), S2 (Foliar spray of soluble silicic acid @ 4 mL L^{-1} at maximum tillering and booting) and S3 (Calcium silicate @ 250 kg ha^{-1} as basal + soluble silicic acid @ 4 mL L^{-1} as a foliar spray at booting).

The rice variety Ajit was transplanted at a spacing of 20 × 15 cm using healthy seedlings of appropriate age. Nitrogen was applied at the recommended dose of 120 kg N ha^{-1} through urea and distributed according to the respective treatment schedules. The entire recommended dose of phosphorus (60 kg P, O… ha^{-1}) and potassium (60 kg K, O ha^{-1}) was applied uniformly as basal before transplanting through single superphosphate and muriate of potash, respectively. Silicon was applied according to the respective treatment schedules. Basal application was made through calcium silicate at 500 kg ha^{-1} before transplanting, whereas foliar application was carried out using soluble silicic acid at 4 mL L^{-1} at the maximum tillering and booting stages. In the combined treatment (S*f*), calcium silicate was applied at 250 kg ha^{-1} as a basal application, followed by a foliar spray of soluble silicic acid at 4 mL L^{-1} at the booting stage. Basal calcium silicate was incorporated into the soil before transplanting, and foliar sprays were applied using a knapsack sprayer.

Observations on the incidence of major sucking pests, namely brown planthopper (*Nilaparvata lugens*), white-backed planthopper (*Sogatella furcifera*) and green leafhopper (*Nephotettix virescens*), were recorded at 30, 45 and 60 days after transplanting (DAT), during panicle initiation and at booting stage. Pest populations were assessed from ten randomly selected hills in each plot and expressed as mean number of insects per hill. Hopper incidence was recorded following the Standard Evaluation System (SES) for rice (IRRI, 2013).

Yield attributes including number of panicles $hill^{-1}$, panicle length, grains $panicle^{-1}$, filled grain percentage and test weight were recorded from five randomly selected hills at maturity. Grain and straw yields were recorded from the net plot area and converted to kg ha^{-1} after adjusting grain moisture content to 14 per cent.

The economics of different treatments were worked out by calculating cost of cultivation, gross returns, net returns and benefit–cost ratio based on prevailing market prices. The experimental data pertaining to growth parameters, pest incidence, yield attributes and yield were subjected to analysis of variance appropriate to a Factorial Randomized Block Design. Treatment means were compared using the least significant difference (LSD) test at the 5 per cent level of significance. Statistical analysis was performed using OPSTAT statistical software.

Results and Discussions

Effect of Nitrogen Scheduling and Silicon Application on Yield Attributes and Productivity

The nitrogen split schedule significantly influenced yield attributes and productivity of rice. The application of 25% basal + 25% active tillering + 50% panicle initiation (N*f*) recorded the highest number of filled grains per panicle (132.05), test weight (23.42 g), grain yield (5.21 t ha^{-1}) and straw yield (6.60 t ha^{-1}). The superior performance under N*f* may be attributed to greater nitrogen availability during the reproductive phase, which enhanced spikelet

Table 1. Damage rating scale (0-9) used for assessing hopper damage under field conditions

Score	Field Symptoms
0	No damage.
1	Slight yellowing of a few plants.
3	Leaves partially yellow, but no hopper burns.
5	Leaves with pronounced yellowing and some stunting or wilting; 10–25% of plants exhibiting hopper burn, with the remaining plants severely stunted.
7	More than half of the plants showing wilting or hopper burn, remaining plants severely stunted.
9	All plants dead.

Hopper incidence was assessed using the Standard Evaluation System (SES) for Rice (IRRI, 2013) based on a 0–9 damage rating scale, where 0 = no damage and 9 = all plants dead.

development, grain filling and assimilate translocation towards developing grains (Xing *et al*., 2019). Nitrogen application near panicle initiation plays a crucial role in increasing sink capacity and improving grain filling, thereby contributing to higher grain yield. Similar findings were reported by (Hirzel *et al*., 2012), who observed increased grain yield when 50% of the total nitrogen was applied at panicle initiation. Likewise, Ayalew & Tadesse, 2017 reported that greater nitrogen allocation during the reproductive stage enhanced effective tillers, panicle length, straw yield, filled spikelets and grain yield. Huang *et al*., 2012 further demonstrated that nitrogen application with a larger proportion supplied at panicle initiation significantly improved spikelet production. In addition, **Kuai *et al*., 2020** reported that delayed nitrogen application promoted carbohydrate accumulation, assimilate translocation and grain filling, ultimately resulting in improved grain yield. These findings collectively support the higher filled grains per panicle, grain yield and straw yield recorded under N*f*.

However, the highest effective tillers m^{-2} (361.78) and panicle length (27.69 cm) were recorded under N, (25% basal + 50% active tillering + 25% panicle initiation). This may be attributed to greater nitrogen availability during the active tillering stage, which stimulated vegetative growth, leaf area development and tiller production. Nitrogen supplied during the vegetative phase promotes vigorous crop growth through enhanced photosynthetic activity and biomass accumulation. Similar observations were reported by **Paliwal *et al*., 2014** who stated that split nitrogen application improves nitrogen-use efficiency and photosynthate supply, thereby enhancing crop growth and yield attributes. (Ding *et al*., 2014) also reported that nitrogen stimulates cell division and promotes panicle formation, while (Zhou *et al*., 2019)) observed improved tiller quality and panicle development under optimized nitrogen management. The higher effective tillers and longer panicles observed under N, may therefore be attributed to enhanced vegetative growth resulting from increased nitrogen availability during the tillering stage. Nevertheless, despite producing more tillers, N, did not record the highest grain yield, indicating that nitrogen availability during reproductive growth was more critical for grain filling and final yield realization than vegetative growth alone (Fituma, 2015).

Silicon nutrition significantly influenced grain yield, while its effect on other yield attributes remained non-significant. The highest grain yield (5.02 t ha^{-1}) was recorded with 100% basal calcium silicate application before transplanting (S). The higher grain yield under S may be attributed to increased silicon uptake, improved nutrient-use efficiency and enhanced physiological activity of rice plants. Silicon deposition in plant tissues improves structural integrity, photosynthetic efficiency and stress tolerance, thereby

contributing to better crop performance and yield (Zargar *et al*., 2019).

The interaction between nitrogen split scheduling and silicon nutrition significantly influenced effective tillers m^{-2}, filled grains per panicle, test weight, grain yield and straw yield. The significant N × Si interaction indicates that silicon improved the utilization of nitrogen supplied at different growth stages, resulting in enhanced grain filling and yield formation. Silicon application has been reported to promote root growth, maintain higher photosynthetic activity and improve nutrient uptake, thereby increasing nitrogen-use efficiency and crop productivity (Ali *et al*., 2020). Mohanty et al., 2020 reported that combined nitrogen and silicon fertilization enhanced photosynthetic efficiency, nitrogen metabolism and nutrient accumulation, leading to higher grain yield. Likewise, Zhang *et al*., 2018 improved spikelet formation, grain yield and overall rice productivity under integrated nitrogen and silicon management. Therefore, the superior yield attributes and productivity observed under nitrogen–silicon interaction in the present study may be attributed to improved nitrogen uptake, efficient nutrient utilization and enhanced physiological performance.

Effect of Nitrogen Scheduling and Silicon Application on Insect Pest Incidence in Rice

The incidence of stem borer and hopper damage was influenced primarily by nitrogen scheduling, whereas silicon application did not produce a statistically significant response. Variations in dead heart, white ear formation, and hopper damage scores among nitrogen treatments indicate that the timing of nitrogen availability played an important role in determining pest pressure during crop growth.

Dead heart incidence was highest under N2, recording 4.53%, while N1 and N3 exhibited similar values. A comparable trend was observed for white ear formation, where N2 produced the maximum value of 6.37%. Since dead heart and white ear are symptoms of stem borer infestation expressed at vegetative and reproductive stages, respectively, the results suggest that greater nitrogen availability during the active tillering period may have created conditions favourable for stem borer establishment and survival. Enhanced vegetative growth often increases the production of tender tissues, which can serve as attractive feeding and oviposition sites for stem-boring insects (Sunitha, 2018). The higher pest incidence observed under N2 may therefore be associated with improved host suitability rather than a direct effect of nitrogen itself.

Unlike stem borer damage, hopper injury responded differently to nitrogen distribution. The highest hopper damage scores were recorded under N3 at both vegetative and reproductive stages. This treatment allocated a larger proportion of nitrogen near panicle initiation, which may have prolonged the availability of nitrogen-rich plant tissues during later growth stages (Basuchaudhuri, 2016). Sap-feeding insects are generally favoured by crops with higher concentrations of soluble nitrogen compounds because these compounds improve food quality and support rapid population development. The greater hopper damage observed under N3 therefore indicates that nitrogen supplied during the reproductive transition stage may have enhanced the suitability of rice plants for hopper feeding and multiplication (Rashid *et al*., 2017).

Although numerical differences were observed among silicon treatments, none of the silicon effects reached statistical significance. The lowest values for dead heart, white ear, and reproductive-stage hopper damage were generally associated with the combined basal and foliar silicon treatment (S3), indicating a tendency toward reduced pest injury. However, the magnitude of reduction was insufficient to produce a significant response under the prevailing field conditions. The effectiveness of silicon in suppressing insect pests often depends on factors such as plant uptake, soil characteristics, environmental conditions, pest population density, and crop genotype. It is therefore possible that the silicon supplied during the

experiment was adequate to maintain plant health but insufficient to generate measurable reductions in pest incidence.

The absence of a significant nitrogen × silicon interaction further suggests that silicon application did not alter the response pattern created by different nitrogen schedules. Nitrogen management remained the dominant factor affecting both stem borer and hopper damage. The contrasting responses of stem borers and hoppers to nitrogen distribution highlight the importance of balanced nutrient management. Greater nitrogen availability during active tillering appeared to favour stem borer damage, whereas increased nitrogen availability near panicle initiation promoted hopper infestation. These findings indicate that careful adjustment of nitrogen application timing may provide an effective approach for reducing pest pressure while maintaining crop productivity in transplanted rice.

Summary and Conclusion

The present investigation demonstrated that nitrogen split scheduling exerted a greater influence on rice productivity and insect pest incidence than silicon nutrition. Redistributing nitrogen with a higher proportion applied at the panicle initiation stage (25% basal + 25% active tillering + 50% panicle initiation) significantly improved grain filling, test weight, grain yield, and straw yield, indicating that an adequate nitrogen supply during the reproductive phase is essential for maximizing yield. In contrast, allocating a larger proportion of nitrogen at the active tillering stage enhanced tiller production and panicle length but also increased stem borer infestation, suggesting that excessive nitrogen availability during vegetative growth may create favourable conditions for pest establishment. Similarly, higher nitrogen availability during the reproductive stage increased hopper incidence, emphasizing the need to optimize nitrogen timing to balance crop productivity and pest management. These findings are supported by the experimental results and treatment comparisons reported in the study.

Silicon application improved grain yield, with basal application of calcium silicate producing the highest productivity, although its effects on most yield attributes and insect pest incidence were not statistically significant under the prevailing field conditions. Nevertheless, numerical reductions in pest damage under combined soil and foliar silicon application suggest that silicon may contribute to improved crop resilience, particularly under environments where pest pressure or abiotic stress is more severe. The significant interaction between nitrogen scheduling and silicon nutrition for several yield-related parameters further indicates that silicon can enhance the efficiency of nitrogen utilization and support improved crop performance when integrated with appropriate nutrient management practices.

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Table 2. Effects of Treatments on Insect Pest Incidence

Treatments	Dead heart (%)	White Ear (%)	Hopper burn score at vegetative stage	Hopper burn score at reproductive stage
Nitrogen Split Schedules (N)				
50% Basal + 25% AT + 25% PI	3.72	5.16	2.85	3.91
25% Basal + 50% AT + 25% PI	4.52	6.36	2.84	3.75
25% Basal + 25% AT + 50% PI	3.72	5.16	5	4.66
SEm(±)	0.23	0.29	0.16	0.21
CD (P=0.05)	0.70	0.87	0.48	0.63
Silicon Regimes (S)				
No silicon	3.88	5.51	3.46	4.18
Basal application of calcium silicate @ 500 kg ha^{-1} before transplanting.	4.18	5.69	3.77	4.46
Foliar spray of soluble silicic acid @ 4 mL L^{-1} at maximum tillering and booting.	4.07	5.61	3.5	4.13
Calcium silicate @ 250 kg ha^{-1} as $^{-1}$ basal + soluble silicic acid @ 4 mL L^{-1} as a foliar spray at booting.	3.84	5.44	3.53	3.68
SEm(±)	0.28	0.34	0.19	0.25
CD (P=0.05)	NS	NS	NS	NS
Interaction (N × S)				
SEm(±)	0.47	0.59	0.33	0.43
CD (P=0.05)	NS	NS	NS	NS

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Table 3. Effects of Treatments on Productivity of rice

Treatments	Effective tillers m^{-2}	Panicle length (cm)	Filled grains (Panicle^{-1})	Test weight (g)	Grain yield (t ha^{-1})	Starw Yield (t ha^{-1})
Nitrogen Split Schedules (N)						
50% Basal + 25% AT + 25% PI	342.35	26.81	124.23	23.30	4.60	6.11
25% Basal + 50% AT + 25% PI	361.78	27.69	130.66	23.35	4.87	6.28
25% Basal + 25% AT + 50% PI	352.34	25.57	132.05	23.42	5.21	6.60
SEm(±)	3.72	0.30	1.24	0.07	0.04	0.06
CD (P=0.05)	10.74	0.86	3.59	NS	0.10	0.18
Silicon Regimes (S)						
No silicon	349.07	27.49	130.02	23.36	4.80	6.26
Basal application of calcium silicate @ 500 kg ha^{-1} before transplanting.	351.59	26.43	128.82	23.38	5.02	6.39
Foliar spray of soluble silicic acid @ 4 mL L^{-1} at maximum tillering and booting.	355.08	26.33	130.29	23.35	4.89	6.38
Calcium silicate @ 250 kg ha^{-1} as basal + soluble silicic acid @ 4 mL L^{-1} as a foliar spray at booting.	352.90	26.50	126.79	23.35	4.87	6.28
SEm(±)	4.29	0.34	1.43	0.09	0.04	0.07
CD (P=0.05)	NS	NS	NS	NS	0.12	NS
Interaction (N × S)						
SEm(±)	7.43	0.59	2.48	0.15	0.07	0.12
CD (P=0.05)	21.48	NS	7.17	0.43	0.21	0.36

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Genotype Stability and Adaptability of Rice (*Oryza sativa* L.) across Irrigated and Rainfed Environments in West Bengal: Eberhart-Russell and AMMI Analyses of 60 Diverse Genotypes

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Abstract

Genotype × environment interaction (GxE) is a critical challenge in rice improvement for rainfed ecosystems. The present study evaluated sixty diverse rice genotypes (including traditional landraces, released varieties, and advanced lines) across four environments - Chinsurah Irrigated (E1), Chinsurah Rainfed (E2), Purulia Irrigated (E3), and Purulia Rainfed (E4) - in West Bengal, India, using both Eberhart-Russell (E-R) joint regression and Additive Main effects and Multiplicative Interaction (AMMI) analyses for grain yield. The grand mean yield was 3,781 kg ha{ ¹. Environment indices ranged from +1,236 kg ha{ ¹ (E3) to "1,337 kg ha{ ¹ (E4), confirming Purulia Rainfed as the most stressful test environment. AMMI analysis showed that IPCA1 and IPCA2 explained 84.7% and 9.3% of the GE interaction sum of squares, respectively (94.0% total), with IPCA1 reflecting the dominant irrigated–rainfed contrast. Eight traditional and released genotypes (*Brown Gora, Vutmuri, Narendra-97, Sahbhagidhan, Dular, N 22, Puspo, Azusena*) showed below-average environmental responsiveness (bi = 0.217–0.371) with mean yields of 4,899–5,199 kg ha{ ¹, classifying them as specifically adapted to rainfed stress environments. Sixteen genotypes showed above-average responsiveness (bi > 1.1), suitable for irrigated conditions. *Krishnahansa* (bi = 1.025, S²di = 90) and CR Dhan 40 (bi = 0.898, mean = 4,265 kg ha{ ¹) were identified as ideally broadly stable and the best dual-purpose variety, respectively. Both analytical frameworks converged on the same adaptive groupings, with the rainfed-adapted group clustering near the negative IPCA1 pole and the irrigated-adapted group near the positive IPCA1 pole. *Vutmuri, N 22*, and *Azusena* showed the combination of low bi, low S²di, and IPCA1 scores near the rainfed environments - making them the most consistently stable drought-tolerant candidates for recommendation in rainfed West Bengal.

***Key words**: Genotype × environment interaction; AMMI biplot; Eberhart-Russell stability; rice drought tolerance; rainfed rice; West Bengal; IPCA; stability parameter.*

Introduction

Rice (Oryza sativa L.) is the staple food for over half the global population, with Asia accounting for approximately 90% of world production (FAOSTAT, 2026; Khush, 2005). In India, rice is cultivated on 51.27 million hectares (Mha) with a

national production of 150.18 million tonnes (Mt) in 2024–25 (DA&FW, 2025). West Bengal ranks among the top three rice-producing states nationally, contributing approximately 10.7% of India's total output from 5.59 Mha (DA&FW, 2025). Despite this importance, a substantial portion of the West Bengal rice area - particularly the lateritic tracts of western districts such as Purulia, Bankura, and Birbhum - remains rainfed and drought-prone, with average yields frequently below 2,000 kg ha^{-1} in stress years (Mandal *et al*., 2010; Ghosh *et al*., 2016).

Drought is the most damaging abiotic stress in rainfed rice, causing estimated annual yield losses of 15–20 million tonnes in Asia alone (Pandey *et al*., 2007; Serraj *et al*., 2011; Wassmann *et al*., 2009). Bridging the yield gap between irrigated and rainfed production environments requires the identification of genotypes that either maintain stable yields across conditions (broad adaptation) or achieve specifically high performance under rainfed stress (specific adaptation). However, the relative performance of genotypes is rarely constant across environments - the phenomenon of genotype × environment interaction (GxE), in which different genotypes respond differently to the same change in environmental quality - is ubiquitous in multi-environment rice yield trials and makes varietal recommendation substantially more complex than selecting the highest mean-yielding genotype (Kang, 2002; Yan and Kang, 2003; Verulkar *et al*., 2010).

Two complementary statistical approaches are widely employed to characterise GxE structure and identify adapted genotypes. The joint regression model of Eberhart and Russell (1966), building on Finlay and Wilkinson (1963), regresses each genotype's yield on the environmental mean (environment index) to estimate a linear response coefficient (bi) and a deviation from regression (S^2di). Genotypes with bi < 1 and small S^2di are specifically adapted to poor (stress) environments; bi > 1 with low S^2di indicates specifically adapted to favourable environments; bi H" 1 with S^2di H" 0 represents ideal broad stability (Lin *et al*., 1986; Becker and Leon, 1988). The AMMI model (Gauch, 1988; Zobel *et al*., 1988) decomposes the GxE interaction matrix into multiplicative interaction principal component axes (IPCA), enabling simultaneous display of mean performance and interaction through biplots (Gauch and Zobel, 1996; Yan *et al*., 2000). AMMI has been shown to capture GxE structure more parsimoniously than regression-based methods in rice multi-environment trials (Anandan *et al*., 2009; Balestre *et al*., 2009).

The combination of both methods is advocated in the literature (Becker and Leon, 1988; Gauch, 1992) because they are complementary: E-R regression quantifies linear response magnitude and unpredictability, while AMMI provides geometric visualisation of which environments drive the interaction and which genotypes are most responsive to the irrigated –rainfed contrast. Despite extensive research on rice GxE in South Asia (Mandal et al., 2010; Verulkar *et al*., 2010; Raman *et al*., 2012), a comprehensive stability analysis integrating traditional drought-tolerant landraces, released varieties of the Aman season, and advanced breeding lines simultaneously evaluated under both irrigated and rainfed conditions at both alluvial (Chinsurah) and lateritic (Purulia) ecologies of West Bengal is lacking. The present study addresses this gap, applying both E-R and AMMI analyses to a 60-genotype panel across four environments to identify stable, broadly adapted, and specifically rainfed-adapted genotypes for recommendation in the West Bengal rice system.

Materials and Methods

2.1 Genetic Material

A total of 60 rice genotypes were evaluated, comprising 59 test entries and one local check (*Azusena*). The panel included traditional drought-tolerant landraces (e.g. *Brown Gora, N22, Dular, Puspo, Vandana, Ahu Joha*), released varieties of various agro-ecological suitability (*Krishnahansa, CR Dhan 40, Jaya, Lalat*, IR series, IET series lines), and materials representing a range of yield potential and adaptation types. All 60 entries are listed in Table 1 along with their stability parameters.

2.2 Experimental Environments

Experiments were conducted at two locations across two water management situations, giving four environments (Table 2): E1 (Rice Research Station, Chinsurah, Hooghly, West Bengal - alluvial soil, irrigated), E2 (Chinsurah - rainfed, same plots without supplementary irrigation), E3 (Zonal Drought Resistant Paddy Research Station, Hathwara, Purulia - lateritic red-yellow soil, irrigated), and E4 (Purulia - rainfed). Chinsurah lies in the Gangetic alluvial belt (22.9°N, 88.4°E; average annual rainfall ~1,500 mm); Purulia lies in the Chota Nagpur Plateau rain shadow zone (23.3°N, 86.4°E; average annual rainfall ~1,200–1,400 mm with high inter-annual variability). Experiments were conducted during the *Aman* (*kharif*) season.

2.3 Experimental Design and Yield Measurement

Experiments at each environment were laid out in a randomised complete block design (RCBD; Gomez and Gomez, 1984) with three replications. Plot size was 4 m × 3 m (12 m²) with transplanting at 25 × 15 cm spacing. Standard agronomic practices (fertiliser: 80:40:40 N:P, O… :K, O kg ha^{-1} for irrigated; 60:30:30 for rainfed) were followed. Grain yield was determined by harvesting the net plot area and adjusting to 14% moisture content (IRRI, 2013).

2.4 Eberhart-Russell Joint Regression Stability Analysis

Genotype stability was evaluated using the joint regression model of Eberhart and Russell (1966), which estimates the regression of genotype mean yield on the environment index ($Ij = \bar{Y}.j - \bar{Y}..$), yielding a linear regression coefficient (bi) and deviation from regression mean square (S^2di) for each genotype. Genotypes with bi < 1 and low S^2di are specifically adapted to poor environments; bi > 1 and low S^2di indicate specifically adapted to favourable environments; bi H" 1 with S^2di H" 0 represent broadly stable types (Finlay and Wilkinson, 1963; Eberhart and Russell, 1966). Regression coefficients were tested against H€ : bi = 1 using a t-test. Analysis was implemented in Python using NumPy and SciPy.

2.5 AMMI Analysis

The AMMI model (Gauch, 1988; Zobel *et al.*, 1988) was fitted to the 60 × 4 genotype × environment mean yield matrix. The model partitions total yield variation into genotype main effects (G), environment main effects (E), and GxE interaction, with the GxE matrix further decomposed by singular value decomposition (SVD; Golub and Van Loan, 2013) into interaction principal component axes (IPCA). The percentage of GxE interaction sum of squares (SS) explained by each IPCA was calculated as $(\lambda^2 n / \Sigma n\lambda^2 n) \times 100$, where λn is the nth singular value. AMMI1 biplots (mean yield × IPCA1 score) and AMMI2 biplots (IPCA1 × IPCA2 scores) were constructed. Analyses were performed in Python using scikit-learn (Pedregosa *et al.*, 2011) and NumPy.

Results and Discussion

3.1 Environment Characterisation and GxE Structure

The grand mean grain yield across all 60 genotypes and four environments was 3,781 kg ha^{-1} (Table 2). Environment indices (Ij) differentiated environments sharply: the two irrigated environments had strongly positive indices (E1: +1,170 kg ha{ ^{1}; E3: +1,236 kg ha^{-1}), confirming their above-average productivity, while the two rainfed environments had strongly negative indices (E2: "1,051 kg ha^{-1}; E4: "1,337 kg ha^{-1}). E4 (Purulia Rainfed) was the most stressful environment, with the most negative index and a mean yield of 2,444 kg ha^{-1} - 1,573 kg ha^{-1} (39.2%) below the grand mean. The range of environment means (E3: 5,017 kg ha^{-1} to E4: 2,444 kg ha^{-1}, a difference of 2,573 kg ha^{-1}) demonstrates the breadth of the environmental gradient covered by this trial.

AMMI analysis of the GxE interaction matrix revealed that IPCA1 explained 84.7% of the GE interaction SS, and IPCA2 explained a further 9.3%, for a cumulative total of 94.0% in just two axes (Table 2). This high proportion indicates that the GxE structure in this trial is highly patterned and almost

fully captured by two multiplicative axes, with minimal unpatterned noise. The environment IPCA1 scores were strongly positive for both irrigated environments (E1: +3,450, E3: +2,993) and strongly negative for both rainfed environments (E2: –2,724, E4: –3,719), confirming that the dominant axis of GxE interaction corresponded to the irrigated–rainfed contrast rather than to location (Chinsurah vs. Purulia). IPCA2 discriminated between the two irrigated locations: E1 (Chinsurah Irrigated) had a positive IPCA2 score (+1,445) while E3 (Purulia Irrigated) had a negative IPCA2 score (–1,576), indicating a secondary location × situation interaction within the irrigated sub-set. Both rainfed environments had near-zero IPCA2 scores, indicating similar rainfed adaptation requirements at both locations.

Table 2. Environment characterisation: mean grain yield, environment index (Ij), and AMMI IPCA1 and IPCA2 scores for the four test environments. The percentage of genotype × environment interaction sum of squares (GE SS) explained by IPCA1 and IPCA2 was 84.7% and 9.3%, respectively.

Environment	Mean Yield (kg ha{ ¹)	Env. Index (Ij)	IPCA1 Score	IPCA2 Score	Classification
E1: Chinsurah – Irrigated	4,951	+1,170	**+3,449.6**	+1,444.9	Favourable
E2: Chinsurah – Rainfed	2,730	“1,051	**“2,723.6**	+217.2	Stress
E3: Purulia – Irrigated	5,017	+1,236	**+2,992.5**	“1,575.6	Favourable
E4: Purulia – Rainfed	2,444	“1,337	**“3,718.5**	“86.5	Severe stress

3.2 Eberhart-Russell Stability Parameters

Table 1 presents the mean yield, bi, S²di, and stability classification for all 60 genotypes. Three distinct adaptive groups were identified on the basis of the bi classification of Eberhart and Russell (1966) and Lin *et al*. (1986).

Below-average responsive genotypes (bi < 0.50, specifically adapted to poor environments): Eight genotypes had bi values ranging from 0.217 to 0.371 and mean yields from 4,899 to 5,199 kg ha^{-1} - all substantially above the grand mean. *Brown Gora* (bi = 0.247, mean = 5,199 kg ha^{-1}) and *Vutmuri* (bi = 0.247, mean = 5,194 kg ha^{-1}) had identical bi values and the highest means in the panel. *Narendra-97* showed the lowest bi overall (0.217), indicating the strongest buffering against environmental deterioration. Three genotypes in this group had low S²di values (*Vutmuri*: 1,477; *Azusena*: 2,600; *N 22*: 4,880), confirming both stability and predictability of their linear response. *Narendra-97* (S²di = 28,889) and *Sahbhagidhan* (S²di = 32,442) had higher S²di, indicating non-linear responses to specific environments beyond the general rainfed–irrigated axis.

Average-stable genotypes (bi = 0.73–1.15): Thirty-three genotypes fell in this class with widely varying mean yields and S²di values. *Krishnahansa* was the statistical ideal of this class with bi = 1.025 and the lowest S²di in the entire panel (90.25) - indicating a near-perfectly linear, average response across all environments - though its mean yield (3,740 kg ha^{-1}) fell below the grand mean. *CR Dhan 40* (bi = 0.898, S²di = 24,018, mean = 4,265 kg ha^{-1}) had the highest mean yield in the average-stable class and slightly sub-unity bi, combining acceptable broad stability with a marginal rainfed advantage. *PR 113* (bi = 1.070, S²di = 2,313) had the second lowest S²di after *Krishnahansa*, confirming highly predictable, near-average linear responsiveness. Genotypes with high S²di in this class (*Sadabahar*: 155,238; *TN-1*: 96,231; *Ratna*: 94,832) showed substantially non-linear responses despite bi values near 1.0, reflecting environment-specific performance not captured by the regression.

Above-average responsive genotypes (bi > 1.1, specifically adapted to favourable environments): Sixteen genotypes were classified here. *G. Bidhan-III* (bi = 1.537, mean = 4,454 kg ha^{-1}) had the highest mean yield in this group and the highest bi, indicating strong irrigated-environment specificity. Among above-average responsive genotypes, *IR 36* (bi = 1.317, S²di

= 5,365), *MTU 17* (bi = 1.344, S²di = 4,811), *Lalat* (bi = 1.329, S²di = 9,110), and *PNR 519* (bi = 1.233, S²di = 7,573) showed notably low S²di, meaning their above-average responsiveness was consistent and predictable - a desirable quality for irrigated-environment recommendation.

3.3 AMMI Biplot Analysis

3.3.1 AMMI1 Biplot

(Chinsurah Irrigated, upper-right: highest mean, most positive IPCA1). This trajectory defines the dominant environmental axis of the trial.

The upper-left cluster of genotypes with large negative IPCA1 scores and above-average mean yields - *Brown Gora* (IPCA1 = "22.65, mean 5,199), *Narendra-97* ("23.61, 5,165), *Vutmuri* ("22.38, 5,194), *N 22* ("21.70, 5,114), *Puspo* ("21.42, 5,080), *Sahbhagidhan* ("20.66, 5,146), *Dular* ("19.42, 5,114),

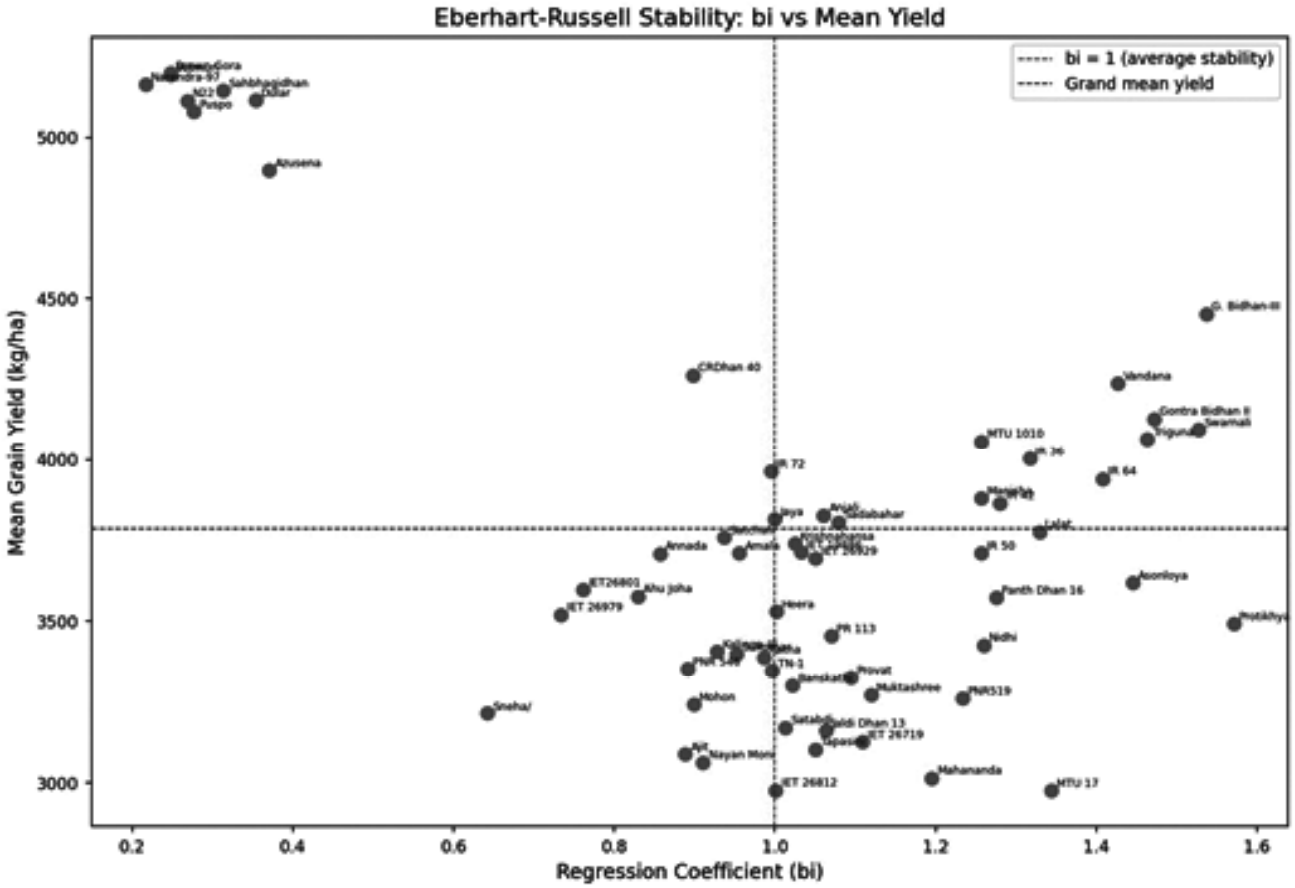

Fig. 1. Eberhart-Russell stability biplot showing regression coefficient (bi) on the x-axis versus mean grain yield (kg ha^{-1}) on the y-axis for all 60 rice genotypes. The vertical dashed red line at bi = 1 separates below-average responsive (drought-adapted, left) from above-average responsive (irrigated-adapted, right) genotypes. The horizontal dashed blue line marks the grand mean yield (3,781 kg ha^{-1}). Genotypes are labelled by name.

The AMMI1 biplot (Fig. 2) simultaneously displays mean yield and IPCA1 interaction score for all genotypes and environments. The four environments form a diagonal trajectory from E4 (Purulia Rainfed, lower-left: lowest mean, most negative IPCA1) through E2 (Chinsurah Rainfed), E3 (Purulia Irrigated), and E1

and *Azusena* ("18.67, 4,899) - represents genotypes specifically adapted to the rainfed environments (E2, E4). Their negative IPCA1 scores place them in the direction of the rainfed environment markers, confirming that their high mean yields were driven predominantly by strong rainfed performance rather than irrigated potential.

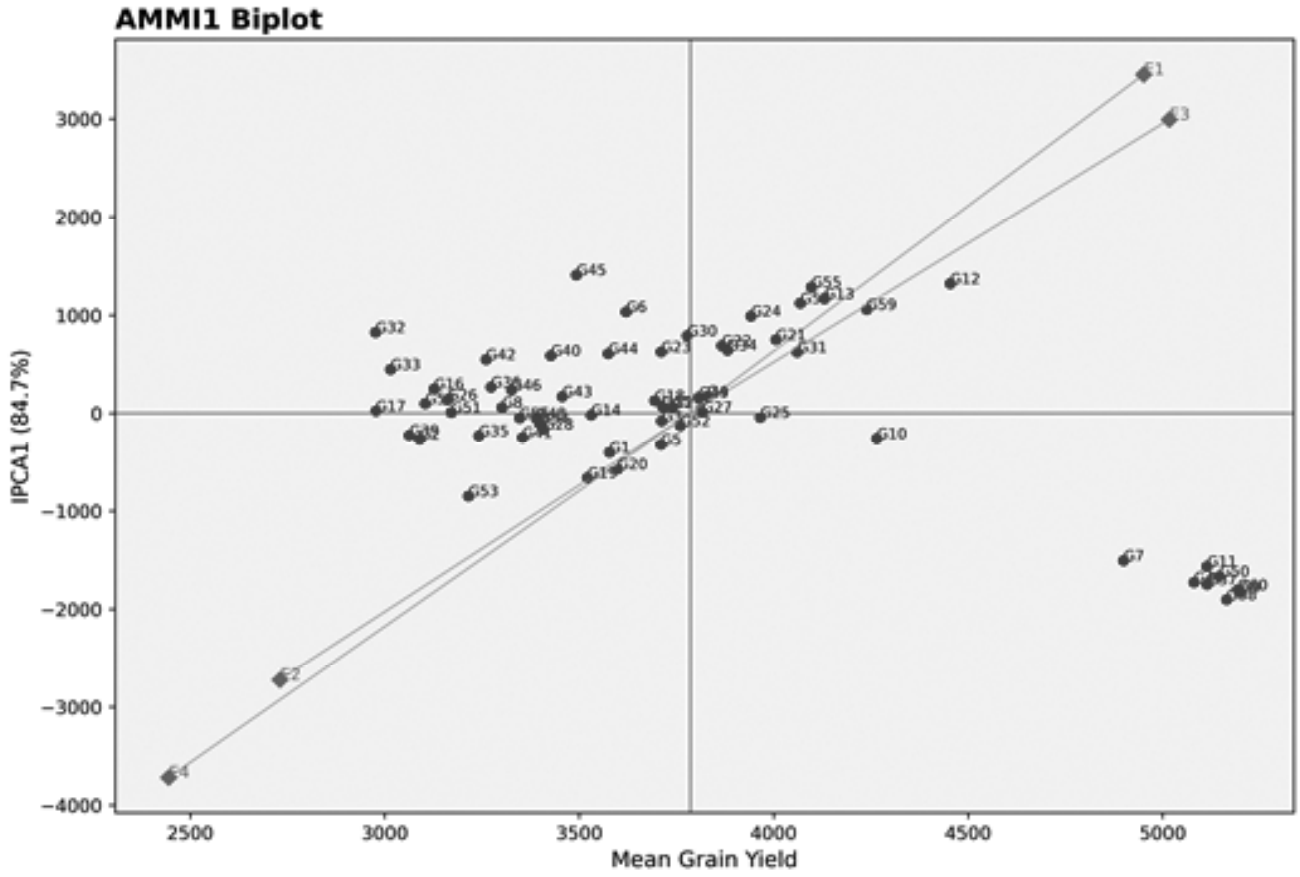

Fig. 2. AMMI1 biplot showing mean grain yield (kg ha{ ¹) on the x-axis and IPCA1 score (accounting for 84.7% of the GE interaction sum of squares) on the y-axis. Blue circles represent genotypes (G1–G60, labelled by name); green diamonds represent environments (E1–E4). Lines connect each environment to the biplot origin. The IPCA1 axis separates rainfed-adapted genotypes (negative IPCA1, lower-left cluster) from irrigated-adapted genotypes (positive IPCA1, right side). Broadly stable genotypes appear near IPCA1 = 0.

The upper-right sector contained irrigated-adapted genotypes with positive IPCA1 and above-average yields: *G. Bidhan-III* (IPCA1 = +16.42, mean 4,454), *Swarnali* (+15.98, 4,097), *Gontra Bidhan II* (+14.51, 4,130), *Vandana* (+14.13, 4,238), *Triguna* (+13.93, 4,068), *IR 64* (+12.31, 3,941), and *IR 36* (+9.33, 4,005). These genotypes are aligned with the irrigated environment markers (E1, E3), confirming their specific irrigated-environment advantage.

Genotypes near IPCA1 = 0 regardless of their mean yield represent broadly stable types. *CR Dhan 40* (IPCA1 = “3.21, mean 4,265) occupied the most desirable region of the biplot: above-grand-mean yield combined with near-zero IPCA1 and a slight lean toward rainfed adaptation. *Krishnahansa* (+0.74, 3,740), *IR 72* (“0.51, 3,965), *Jaya* (+0.18, 3,816), and *PR 113* (+2.12, 3,456) were among the most stable genotypes, plotting closest to the biplot IPCA1 origin.

The AMMI2 biplot (Fig. 3) resolves secondary interaction patterns. On IPCA1, the separation of rainfed-adapted (large negative) and irrigated-adapted (large positive) genotypes replicated the AMMI1 interpretation. On IPCA2, the contrast is between Chinsurah Irrigated (E1, positive) and Purulia Irrigated (E3, negative), with both rainfed environments near zero. Genotypes with positive IPCA2 performed relatively better at E1 than E3; those with negative IPCA2 showed the reverse.

3.3.2 AMMI2 Biplot

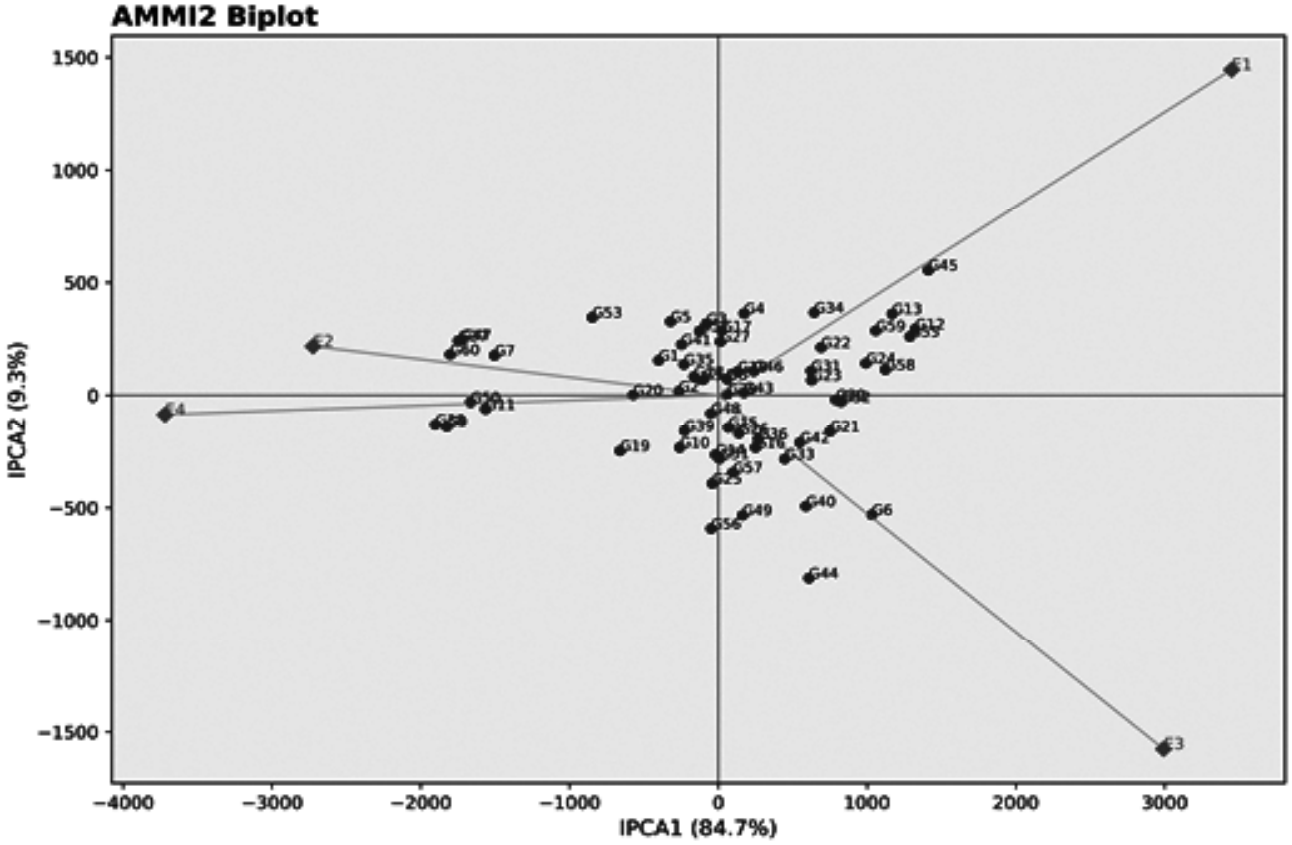

Fig. 3. AMMI2 biplot showing IPCA1 (84.7% of GE interaction SS) on the x-axis and IPCA2 (9.3% of GE interaction SS) on the y-axis. Environment codes: E1 = Chinsurah Irrigated, E2 = Chinsurah Rainfed, E3 = Purulia Irrigated, E4 = Purulia Rainfed. IPCA1 separates rainfed-adapted (negative, left) from irrigated-adapted (positive, right) genotypes. IPCA2 separates Chinsurah-Irrigated-adapted (positive IPCA2) from Purulia-Irrigated-adapted (negative IPCA2) genotypes within the irrigated sub-set. Genotypes near the origin show minimum GxE interaction across all four environments.

Protikhya (IPCA1 = +17.51, IPCA2 = +11.97) showed the most extreme Chinsurah-Irrigated-specific adaptation; Panth Dhan 16 (IPCA2 = "17.51) showed strongest Purulia-Irrigated specificity. Within the rainfed-adapted cluster, IPCA2 differences were small: *N 22* (+5.22), *Puspo* (+5.29), and *Vutmuri* (+3.91) had slight Chinsurah-Irrigated lean; Brown Gora ("3.00) and *Narendra-97* ("2.82) had marginal Purulia advantage. These within-cluster differences were small relative to the dominant IPCA1 signal.

Genotypes near the AMMI2 biplot origin - *Krishnahansa, PR 113*, IET 26929, *Banskathi, Jaya* - showed minimum interaction with all four environments, confirming their broad stability across both the irrigated–rainfed and Chinsurah–Purulia axes. These genotypes also had the most compressed genotype × environment profiles: they responded equally to all four environments with minimal non-linear deviation, making their performance the most predictable in the panel.

3.4 Convergence of Eberhart-Russell and AMMI Frameworks

Both analytical frameworks identified the same three adaptive groups with high concordance (Table 3). The eight below-average responsive genotypes in the E-R framework (bi = 0.217–0.371) were precisely the eight genotypes with the largest negative IPCA1

Table 3. AMMI genotype scores and stability classification for selected genotypes. Yellow shading = rainfed-adapted; blue shading = irrigated-adapted; unshaded = broadly stable. † = local check.

Genotype	Mean Yield (kg ha^{-1})	bi	IPCA1	IPCA2	Adaptation type
Brown Gora	5,199	0.247	**“22.65**	“3.00	Rainfed-adapted (high yield)
Vutmuri	5,194	0.247	**“22.38**	+3.91	Rainfed-adapted (stable)
Narendra-97	5,165	0.217	**“23.61**	“2.82	Rainfed-adapted (high yield)
Sahbhagidhan	5,146	0.313	**“20.66**	“0.66	Rainfed-adapted
N22	5,114	0.269	**“21.70**	+5.22	Rainfed-adapted (stable)
Dular	5,114	0.354	**“19.42**	“1.33	Rainfed-adapted
Puspo	5,080	0.277	**“21.42**	+5.29	Rainfed-adapted
Azusena†	4,899	0.371	**“18.67**	+3.82	Rainfed-adapted (check)
CRDhan 40	4,265	0.898	**“3.21**	“5.02	Broadly adapted
Krishnahansa	3,740	1.025	**+0.74**	+0.13	Broadly stable (ideal)
IR 72	3,965	0.995	**“0.51**	+0.96	Broadly stable
PR 113	3,456	1.070	**+2.12**	+1.67	Broadly stable (low S²di)
IET 26929	3,694	1.051	**+1.88**	+2.31	Broadly stable (low S²di)
G. Bidhan-III	4,454	1.537	**+16.42**	+8.21	Irrigated-adapted (high yield)
Swarnali	4,097	1.527	**+15.98**	“4.12	Irrigated-adapted
Vandana	4,238	1.427	**+14.13**	+5.66	Irrigated-adapted
IR 36	4,005	1.317	**+9.33**	+3.84	Irrigated-adapted (stable)
MTU 17	2,976	1.344	**+8.91**	+2.15	Irrigated-adapted
Lalat	3,777	1.329	**+8.22**	+3.01	Irrigated-adapted (stable)

scores (“18.67 to “23.61) in AMMI. This convergence confirms that the low bi values reflected genuine rainfed-environment adaptation rather than statistical artefact. *Vutmuri* and *N 22* - which combined low bi with low S²di in the E-R framework - also had IPCA2 scores near zero in AMMI2, indicating broad stability within the rainfed-adapted phenotype across both locations. *Krishnahansa*, with the near-perfect bi = 1.025 and S²di = 90 in the E-R model, mapped to IPCA1 = +0.74 and IPCA2 = +0.13 in AMMI - effectively the origin of the interaction space, confirming its minimal GxE across all criteria. CR Dhan 40 emerged from both analyses as the best broadly adapted high-yielding genotype: bi = 0.898 (slight rainfed lean), mean 4,265 kg ha{ ¹ (second highest in average-stable class), IPCA1 = “3.21 (small negative, near origin), IPCA2 = “5.02 (slight Purulia advantage). Its combination of above-grand-mean yield and near-zero interaction classifies it as the most practically useful broadly adapted genotype for dual-purpose recommendation across both environments.

4. Discussion

The present study evaluated GxE interaction for grain yield of 60 diverse rice genotypes across the full alluvial-to-lateritic environmental gradient of West Bengal using both E-R regression and AMMI analysis. The dominant finding - that 84.7% of the GE interaction SS was captured by a single axis (IPCA1) directly corresponding to the irrigated–rainfed contrast — indicates that the primary driver of differential genotype performance in this trial was water management

situation rather than location or season. This result is consistent with meta-analyses of rice GxE across South Asia (Mandal et al., 2010; Verulkar *et al*., 2010; Raman *et al*., 2012), which have consistently found that water management (irrigated vs. rainfed) is the dominant environmental axis of GxE for yield, frequently explaining 60–90% of the interaction variance in multi-environment trials that span this contrast.

The eight genotypes with bi < 0.40 (*Brown Gora, Vutmuri, Narendra-97, Sahbhagidhan, Dular, N 22, Puspo, Azusena*) are overwhelmingly traditional or drought-adapted released varieties: Brown Gora is a traditional *aus*-type landrace with long-recognised drought tolerance in eastern India (Mandal et al., 2010; Vikram et al., 2015); *N 22* is a well-characterised donor for heat and drought stress tolerance carrying major drought QTL (Vikram *et al*., 2011; Jagadish *et al*., 2010); *Vandana* and *Sahbhagidhan* are released varieties derived from upland breeding programmes and carry qDTY1.1 (Kumar *et al*., 2014; Dixit *et al*., 2014). The fact that bi values for this group (0.217–0.371) were far below unity - i.e. these genotypes gained only 217–371 kg ha^{-1} for each 1,000 kg ha^{-1} improvement in environment quality, while losing only the same amount for each 1,000 kg ha^{-1} of deterioration - is the quantitative expression of the yield buffering capacity that characterises drought-adapted germplasm (Ceccarelli, 1996; Blum, 2011). Their high overall mean yields (4,899–5,199 kg ha^{-1}) confirm that this buffering is not simply a consequence of uniformly low yield potential, but reflects genuine maintenance of yield under stress combined with moderate (not maximal) exploitation of favourable conditions.

The divergence in S²di within the rainfed-adapted group is agronomically informative. *Vutmuri* (S²di = 1,477) and *N 22* (4,880) had near-linear responses across all four environments, meaning their E-R regression perfectly or nearly perfectly captured their environmental response - a highly predictable pattern that simplifies recommendation. In contrast, *Narendra-97* (S²di = 28,889) and *Sahbhagidhan* (32,442) showed substantial non-linearity, indicating that they responded differently to specific environments beyond the general rainfed–irrigated axis - possibly reflecting location-specific disease pressure, phenological interactions with the specific rainfall pattern at Purulia, or genotypic sensitivity to soil type differences between the two locations. From a breeder's perspective, the combination of low bi and low S²di - possessed most strongly by *Vutmuri* and *N 22* - represents the most desirable stability profile for rainfed variety recommendation (Becker and Leon, 1988; Lin *et al*., 1986).

The finding that *Krishnahansa* had the statistically ideal stability parameters (bi = 1.025, S²di = 90) while achieving only an average mean yield illustrates a fundamental tension in stability analysis: the genotype with the most predictable, average linear response is not necessarily the most useful variety in any particular environment (Ceccarelli, 1996; Yan and Kang, 2003). Under rainfed conditions, a genotype with bi = 0.25 and a mean yield of 5,100 kg ha^{-1} contributes more food security value than one with bi = 1.025 and a mean of 3,740 kg ha^{-1}. This distinction argues against using statistical stability parameters alone as selection criteria, and in favour of the multi-criterion approach - combining mean yield, bi, S²di, AMMI IPCA scores, and performance in the target environment specifically - that was applied in the present study.

CR Dhan 40's position as the best broadly adapted high-yielding genotype (bi = 0.898, mean 4,265 kg ha^{-1}, IPCA1 = "3.21) is particularly notable because it represents a released ICAR variety specifically bred for rainfed ecosystems. Its combination of above-grand-mean yield, near-average responsiveness with a slight rainfed lean, and small IPCA1 interaction score places it in the most practically valuable region of the E-R × AMMI parameter space: it performs well in both situations, with a predictable (low S²di = 24,018 is moderate) response and no extreme environment-specific interaction. This validates the breeding approach employed by ICAR-NRRI (Mandal *et al*., 2010; Kumar *et al*., 2014) of identifying varieties that capture a portion of the yield gain achievable under irrigation while retaining the yield floor achievable under rainfed stress.

The secondary IPCA2 axis, explaining 9.3% of GxE interaction, discriminated between the two

irrigated environments (Chinsurah vs. Purulia). This location × irrigation interaction is expected given the soil type difference: Chinsurah's alluvial soils (deep, high water-holding capacity, near-neutral pH) support substantially different nutrient dynamics and root architecture utilisation than Purulia's lateritic soils (shallow, acidic, low WHC). The fact that IPCA2 only explained 9.3% of interaction SS - and both rainfed environments were near-zero on IPCA2 — confirms that under rainfed conditions, the location difference was secondary to the stress itself: all genotypes responded to Purulia Rainfed (severe stress) and Chinsurah Rainfed (moderate stress) in broadly the same relative rank order, regardless of soil type. This suggests that drought-tolerance mechanisms in the top performers operate at a level that transcends soil-type specificity, consistent with the importance of constitutive root depth and osmotic adjustment mechanisms that function across soil types (Uga *et al*., 2013; Henry *et al*., 2011; Blum, 2011).

The high concordance between E-R and AMMI groupings (the eight low-bi genotypes mapped precisely to the eight most-negative-IPCA1 genotypes) validates the use of either framework independently for identifying adaptive groups. However, the two approaches provide complementary information: E-R regression quantifies the magnitude of linear environmental sensitivity and its predictability (S^2di), while AMMI2 biplots enable visual identification of which specific environments drove the interaction and which genotypes were most specific to each. The combined use of both methods, as recommended by Becker and Leon (1988) and Gauch (1992), provides a richer and more actionable characterisation of genotype adaptation than either alone.

5. Conclusions

The genotype × environment interaction for grain yield of 60 rice genotypes across four environments in West Bengal was dominated by the irrigated–rainfed water management contrast (84.7% of GE interaction SS on IPCA1), with secondary location-specific effects within the irrigated sub-set (9.3% on IPCA2). Both Eberhart-Russell regression and AMMI analysis converged on three adaptive groups: (i) eight rainfed-adapted genotypes (bi = 0.217–0.371, IPCA1 = $^{-}$18.7 to $^{-}$23.6) with mean yields of 4,899–5,199 kg ha^{-1}; (ii) 33 broadly stable genotypes (bi = 0.73–1.15); and (iii) 16 irrigated-adapted genotypes (bi > 1.1, positive IPCA1). For rainfed and resource-limited environments of West Bengal, *Vutmuri, N22, Brown Gora, Dular,* and *Puspo* are the strongest recommendation candidates - combining the highest mean yields with the lowest environmental sensitivity and, in the case of *Vutmuri* and *N 22*, the lowest within-group S^2di. For dual-purpose (both irrigated and rainfed) recommendation, CR Dhan 40 is the preferred choice on the basis of highest mean yield in the broadly adapted class and minimal interaction scores. *Krishnahansa* provides an alternative where maximum predictability is prioritised over yield level. For irrigated-specific deployment, *IR 36, MTU 17, Lalat,* and *PNR 519* offer predictable above-average yields with low S^2di. These findings provide a directly actionable framework for varietal recommendation in the *Aman* rice system of West Bengal and a methodological template applicable to comparable rainfed rice environments across eastern India.

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Supplementary Table S1
Complete list of 60 rice genotypes evaluated across four environments in West Bengal, India, with Eberhart-Russell stability parameters and AMMI IPCA1 scores for grain yield.

Entry	Genotype	Category	Source / Origin	DFL	Ht (days)	Mean (cm)	Irrig. Yield	Rainfed Yield	bi Yield	S^2di	IPCA1	Adaptation Type
G49	G. Bidhan-III	*Released variety*	BCKV, West Bengal	97	111	4454	6280	2627	**1.537**	78,046	**+16.42**	Irrigated-adapted
G37	Vandana	*Released variety*	ICAR-NRRI	76	97	4238	5933	2544	**1.427**	75,814	**+14.13**	Irrigated-adapted
G12	Swarnali	*Released variety*	BCKV, West Bengal	109	99	4097	5933	2261	**1.527**	34,014	**+15.98**	Irrigated-adapted
G53	Gontra Bidhan II	*Released variety*	BCKV, West Bengal	80	93	4130	5882	2379	**1.472**	76,189	**+14.51**	Irrigated-adapted
G38	Triguna	*Released variety*	BCKV, West Bengal	103	107	4068	5831	2304	**1.464**	20,103	**+13.93**	Irrigated-adapted
G11	IR 64	*IRRI line*	IRRI	98	92	3941	5635	2248	**1.408**	15,011	**+12.31**	Irrigated-adapted
G26	IR 36	*IRRI line*	IRRI	92	103	4005	5587	2423	**1.317**	5,365	**+9.33**	Irrigated-adapted
G17	MTU 1010	*Released variety*	ANGRAU	107	92	4060	5579	2541	1.257	23,902	**+11.56**	Irrigated-adapted
G32	**Dular**	*Traditional landrace*	Bihar/Jharkhand	76	109	5114	5539	4689	**0.354**	7,936	**“19.42**	Rainfed-adapted
G31	**Sahbhagidhan**	*Released variety*	ICAR-NRRI/IRRI	82	96	5146	5534	4757	**0.313**	32,442	**“20.66**	Rainfed-adapted
G20	**Brown Gora**	*Traditional landrace*	Eastern India	97	95	5199	5493	4906	**0.247**	18,229	**“22.65**	Rainfed-adapted
G13	**Vutmuri**	*Traditional landrace*	Andhra Pradesh	96	104	5194	5492	4894	**0.247**	1,477	**“22.38**	Rainfed-adapted
G48	**N22**	*Traditional landrace*	ICAR-NRRI	81	93	5114	5440	4788	**0.269**	4,880	**“21.70**	Rainfed-adapted
G58	**Narendra-97**	*Released variety*	NDUAT, UP	80	86	5165	5432	4897	**0.217**	28,889	**“23.61**	Rainfed-adapted
G09	**Puspo**	*Traditional landrace*	West Bengal	75	90	5080	5409	4752	**0.277**	5,624	**“21.42**	Rainfed-adapted
G22	IR 42	*IRRI line*	IRRI	93	75	3866	5405	2328	1.280	18,112	**+10.87**	Irrigated-adapted
G04	Protikhya	*Released variety*	BCKV, West Bengal	103	98	3492	5395	1590	**1.571**	144,832	**+17.51**	Irrigated-adapted
G06	Manisha	*Released variety*	BCKV, West Bengal	82	97	3880	5392	2369	1.257	43,711	**+10.12**	Irrigated-adapted
G21	Lalat	*Released variety*	OUAT	96	104	3777	5379	2176	**1.329**	9,110	**+8.22**	Irrigated-adapted
G51	Asonloya	*Released variety*	BCKV, West Bengal	90	83	3620	5357	1883	**1.446**	59,075	**+9.88**	Irrigated-adapted
G60	**Azusena†**	*Local check (LC)*	IRRI Philippines	76	97	4899	5341	4458	**0.371**	2,600	**“18.67**	Rainfed-adapted
G01	CRDhan 40	*Released variety*	ICAR-NRRI	74	98	4265	5332	3198	0.898	24,018	**“3.21**	Broadly adapted
G45	IR 50	*IRRI line*	IRRI	87	89	3710	5211	2210	1.257	8,441	**+7.08**	Irrigated-adapted
G18	IR 72	*IRRI line*	IRRI	79	100	3965	5158	2772	0.995	40,048	**“0.51**	Broadly stable
G25	Anjali	*Released variety*	BCKV, West Bengal	75	94	3828	5095	2561	1.060	39,308	**+3.77**	Broadly stable
G42	Panth Dhan 16	*Released variety*	GBPUA&T	85	95	3574	5093	2056	1.275	150,887	**“1.22**	Broadly stable
G19	Sadabahar	*Released variety*	West Bengal	84	100	3807	5072	2542	1.079	155,238	**“0.84**	Broadly stable
G55	Jaya	*Released variety*	IARI	105	95	3816	5020	2612	1.000	17,425	**+0.18**	Broadly stable
G24	Krishnahansa	*Traditional landrace*	West Bengal	86	101	3740	4969	2512	1.025	90	**+0.74**	Broadly stable (ideal)
G42	IET 26929	*IET advanced line*	AICRIP	87	88	3694	4956	2432	1.051	4,028	**+1.88**	Broadly stable
G59	IET 19886	*IET advanced line*	AICRIP	82	91	3714	4948	2479	1.032	5,118	**+1.63**	Broadly stable

Entry	Genotype	Category	Source / Origin	DFL	Ht (days)	Mean (cm)	Irrig. Yield	Rainfed Yield	bi Yield	S²di	IPCA1	Adaptation Type
G28	Nidhi	*Released variety*	West Bengal	86	82	3427	4940	1913	1.260	55,946	**+5.62**	Irrigated-adapted
G30	Satchali	*Traditional landrace*	West Bengal	84	91	3760	4871	2648	0.937	40,452	**+2.14**	Broadly stable
G47	Amala	*Released variety*	West Bengal	105	90	3711	4847	2576	0.956	42,727	**“1.97**	Broadly stable
G05	Annada	*Released variety*	CSAUAT, UP	79	91	3710	4738	2682	0.857	23,025	**“2.43**	Broadly stable
G03	Heera	*Released variety*	West Bengal	65	90	3530	4736	2324	1.001	25,367	**+1.29**	Broadly stable
G54	PNR519	*Released variety*	PAU	79	96	3260	4736	1785	1.233	7,573	**+6.29**	Irrigated-adapted
G50	PR 113	*Released variety*	PAU	100	95	3456	4734	2178	1.070	2,313	**+2.12**	Broadly stable
G56	Provat	*Released variety*	BCKV, West Bengal	69	87	3325	4635	2016	1.095	5,300	**+3.14**	Broadly stable
G52	Muktashree	*Released variety*	BCKV, West Bengal	77	88	3273	4630	1915	1.119	47,549	**+4.63**	Broadly stable
G14	Ratna	*Released variety*	IARI	81	86	3389	4596	2182	0.986	94,832	**“1.88**	Broadly stable
G34	MTU 17	*Released variety*	ANGRAU	94	93	2976	4593	1360	**1.344**	4,811	**+8.91**	Irrigated-adapted
G07	Ahu Joha	*Traditional landrace*	Assam	86	96	3578	4572	2584	0.829	4,004	**“2.15**	Broadly stable
G35	TN-1	*Released variety*	TamilNadu	75	84	3346	4530	2163	0.997	96,231	**+0.31**	Broadly stable
G15	Sukumar	*Traditional landrace*	West Bengal	91	101	3398	4523	2273	0.952	37,466	**+0.51**	Broadly stable
G36	Banskathi	*Traditional landrace*	West Bengal	84	91	3301	4520	2082	1.022	5,613	**+0.74**	Broadly stable
G43	Kalinga-III	*Released variety*	OUAT	65	100	3408	4508	2308	0.928	21,139	**“1.45**	Broadly stable
G44	**IET26801**	*IET advanced line*	AICRIP	80	108	3598	4504	2693	0.762	7,019	**“4.41**	Rainfed-leaning
G16	Mahananda	*Released variety*	West Bengal	86	88	3015	4454	1576	1.195	25,204	**+5.88**	Irrigated-adapted
G08	Jaldi Dhan 13	*Released variety*	BCKV, West Bengal	77	88	3161	4445	1877	1.064	19,971	**+3.05**	Broadly stable
G57	IET 26719	*IET advanced line*	AICRIP	107	90	3127	4443	1811	1.109	29,512	**+4.88**	Broadly stable
G29	PNR 546	*Released variety*	PAU	88	89	3354	4424	2284	0.891	11,142	**+1.07**	Broadly stable
G23	**IET 26979**	*IET advanced line*	AICRIP	94	89	3521	4402	2640	0.734	22,704	**“3.80**	Rainfed-leaning
G33	Satabdi	*Released variety*	BCKV, West Bengal	86	96	3171	4384	1958	1.012	19,906	**+1.55**	Broadly stable
G10	Tapasini	*Released variety*	OUAT	105	101	3104	4355	1852	1.050	31,715	**+2.37**	Broadly stable
G46	Mohon	*Traditional landrace*	West Bengal	76	87	3242	4314	2169	0.899	7,884	**+0.45**	Broadly stable
G40	IET 26812	*IET advanced line*	AICRIP	74	88	2977	4176	1778	1.001	20,778	**+2.22**	Broadly stable
G27	Nayan Moni	*Traditional landrace*	West Bengal	95	95	3064	4153	1973	0.910	7,500	**“1.23**	Broadly stable
G39	Ajit	*Traditional landrace*	West Bengal	81	95	3089	4148	2031	0.888	4,487	**“0.84**	Broadly stable
G02	**Sneha/**	*Released variety*	West Bengal	72	90	3215	4005	2425	0.642	74,900	**“5.29**	Rainfed-leaning

All yield values in kg ha{ ¹. DFL = days to 50% flowering; Ht = plant height; bi = Eberhart-Russell regression coefficient; S²di = deviation from regression mean square; IPCA1 = first interaction principal component axis score (AMMI). Shade key: yellow = rainfed-adapted (bi < 0.50); blue = irrigated-adapted (bi > 1.10); unshaded = broadly stable. † = Local check.

Sources/Abbreviations: BCKV = Bidhan Chandra Krishi Viswavidyalaya; ICAR-NRRI = National Rice Research Institute; IRRI = International Rice Research Institute; IARI = Indian Agricultural Research Institute; AICRIP = All India Coordinated Rice Improvement Programme; OUAT = Odisha University of Agriculture and Technology; PAU = Punjab Agricultural University; GBPUA&T = Gobind Ballabh Pant University of Agriculture and Technology; ANGRAU = Acharya N.G. Ranga Agricultural University; NDUAT = Narendra Deva University of Agriculture and Technology; CSAUAT = Chandra Shekhar Azad University of Agriculture and Technology; TamilNadu = Tamil Nadu Agricultural University; LC = Local check.

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Management of *Parthenium* Weed with Special Reference to Biological Control: A Comprehensive Review

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Abstract

Parthenium hysterophorus L., an alien invasive species, locally called "Gajar ghas" in India, significantly affects crops, human health, and biodiversity. This review takes a closer look at various methods for managing *Parthenium* with special reference to biological control method, focusing on agents like *Zygogramma bicolorata*, *Puccinia abrupta* var. *partheniicola* etc. The philosophy behind biological weed control is that, in nature, the proliferation of many weeds is controlled by biotic pressure from their natural antagonists, chiefly insect pests and plant pathogens as well as biological management can easily replace the chemical use in agriculture which mitigate the safe for the environment and reduces residue problems. Biological weed control provides an eco-friendly and effective alternative to chemical methods, fostering long-term weed management while maintaining ecological equilibrium. However, biological control often encounters challenges such as climatic adaptability and host specificity. Its integration with cultural and mechanical strategies enables sustainable *Parthenium* management, mitigating environmental degradation and bolstering agroecosystem resilience.

Keywords: Weed management, Biological control, Allelopathy, *Parthenium hysterophorus*, *Zygogramma bicolorata, Puccinia abrupta.*

Introduction

Parthenium hysterophorus L. (Heliantheae: Asteraceae), commonly called congress grass, feverfew, ragweed, or white top, is a toxic and invasive weed. The genus name *Parthenium* originates from the Latin word "*parthenice,"* referring to the plant *Tanacetum parthenium* (L.) Bernh., commonly called feverfew. The species name *hysterophorus* is derived from two Greek words "*hystera"* (womb) and "*phoros"* (bearing), due to its prolific seeding (Parsons and Cuthbertson, 1992). Indigenous to Tropical America, it has spread across tropical and subtropical regions, emerging as a severe threat to crops as well as human and animal health (Kohli, 2009). Currently, *Parthenium* weed is rampant throughout India, with no state free from its presence (Sushilkumar, 2012). It is an aggressive invader that establishes itself in both natural and human-altered ecosystems, including grasslands, open woodlands, riverbanks, floodplains, wildlife parks, roadsides, crop fields, gardens, and urban areas (Tiwari *et al.*, 2005). The allelochemicals released by the weed, either directly or through seed leaching, suppress the germination and growth of Pasteur grasses, legumes, cereals, vegetables, other weeds, and even trees (Singh *et al.*, 2005). It displaces palatable rangeland grasses, adversely affecting animal health and deteriorating the quality of milk and meat (Wegari, 2008). Manual removal is challenging as it can trigger dermatitis, hay fever, asthma, severe allergies, and even fatal reactions in humans (Bhowmik *et al.*, 2007). Therefore, this review is presented to address the management of one of the most dangerous invasive weeds in India, *Parthenium hysterophorus*, with special reference to biological control.

Distribution and spread of *P. hysterophorus*

P. hysterophorus was thought to be indigenous to the West Indies and the nearby coastal regions of North and South America, or South-Central South America, from its first taxonomic identification on the Island of Jamaica in 1753. The centre of the genus' diversity and distribution lies on the mainland of North and Central America, suggesting that its spread to the Caribbean is a result of recent human-mediated dispersal from Mexico (Navie *et al.*, 1996). The absence of specialist insects associated with the weed on these islands further supports the theory of their recent introduction (Adkins *et al.*, 2019). *Parthenium* is found in about twenty countries where it is considered native. From there, it has spread to thirty-four other countries, covering most major continents except Europe and many islands (Adkin and Shabbir, 2014). Today, it has become established in several tropical and subtropical regions worldwide. Its spread across borders happens mainly through contaminated grain used for food or animal feed, as well as by vehicles and wind. The history of invasion most likely began with the accidental introduction of *P. hysterophorus* to the island of Mauritius in the 18th century (Fusée Aublet, 1775). These and other early introductions were sporadic but were usually associated with maritime trade (Binggeli, 2003). Thus, the global distribution of *P. hysterophorus* initially comprised island populations or locations close to large ports, including Kolkata, India (1810); Reunion in the Mascarenes (1878); Natal in South Africa (1880); the islands of New Caledonia (1881); and French Polynesia (1909) (Mao et al., 2021b). The plant's distribution is now extensive, encompassing India, Africa, China, Vietnam, the Pacific Islands, and Australia. In India, its earliest recorded presence was in 1810 in Arunachal Pradesh and Nagaland, followed by Pune in 1955. By 1972, it had colonised the majority of western states, from Kashmir in the north to Kerala in the south. Its continued spread led to its discovery in Assam in 1979, and it now spreads nearly the entire subcontinent. It is arguably the most prevalent weed in Karnataka, where it infests approximately 5 million hectares. The presence of *Parthenium* weed has been recorded in all states of India. The density and severity of infestation are most pronounced in Andhra Pradesh, Bihar, Chhattisgarh, Delhi, Haryana, Karnataka, Maharashtra, Madhya Pradesh, Punjab, Tamil Nadu, and Uttar Pradesh. The spread and infestation level are moderate in Assam, Gujarat, Himachal Pradesh, Jharkhand, Jammu & Kashmir (Jammu & Kasmir, and Ladakh), Uttarakhand, Odisha, West Bengal, and Rajasthan. On the other hand, its spread is limited in Andaman & Nicobar, Arunachal Pradesh, Daman and Diu, Goa, Kerala, Manipur, Mizoram, Meghalaya, Nagaland, Puducherry (Pondicherry), and Sikkim (Sushilkumar, 2012).

It is crucial to control the invasive weed *P. hysterophorus* promptly to prevent its spread, due to its harmful effects on both natural and agricultural ecosystems. Many attempts have been made to eradicate *P. hysterophorus* after its invasion; however, this has proven extremely difficult. To date, eradication has been successful only in countries and regions where small populations were detected early. Examples include Papua New Guinea (Kawi and Orapa, 2010), the state of New South Wales, Australia (Blackmore and Johnson, 2010), and Espiritu Santo Island, Vanuatu. In locations where the weed is well-established, containment rather than eradication is the preferred approach (Khan et al., 2018). Several methods are available for managing *Parthenium*, including cultural control, mechanical control, biological control and chemical control.

a) Cultural control

Cultural control of parthenium hysterophorus, also known as ragweed parthenium, can include:

- **Cover crops**: Fast-growing cover crops can suppress parthenium growth during fallow periods. Some fast-growing species of fodders like berseem and sorghum can be taken to suppress *Parthenium* and its seed bank in the field (Sushilkumar, 2012).
- **Clean equipment**: Clean equipment before moving between fields to limit seed spread.
- **Deep ploughing**: Deep ploughing before flowering can turn the weed into green manure. Slashing and ploughing are not very effective

TABLE 1. The morphological and other characteristics of *P. hysterophorus*

Sl. No.	Characteristic	Details
1.	**Growth habit**	Quick-growing, erect, highly branched annual or ephemeral herb
2.	**Life stages**	- Juvenile (rosette or vegetative stage) - Adult (mature or reproductive stage)
3.	**Stem characteristics**	Hairy, four-sided, becomes tough and woody with maturity.
4.	**Leaf characteristics**	- Simple, alternate, pinnate or bipinnate. - Size: 20–30 cm long, 12–25 cm wide. - Smaller leaves as the plant branches.
5.	**Trichomes**	Stem and leaves covered in white, multicellular trichomes of four distinct types.
6.	**Flower characteristics**	- Small, creamy white, 4 mm wide. - Grow in clusters at the base of the leaves. - Anemophilous (wind-pollinated).
7.	**Seed characteristics**	- Small, black seeds (2 mm long) with white scales, hard to see. - Each flower produces 4–5 seeds. - Total seeds per plant: Up to 25,000.

Impact of *P. hysterophorus* as a weed in agriculture

in the long run, as these strategies stimulate regrowth and seed germination, respectively (Bhowmik and Sarkar 2005).

- **Mulching:** Mulching suppresses weed growth by restricting photosynthesis. It also conserves soil moisture, lowers surface temperature, enhances soil fertility, protects the soil during the rainy season, and improves overall soil quality.

b) Mechanical control

Mechanical methods such as grading, slashing, and ploughing for controlling ragweed parthenium have proven ineffective. Manual techniques such as mowing or slashing lead to quick regrowth of plants, often accompanied by flowering and prolific seed production (Dhawan & Dhawan, 1996). While hand-pulling ragweed parthenium is a widespread practice in India, it poses significant risks due to severe health issues it can cause. Manual removal is challenging as it can trigger dermatitis, hay fever, asthma, severe allergies, and even fatal reactions in humans (Bhowmik *et al.*, 2007). Moreover, without an appropriate disposal strategy, hand weeding proves to be an inefficient control measure (Navie *et al.*, 1996).

c) Biological control

The need for alternative management strategies were felt as most of the physical and chemical methods have been proven to be ineffective against *Parthenium*, cost-inefficient, and environmentally hazardous. The natural suppression of *Parthenium* by biological agents in its native habitat, as compared to its enhanced fitness and vigour in non-native environments lacking natural enemies, led to the conceptualization of biological control as a viable, sustainable solution for the long-term management of the weed *P. hysterophorus*. Various insects and pathogens have been employed over time to control the invasive weed *P. hysterophorus*.

Management by insects

The leaf-feeding beetle *Z. bicolorata* (family: Chrysomelidae, order: Coleoptera) and the stem-galling moth *Epiblema strenuana* (family: Tortricidae, Order: Lepidoptera) are extensively utilized in several countries to manage this weed. In India, *Z. bicolorata* has

become a prominent biological control agent for *Parthenium*. The moth, *E. strenuana*, is particularly effective in curbing the weed's flower and seed production, especially during its juvenile stages. This species demonstrates high reproductive potential within a short timeframe. In 1983, the chrysomelid beetle *Z. bicolorata* was introduced to India from Mexico to mitigate the proliferation of *Parthenium*. Host specificity trials were conducted on 40 plant species across 25 families, confirming the beetle's safety for economically important crops. Both adult and larval stages of *Z. bicolorata* feed voraciously on *Parthenium* leaves. The early instar larvae primarily consume terminal and axillary buds before transitioning to the leaf blades as they develop. Mature larvae penetrate into the soil for pupation. An optimal density of one adult beetle per plant can induce complete defoliation or 'skeletonization' of leaves within 4–8 weeks, provided this density is established early in the monsoon season. Within three years of its introduction, *Z. bicolorata* became widespread in India, significantly reducing *Parthenium* density in localized areas. The Mexican beetle is undoubtedly an effective biological agent for managing *Parthenium* infestation in most seasons. However, its efficacy diminishes during periods of high humidity and winter. Observations by Dolai et al. (2016) revealed that under such climatic conditions, egg-laying and larval development are significantly reduced, leading to lower infestation rates of *Parthenium* due to the beetle's limited adaptability to these environmental factors.

Other major biocontrol agents include *Listronotus setosipennis* (stem-boring weevil), *Smicronyx lutulentus* (seed-feeding weevil), *Bucculatrix parthenica* (leaf-mining moth), *Platphalonidia mystica* (stem-boring moth), *Conotrachelus albocinereus* (stem-galling weevil), and *Carmenta ithacae* (root-boring moth) (Table 2).

Table 2. Insects responsible for biological management of *P. hysterophorus*

Sl. No.	Organism	Scientific name	Order	Family	Origin (Country)
1.	Mexican beetle	*Zygogramma bicolorata*	Coleoptera	Chrysomelidae	Mexico
2.	stem-galling moth	*Epiblema strenuana*	Lepidoptera	Tortricidae	Mexico
3.	Stem-boring weevil	*Listronotus setosipennis*	Coleoptera	Curculionidae	Argentina
4.	Seed-feeding weevil	*Smicronyx lutulentus*	Coleoptera	Curculionidae	Mexico
5.	Leaf-mining moth	*Bucculatrix parthenica*	Lepidoptera	Bucculatricidae	Mexico
6.	Root-boring moth	*Carmenta ithacae*	Lepidoptera	Sesiidae	Mexico
7.	Stem-boring moth	*Platphalonidia mystica*	Lepidoptera	Tortricidae	Argentina
8.	Stem-galling weevil	*Conotrachelus albocinereus*	Coleoptera	Curculionidae	Argentina

Management by fungi

Table 3. Fungi responsible for biological management of *P. hysterophorus*

Sl. No.	Organism	Scientific name	Order	Family
1.	Winter rust fungus	*Puccinia abrupta* var. *parthenicola*	Pucciniales	Pucciniaceae
2.	Summer rust fungus	*Puccinia melampodii*	Pucciniales	Pucciniaceae

Management by allelopathic plants

The utilization of plants with allelopathic properties constitutes a significant aspect of the biological management of *P. hysterophorus* (Table 4). A recent botanical survey conducted across India identified several plant species (Table 4), including *Cassia sericea*, *Cassia tora*, *Cassia auriculata*, *Croton bonplandianum*, *Amaranthus spinosus*, *Tephrosia purpurea*, *Hyptis suaveolens*, *Sida spinosa*, and *Mirabilis jalapa*, as highly effective in controlling *P. hysterophorus* in natural ecosystems (Wahab, 2005).

TABLE 4. Allelopathic plants responsible for biological management of *P. hysterophorus*

Sl. No.	Common Name	Botanical Name	Family	Origin
1.	Golden Shower Senna	*Cassia sericea*	Fabaceae	Tropical regions of the Americas
2.	Sickle Senna	*Cassia tora*	Fabaceae	Asia, particularly India
3.	Tanner's Cassia	*Cassia auriculata*	Fabaceae	India, Sri Lanka, and Southeast Asia
4.	Purging Croton	*Croton bonplandianum*	Euphorbiaceae	Tropical regions of South America
5.	Spiny Amaranth	*Amaranthus spinosus*	Amaranthaceae	Tropical regions worldwide
6.	Wild Indigo	*Tephrosia purpurea*	Fabaceae	Indian subcontinent
7.	Bushmint	*Hyptis suaveolens*	Lamiaceae	Tropical America
8.	Prickly Fanpetals	*Sida spinosa*	Malvaceae	Tropics and subtropics worldwide
9.	Four O'clock Flower	*Mirabilis jalapa*	Nyctaginaceae	Tropical South America

Conclusion

The biological control of *Parthenium hysterophorus* is very much effective for mitigating the ecological, agricultural, and health challenges posed by *P. hysterophorus*. By using natural enemies such as the leaf-feeding beetle *Zygogramma bicolorata*, the stem-galling moth *Epiblema strenuana*, and pathogenic rust fungi like *Puccinia abrupta* var. *parthenicola*, biological control offers an environmentally sustainable and eco-friendly alternative to conventional methods. These agents not only check the proliferation of *Parthenium*, but also restore ecological balance by targeting the weed's growth, seed production, and competitiveness. Allelopathic plant species like *Tephrosia purpurea* and *Cassia tora* are also incorporated to support these initiatives and offer a comprehensive method of controlling infestations. But relying only upon the biological control methods would not help. Rather, an integrated approach should be taken. Manual or mechanical, chemical, biological approaches altogether are recommended to combat this *Parthenium* problem.

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Compensatory Mechanisms in *Japonica* Rice: A Review of the Interactive Effects of Seedling Age and Spacing Configuration on Source-Sink Relationships and Yield

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Abstract

Japonica rice cultivars differ significantly from *Indica* varieties in their tillering dynamics and vegetative duration, making them highly sensitive to agronomic management. Among the most critical constraints to yield stability are the age of seedlings at transplanting and the geometric configuration (spacing) of the crop. While early transplanting is widely recommended, labour shortages and erratic climate patterns often force farmers to utilize aged seedlings, leading to reduced tillering and yield penalties. This review synthesizes recent literature to evaluate the hypothesis that altering plant density can compensate for the yield drag caused by aged seedlings. We analyze the physiological impact of the phyllochron gap, root oxidation activity, and light extinction coefficients under varying densities. The synthesis suggests that while 15-day-old seedlings perform optimally at wider spacing (30 × 20 cm), yield losses in aged seedlings (>35 days) can be significantly mitigated by increasing planting density to 20 ×10 cm or 15 ×15 cm. We conclude by proposing a dynamic agronomic model where spacing is adjusted as a function of seedling age to maximize resource use efficiency.

Key words: *Oryza sativa* L.; Phyllochron; Transplanting Shock; Planting Geometry; Source-Sink Partitioning.

Introduction

Rice (*Oryza sativa* L.) is the primary source of nutrition for over 50% of the earth's population and is highly essential for ensuring global food security. The demands for rice are growing globally due to an increasing population, increased urbanization, and shifts in diets, thus putting pressure on rice-growing systems to produce more sustainably (Papademetriou, 2000; Pede, V. O., *et al*. 2023). There are two major groups of cultivated rice: one of these is japonica rice, which is mostly grown in temperate and subtropical regions such as China, Japan, South Korea, northern US states, Australia, and some European countries. Japonica rice is renowned for its excellent grain quality and is highly favoured in many lucrative markets (Alam, M., *et al*. 2024).

Despite substantial genetic improvements and advances in crop management, yield gains in japonica rice have slowed in many production regions. Modern rice production faces increasing challenges associated with climate variability, labor shortages, declining water availability, rising production costs, and environmental concerns linked to intensive agricultural practices . Temperature extremes during reproductive development are particularly problematic in temperate japonica-growing regions because they adversely affect photosynthesis, assimilate translocation, grain filling, and ultimately grain quality and yield (Fernando, Y. *et. al.,* 2025).

Apart from the climatic challenges, shortage of labour is another factor that is increasingly becoming a problem in many countries where rice is cultivated. The rising cost of labour and its limited availability have led to the greater acceptance of mechanical rice transplanting techniques. Mechanical farming necessitates changes in nursery operation, seedling age, and planting density in order to ensure optimal crop

establishment and production (Bian, J *et al*.,2018). Nevertheless, late transplantation and utilization of mature seedlings can lead to poor tillering capacity, shorter vegetative stage, and reduced biomass production.

Plant population structure has also been identified as a crucial factor in determining the yield of japonica rice. Plant spacing affects aspects such as canopy structure, photosynthesis rate, root development, nutrient uptake, and source-to-sink relationship. The planting of very dense plants may cause increased plant competition and decreased panicle performance. Similarly, the planting of very wide spaces may cause reduced sink size, even as it facilitates better plant growth (Dong *et al*., 2025). This explains why plant spacing optimization is now a vital approach to achieving efficiency in yield.

Management strategies described above can be associated with the physiology of source-sink relations. Source-sink relation controls the production, translocation, and consumption of assimilates in the rice plant. The source part includes photosynthetic leaves and carbohydrate reserves, whereas the sink part comprises the developing panicles and grains demanding assimilation for their development. Yield determination involves an optimal interaction between the size of source potential and sink demand. In case when any yield determining factor limits crop production, compensation might take place via tillering, panicle number, grain number, grain filling, and dry matter distribution (Fei, L. *et al*., 2024).

In rice cultivation systems, especially for mechanized transplanting, the age of the seedlings plays a vital role in terms of determining the growth and productivity of the plants. As per agronomic advice, it is always better to transplant young seedlings that will help overcome the initial stress caused by transplantation and also enable them to grow tillers that are more effective for grain production. The period of vegetative growth will also increase in such plants, allowing greater production of biomass and sinks. However, due to the realities of modern-day rice cultivation, farmers are not able to achieve this ideal time frame for transplantation (Elamathi, S. *et al*., 2025).

The growing scarcity and high costs of labour for agriculture have increased the rate at which farmers have adopted mechanized rice transplantation. Although mechanization ensures increased efficiency and timely completion of farming activities, mechanization is also characterized by logistical challenges related to the nursery and transplant timing. Problems such as unfriendly weather conditions, inadequate machinery, vast farming land, or lack of sufficient labour often cause delays, resulting in seedlings staying longer in nurseries and the farmers having to rely on over-aged seedlings when transplanting (Liu, Q. *et al*., 2015).

Physiological aspects show that aged seedlings tend to have less vitality during transplantation and lower tiller forming ability. Extended periods of stay in trays in nurseries will limit root development, enhance competition amongst seedlings for nutrition and sunlight, and lower their ability to recover quickly after transplantation. These factors might cut down the growth period, reduce leaf surface formation, and reduce source strength needed for further grain production. This will, therefore, lower the sink size in terms of panicles and spikelets formed, hence lowering the yield (Ling, Y. *et al* .,2024).

However, mechanized rice cultivation under modern conditions does not always allow working within the optimal window of seedling age. The production process takes precedence over agronomic considerations in large-scale operations, in terms of efficiency, machine usage, and workforce utilization. In such a case, one faces the problem of obtaining good yields despite the operationally driven necessity of using seedlings which are past their physiological age optimum. Modern scientific research suggests that rice is capable of overcoming age-associated disadvantages through canopy changes, biomass partitioning, carbon-nitrogen balance, and source-sink dynamics, especially when combined with agronomic measures like spacing design (Wu, X., *et al*., (2025).

Given that there is an increased utilization of mechanical rice farming, the importance of finding out the optimal age of the seedlings and optimal planting pattern becomes important when growing japonica rice. Although the effect of each of these variables has been

well investigated, their interaction and the way the plant can compensate for the poor condition has not(Hu, Q. *et al*.,2020).

The current literature review attempts to highlight the impact of differences in rice (*Oryza sativa* L. ssp. japonica) seedling age and spacing arrangement in a transplanting and mechanized growing system on the physiology, morphology, and agronomy of japonica rice. Special attention is paid to how such variables affect the source-sink interactions, including photosynthetic source strength, assimilate transport, sink development, grain-filling mechanism, and compensatory yield components. The present study tries to summarize the existing data about the adaptation of rice plants to changes in their tillering behaviour, canopy structure, biomass allocation, carbon-nitrogen balance, and panicle formation due to delay in transplanting and plant density (Liu, Q. *et al*., 2015).

In addition to this, the topic under discussion also addresses the phenomenon known as yield compensation. This means that decreases in some yield components could be compensated for by increases in other components. More emphasis will be placed on the relationship between seedling age and planting pattern. Appropriate planting pattern may help minimize the detrimental effects of excessive seedling age through better light capture, less competition between plants, improved sink strength, and improved distribution of assimilates. These mechanisms are especially critical in mechanized cultivation systems due to a lack of manpower, weather conditions, and operational difficulties (Wu, X. *et al.* 2025).

Physiological Basis of Seedling Age

The physiological aspects of age in relation to seedlings of rice plants may be explained by use of the concept known as phyllochron, defined as the period of time between the development of two successive leaves on the rice plant's main stem. For rice plants, each phyllochron constitutes one developmental unit of leaves, roots, and tillers. Tillers develop simultaneously with leaves, so this is an ideal method of explaining the impact of age of seedling on rice tillering capacity, growth, and yield production(Nemoto *et al*., 1995; Miyamoto *et al*., 2004).

Generally, in the case of rice plants, tillering tends to follow a pattern that is in relation to the process of leaf formation. The process of forming leaves involves the activation of axillary buds which form tillers. Therefore, the process of leaf formation, as measured by the phyllochron is highly indicative of the ability of the plant to form productive tillers and sink tissues. It is even more clear when transplanting age is taken into consideration. Seedlings that have not reached a high phyllochron stage can still produce tillers since the developmental activities have not yet been limited by the nursery stress. Older seedlings, however, suffer from being confined in the nursery trays and the roots of such seedlings may develop abnormally due to lack of space. This leads to losing some tillering possibilities at the early phyllochron stage, and thereby results in the lack of compensation after transplanting. As a consequence, fewer panicles will form sinks (Veeramani & Singh, 2012).

Additional research related to the SRI method has shown that planting seedlings before the fourth phyllochron allows for the maintenance of tillering capacity and vigorous growth after transplantation. Transplanting after this stage would result in low tiller bud activation, thus preventing proper canopy formation and biomass development .While these observations were primarily made in relation to the SRI technology, the same physiological mechanisms apply to mechanized japonica rice farming, where transplanting late usually leads to working with over-aged seedlings (Nemoto, K. *et al*., 1995).

The growth of roots is among the most vital physiological factors that influence the survival of the seedlings as well as the process of yield production during transplantation of rice. Seedlings' capability of producing roots after transplantation is what influences their ability to uptake water and minerals, begin photosynthesis, start tillering, and maintain a good source-sink relationship. Therefore, variations in the age of the seedlings become evident through changes in root physiology and root vigor and transplanting shock (Mishra & Salokhe, 2008).

The increased age of seedlings in the nursery results in densely tangled roots due to the lack of space,

resulting in increased nutrient competition. This means that old seedlings will have less root growth and less regeneration of the roots than young ones. Furthermore, mechanical transplanting can result in root damage.

Transplanting shock can be defined as a growth suppression phase experienced by seedlings when transplanted from nursery to the field. Some of the characteristics associated with transplanting shock include reduced water uptake, reduced nutrient uptake, reduced photosynthesis, slow leaf development, and slow tiller development. According to (Lee *et al*., 2021), transplanting shock plays an important role in slowing down plant growth and development since it interferes with some physiological functions right after transplanting.

Transplant shock is minimized in younger seedlings due to their increased plasticity and quicker regeneration of roots, which enables quick establishment and effective utilization of water and nutrients. Older seedlings are comparatively slower to recover from root injury, leading to reduced vegetative growth and tiller development and subsequently less panicle development.

Source–Sink Transplanting Shock causes inhibition in the functioning of the source system due to inhibition of photosynthesis and restriction of leaf expansion. Meanwhile, root damage results in inability to absorb nutrients needed for the growth of sinks. When there is delayed regeneration of roots, assimilation will not be adequate to form more productive tillers. Nevertheless, japonica rice can partly cope by stimulating rapid root growth and improved assimilation partitioning after recovery, particularly under favorable plant spacing to minimize competition (Wang *et al*., 2024).

The Role of Spacing Configuration

Interception of solar radiation is an essential aspect in determining the biomass and yield formation in rice since 90-95 percent of the dry biomass content in the crop is due to solar energy. The arrangement of spaces in japonica rice determines how the canopy structure will be formed and also how many plants can be accommodated in such arrangements. This means that the interception of photosynthetically active radiation (PAR) will differ in wide spacings and narrow spacings in terms of both magnitude and pattern. Source strength depends mainly on the rate of photosynthesis (Monteith, 1969).

With more space between individual rice plants, each one receives more sunlight since there is reduced competition between individual plants. The penetration of sunlight deeper into the canopy layer improves light absorption by individual leaves. This leads to improvement in the photosynthesis process for each individual plant. Wide spacing facilitates development of larger leaf size, increased tillering, better root development, and good air circulation within the canopy layer (Thakur *et al*., 2010).

Nevertheless, too large spacing would cause inadequate capture of radiation by the population as a whole, particularly during the vegetative phase of plant growth. The few numbers of plants that would exist within a certain area would result in delayed canopy closure, such that parts of the incident radiation would be wasted. Hence, while each plant might have performed optimally, the overall canopy of crops might not have been able to capture enough cumulative radiation due to small biomass production and sink size (Baskar & Siddeswaran, 2013).

With closer spacing, there will be an increase in plant numbers and quicker closure of the canopy, thus enabling more solar energy to be intercepted by the plants. Canopies formed by dense vegetation usually have higher values of leaf area index (LAI), thus improving radiation interception and biomass accumulation; observed that with an increase in planting density, there is better interception of sunlight and radiation usage, resulting in increased grain yields. overcrowding may cause shading within the canopy because upper parts capture an excessive amount of radiation, but low parts have poor access to light and consequently do not photosynthesize efficiently enough. Self-shading lowers the radiation use efficiency and, therefore, reduces assimilate production at important reproductive stages . Crowded plants may increase water and nutrient competition among plants,

thus weakening the source capacity even if radiation interception is high (Hou *et al*., 2019).

The spacing arrangement has an impact on the uptake and use of nutrients by the rice crop. The high density resulting from closer spacing increases competition among the plants for vital nutrients such as nitrogen, phosphorous, and potassium, which can lower nutrient availability to the plant and negatively affect root development and tiller formation. On the other hand, spacing that is wider reduces competition among the plants, giving each plant more access to soil nutrients, thereby enhancing root growth and nutrient absorption ability. Nevertheless, overly wide spacing may not maximize the use of soil nutrients (Hu, Q. *et al*., 2020).

Interaction Effects: Can Density Compensate For Age ?

According to the compensatory hypothesis, rice yield depends on how well the plant compensates for its own source-to-sink ratio in response to the management-related restrictions imposed on it. Compensation can happen because of the changes made in tillering, panicle development, dry matter allocation, and grain filling when there is any reduction in one factor responsible for yield formation. In the mechanization system of japonica rice, the interaction between seedling age and spacing configuration offers an excellent case of compensation. The proper density can compensate for any physiological problems that come from the seedling age (Liu *et al*., 2017).

Generally, young seedlings transplanted with wide spacings have a high compensatory growth capability. This is due to the fact that transplant shock is low and the roots regenerate quickly, and thus there is more room for growth in terms of tiller formation, leaf expansion, and better root system formation. The plants will experience low levels of competition for light, water, and nutrients, hence photosynthesis will increase, improving the source capacity of individual plants. Additionally, tillering and panicle formation increase the sink capacity of each plant such that each plant contributes significantly to yield formation. In spite of lower population levels, individual plants usually compensate through an increase in number of panicles per plant, spikelets per panicle, and grain filling (San-oh *et al*., 2006).

The older seedlings usually exhibit problems of reduced capacity for tillering, restriction of roots, and high transplanting shock leading to low sink development. In such cases, close planting can be viewed as an alternative where increased numbers of plants per hectare will compensate for their reduced tiller and sink development. Although each plant might not tiller and develop large sinks, the high number of plants per hectare could partly make up for this problem (Liu *et al*., 2017).

But the compensation does not come without a limit. Planting seedlings in a very high density will result in competition among seedlings, making it difficult for them to receive sufficient sunlight and nutrients and decreasing their ability to photosynthesize and serve as a source. In this regard, the success of this type of compensation will depend on reaching the optimal planting density. With the right management, increasing planting density can help to compensate for problems associated with over-age seedlings (Hou *et al*., 2019).

The grain yield of rice plants depends on the contribution of different components of yield which mainly include number of panicles per unit area, number of spikelets per panicle, percent grain fill, and test weight of thousand grains. The relationship between the age of seedlings and spacing pattern affects the various yield components through the process of tillering, source-sink relationships, and assimilation partitioning. Compensation takes place amongst the components of yield where yield loss due to any yield component is offset (Yoshida, 1981).

The yield component whose production is mostly influenced by seedling age and plant density is the panicle number. The younger the seedlings, the better their ability to form tillers that lead to the formation of more panicles as compared to the mature ones due to vigorous growth and a long vegetative stage. Increased plant spacing enhances the process of tillering as plants compete less for nutrients, water, and space. In other circumstances where tillering ability

is compromised by seedling age due to shocks associated with transplantation, then high densities provide an alternative method for increasing panicle numbers per area through increased plant numbers per unit area (Ling *et al*. 2024).

Spikelets per panicle are indicative of the sink size of each panicle, which is greatly affected by resource availability when the panicles are developing. Increased spacing tends to result in more spikelet development due to increased light capture, nutrient absorption, and photosynthesis that facilitate the growth of bigger panicles. Younger plants benefit more from these conditions since they have higher growth and production capacity. On the other hand, more spacing can lead to increased competition among the plants, thus lowering assimilate availability for each plant. This will hinder the process of spikelet development (Thakur *et al*., 2010).

Generally, the test weight is believed to be the most stable yield component due to the high percentage of genetics involved in determining its magnitude. However, environmental conditions and the source-sink interaction during the grain-filling period play an important role in influencing grain weight. A higher spacing can contribute to improved grain-filling processes through proper light distribution and lower competition for assimilates, hence promoting increased grain weights. Inversely, very high seeding densities can create too many sinks compared to sources, thus leading to inadequate assimilate supply to developing grains and reduced grain weight. Nonetheless, test weight variations as compared to panicle numbers and spikelets per panicle are relatively lower under different seedling ages and spacing levels (Yoshida, 1981).

Economic and Agronomic Implications

Seed cost is among the very first economic factors affected by the pattern of planting. More crowded planting will need more number of plants per unit area and hence a higher seed rate relative to less crowded planting. For the mechanically transplanted rice, the more seed required also means that there will be a need for more nursery tray and hence higher costs in the nursery. But for aged seedlings, the increased seedlings required by crowding can be made up by their lesser tillering ability to achieve the desired panicle density per square meter. Although the cost of seed at the beginning increases, the added cost of seeds will normally be compensated by better crop stand and higher grain yield. On the other hand, younger and vigorous seedlings will have high tillering ability and hence perform well under moderate or less crowded planting, hence lower seed cost without affecting productivity (Liu *et al.,* 2017; Ling *et al*., 2024; Dong *et al*., 2025).

Availability of labour force has emerged as one of the most serious limiting factors in the production of rice in many Asian countries, and hence there is rapid acceptance of mechanized transplanting technology. The use of mechanized transplanting not only cuts down labour requirements but also ensures timely planting of crops, however, economic viability of this process largely depends upon management of nurseries, seedling age and planting densities. High plant density leads to higher numbers of hill formations in a hectare; thus a larger number of nursery mats will be required along with an increased operating time of machines and usage of fuel. However, the cost of operation involved here is much lower than the costs incurred by manual transplanting. Lack of availability of labour leads to late transplanting and use of old seedlings, which leads to low tillering rates. In such cases, mechanical transplanting can help in enhancing field capacity, reduce labour dependence, increase efficiency of transplanting and increase production sustainability (Bian *et al*.,2018; Singh *et al*., 2023).

Net economic returns depend on the relative relationship of cost of production and yield. Young transplanted seedlings with good spacing always achieve higher net returns due to their better ability to tiller, high accumulation of biomass, source-sink relationship, and reduced number of seeds. Even though wide spacing of seedlings leads to reduced seed and nursery cost, increased wideness reduces plant populations and hence yield levels. In case transplanting is done late, use of old seedlings leads to high seed and nursery cost but minimizes yield losses through increased number of panicles. Thus, higher cost due

to higher seeding density ends up being offset through increased yield levels. Economic analyses always show that the most economical method of production is that which involves optimal match between planting densities and the physiological age of seedlings and not just adopting a fixed spacing regardless of physiological state of crops (Dong *et al*., 2025).

Future Prespectives

The use of mechanical transplanting will be inevitable in the cultivation of japonica rice because labour shortage, high production cost, and increased demand for efficiency will make it necessary. The effectiveness of mechanization will not depend on the replacement of labor by machinery but on the optimum combination of age of seedlings, planting distance, and the sink-source effect. It is recommended, therefore, that future studies should concentrate on finding the best integrated management practices taking into account the physiology of mechanical transplanting and the negative effects of delayed transplanting (Singh *et al*., 2023).

One such possible way forward would be the development of precision transplanting technologies that allow adjustment of the spacing of hills, number of seedlings per hill, and even planting geometry based on conditions prevailing in the field and needs of the variety grown. Precision transplanting could facilitate site-specific population manipulation and thus ensure canopy architecture conducive to better light interception and nutrient use efficiency while ensuring a source-sink balance (Dong *et al*. 2025).

High-quality nursery seedlings that can be machine-transplanted should also be emphasized in the future for mechanized production systems. Studies have proven that there is still possibility in saving nursery costs without compromising the vigor of seedlings through high density nursery production, mat-type seedlings, and tray handling systems .The determination of the best seedling age range for each cultivar of japonica rice is another important study area for the future (Cheng *et al*., 2018; Shang *et al*., 2025).

Another field to consider relates to incorporating source-sink based farming practices into mechanical farming processes. It would be necessary for researchers to study the role of transplanting machines, together with spacing optimization strategies, to offset the lower tillering capability of aged plants. Knowledge gained from this research will allow the development of management packages that ensure yield constancy despite delays and climate changes (Dong *et al*., 2025; Singh *et al*., 2023).

Climate change has come up to be one of the major threats to the sustainability of the production of japonica rice. High temperatures, rainfall patterns, floods, droughts, and erratic weather conditions have been causing problems for japonica rice production in terms of plant establishment, photosynthesis, grain filling, and stability in production. In this scenario, studying the relation between age of the seedling and the spacing pattern provides an advantage to mitigate climatic risks (Fernando *et al*., 2025; Singh *et al*., 2023).

Future studies need to determine the specific seedling age and spacing required to enhance rice crop tolerance against the climate-related environmental stresses without compromising their source-sink balance. Younger seedlings have been found to show higher development flexibility and recovery potential from any climatic shocks, whereas proper spacing helps in achieving better aeration of the plant canopy, light diffusion, better root development, and water utilization efficiency (Thakur *et al*., 2010; Dong *et al*., 2025).

Production systems resilient to climatic change will also need higher integration of agronomic practices with cultivar development. The future japonica cultivars must possess stress tolerance together with high tillering capacity and assimilate partitioning efficiency, while being adapted to transplanting through mechanical means. These types of cultivars will be more capable of sustaining sink development and grain filling when exposed to unfriendly environments. Moreover, dynamic spacing will prove to be a viable adaptation technique for farmers to manage planting densities based on the climate risk and resource availability for each season (Fernando *et al*., 2025).

Conclusion

The scientific research conducted indicates that the age of seedling and planting pattern are two agronomic variables that interact to control the growth, source-sink relationship, and yield of japonica rice, and not operate independently. The younger seedlings (15-20 days) are physiologically more flexible, have better regenerative capacity for roots, quicker adaptation from transplanting stress, and a prolonged duration of vegetative growth allowing better tillering, biomass production, and formation of sinks. Along with proper plant spacing (20 × 20 cm and 25 × 15 cm), such physiological attributes lead to better canopy formation and light interception, resulting in higher yield.

On the other hand, late transplantation employing old seedlings (>35 days) causes low potential of tillering since it advances phyllochron, limits root functioning, shortens the vegetative period, and enhances stress during transplantation. In such cases, greater spacing lowers panicle density per unit area and causes more yield loss. However, recent research suggests that an increase in planting density to either 15 × 15 cm or 20 × 10 cm can somewhat balance out the lesser productive tillers per hill through increasing hill density, hence ensuring proper panicle density and yield stability in spite of physiological drawbacks of old seedlings.

Thus, this paper endorses the Dynamic Spacing Protocol, where planting arrangement needs to be decided on the basis of seedling age and not using the same spacing regime for all seedlings. In optimum management practices, farmers need to transplant 15-20 day old seedlings at moderate spacing (20 × 20 cm or 25 × 15 cm) to ensure maximum performance by individual plants as well as resource efficiency. However, in case the operational limitations such as lack of labour force, delay in arrival of monsoons, or transplanting through mechanical methods require the use of larger seedlings, the planting needs to be done at close spacing (15 × 15 cm or 20 × 10 cm) owing to limited tillering ability of such plants.

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Selection Indices, Genetic Variability and Economic Heterosis for Yield Improvement in Maize (*Zea mays* L.) Under Rabi Conditions

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Abstract

Enhancing maize productivity requires identification of high-yielding superior hybrids and key yield attributing traits integrated through genetic analysis and breeding programme. The present study evaluated 24 maize hybrids along with three check varieties at the Agricultural Instructional Farm of RKMVERI, Narendrapur under Rabi conditions in Eastern India using randomized block design with three replications. Substantial genetic variability was observed for all the traits that indicate scope for genetic improvement and selection.

Higher estimates of genotypic and phenotypic coefficients of variation were recorded for grain yield per plant, cob weight per plant, number of kernels per row indicating greater exploitable variability. High heritability coupled with high genetic advance for the mentioned traits indicated the greater effect of additive genetic action. Correlation analysis suggested strong positive associations of grain yield with cob weight, kernel number and 100-seed weight, which was further supported by path coefficient analysis where cob weight exerted direct effect on yield.

Economic heterosis analysis identified superior hybrids with significant yield advantage over standard national and state checks with 64×T1 (33.47%), 62×T2 (33.27%), and 38×T3 (31.06%) emerged as most promising performers. The integration of trait association with variability parameters and heterosis analysis enabled the identification of cob weight, kernel number and seed weight as effective selection indices for yield improvement.

These findings may be useful for superior hybrid selection and breeding strategies for improving maize productivity under Rabi conditions.

Keywords: *maize, economic heterosis, yield advantage, genetic variability, hybrid selection, selection indices.*

1. Introduction

Maize (*Zea mays* L.) is one of the most important cereal crops globally, serving as a staple food, feed and industrial raw materials due to its high genetic yield potential and broader adaptability base. Despite these facts, average Indian maize productivity remained much lower than global average indicating substantial scope for yield improvement. Specifically, this yield gap is evident under Rabi conditions in Eastern India due to sub-optimal environmental conditions and improper genotype specific responses that affects crop performance. Therefore, developing high yielding superior hybrids suitable for the specific environment remains a key priority in maize breeding.

Harnessing heterosis has been a cornerstone in maize improvement, leading to remarkable increase in productivity through hybrid evaluation. Among different measures, economic heterosis is of particular relevance as it evaluates hybrid performance over the commercially available check varieties, thereby reflecting its practical and economic importance. The identified hybrid varieties are considered essential for ensuring promising yield advancement and yield stability and enhancing farmer profitability under the specified region.

Genetic variability determines the effectiveness of selection through the breeding program thereby indicating strong potential for genetic gain. Quantitative genetic parameters such as genotypic and phenotypic

coefficients of variations (GCV and PCV), heritability and genetic advance provide valuable insights into the nature and magnitude of variability governing yield and its associated traits. These parameters facilitate the identification of more genetically controlled trait with less environmental impact ensuring greater varietal stability and efficient selection.

Grain yield in maize is a complex quantitative trait influenced by several interrelated components. Hence, character association analysis assumes crucial importance in understanding the relationships among various traits. Correlation analysis provides an idea and strength of association, while path coefficient analysis further dissects these relationships into direct and indirect effects, identifying key yield contributing traits that can be further utilized as selection indices to improve selection efficiency in the breeding program.

Although considerable progress has been made for maize improvement, studies integrating genetic variability, trait association analysis with economic heterosis estimation under specified geographical location remained limited. In particular, there is a serious lacuna of comprehensive evaluation of maize hybrids under Rabi conditions in Eastern India using an integrated analytical approach. Such integrated analysis are essential to understand stable and high performing hybrids adapted to specific agro-climatic conditions (Badu-Apraku et al., 2020; Zhang et al., 2021). Addressing this gap is crucial for identifying superior hybrids and formulating effective breeding strategies tailored for the specified region.

Therefore the present investigation was undertaken to evaluate maize hybrids for substantial genetic variability, character association and economic heterosis, with the objective to identify key selection indices and superior hybrids for genetic gain under Rabi conditions.

2. Materials and Methods

2.1 Experimental Site

The field experiment was conducted during Rabi season (2024-25) at Agricultural Instructional Farm of Ramakrishna Mission Vivekananda Educational and Research Institute (RKMVERI), Narendrapur, Kolkata, West Bengal, India (22.45° N latitude, 88.38° E longitude; 9.1 m above mean sea level). The region belongs to humid subtropical agro–climatic zone, characterized by moderate rainfall and mild winter. The experimental soil was well drained and suitable for maize cultivation and standard agronomic management practices were followed to minimize non-experimental variation.

2.2 Experimental Material

The experimental materials comprised 24 maize hybrids along with three widely cultivated commercial check varieties i.e. DMRH1305, DMRH1308 and PIONEER3355. These genotypes were evaluated to assess their performance for yield improvement and associated quantitative traits under Rabi condition.

2.3 Experimental Design and Crop Management

The experiment was performed through a Randomized Block Design (RBD) with three replications. Genotypes were grown in uniform plots having a spacing of 60cm between rows and 30cm between plants. Standard agronomic practices including fertilizer application, irrigation scheduling, plant protection measures were adopted to ensure minimal environmental variation therefore optimal plant growth.

2.4 Observations Recorded

Data were recorded from five randomly selected plants from each plot for twelve quantitative traits, namely days to 50% tasseling, days to 50% silking, days to maturity, plant height (cm), cob height (cm), cob length (cm), cob diameter (cm), number of rows per cob, number of kernels per row, 100-seed weight (g), cob weight per plant (g), and grain yield per plant (g). Mean values of these characters were estimated for statistical analysis.

2.5 Statistical Analysis

The experimental data were analysed to assess different variability parameters, trait association and heterosis among the evaluated hybrids. Analysis of

Variance (ANOVA) was performed following the procedure described by Panse and Sukhatme (1967) to determine significant differences among genotypes.

Genotypic and Phenotypic coefficient of variations (GCV and PCV) were computed to estimate extent of variability, whereas broad sense heritability (h^2) and genetic advance (GA) as percentage of mean were calculated to evaluate heritable component of variation and expected response to selection.

Correlation coefficients were estimated to determine the nature and magnitude of association between traits. Path coefficient analysis was carried out following the method of Wright (1921), as described by Dewey and Lu (1959) to dissect correlation coefficients into direct and indirect effects.

Economic heterosis was estimated as the percentage deviation of hybrid performance over standard commercial check variety. All statistical analysis were performed using R software (version 4.4.1). Data visualization including bar graph and heat map generation was carried out using appropriate packages in R to facilitate interpretation.

3. Results and Discussion

3.1 Analysis Of Variance

The analysis of variance revealed highly significant differences among maize hybrids for all the traits studied, showing substantial genetic variability within the experimental material. Presence of such variability is a prerequisite for effective selection and genetic improvement in breeding programme. The existence of significant variation in yield and its component traits suggests broader genetic backgrounds which can be efficiently exploited for hybrid selection and development. Similar observations have been reported in maize by Yadav *et al*. (2015), Badu-Apraku *et al*. (2020) who highlighted that significant genotypic variation provides a strong foundation for selection of superior hybrids.

3.2 Genetic Variability, Heritability and Genetic Advance

The estimated genotypic and phenotypic coefficients of variation (GCV and PCV) suggested significant variability among the characters studied. In general, environmental impact on trait expression can be observed by higher PCV value than GCV for the concerned trait. However, a relatively narrow difference between these two parameters for key yield trait suggests limited environmental impact, thereby enhancing the reliability of phenotypic selection (**Figure 1**). Similar trends have been reported in maize by Kumar et al. (2014) and Zhang et al. (2021).

Significant GCV and PCV values were observed for grain yield per plant, cob weight per plant and number of kernels per row indicating substantial scope for genetic improvement through selection. In contrast, few phenological traits such as days to tasseling, silking, and maturity exhibited lower variability, suggesting relatively stable expression under given environmental conditions.

Estimation of broad sense heritability was generally high for most traits, suggesting stronger genetic influence on observed variation. High heritability coupled with high genetic advance for traits such as cob weight per plant, grain yield per plant and 100-seed weight suggests predominance of additive genetic action, therefore validates effectiveness of direct selection (**Figure 2**). These findings are in accordance to classical genetic principles described by Johnson et al. (1955) as well as with the findings of Liu et al. (2020).

In contrast, traits exhibiting high heritability with comparatively low genetic advance may be influenced by non–additive genetic action, suggesting hybrid breeding strategies for their development (**Figure 2**). Overall, the results indicate that cob weight, kernel number and seed weight are key traits that can serve as selection indices for yield improvement in maize.

1.1 Character Association and Path Coefficient Analysis

Correlation analysis showed strong and significant positive associations of grain yield with cob weight per plant, number of kernels per row and 100-

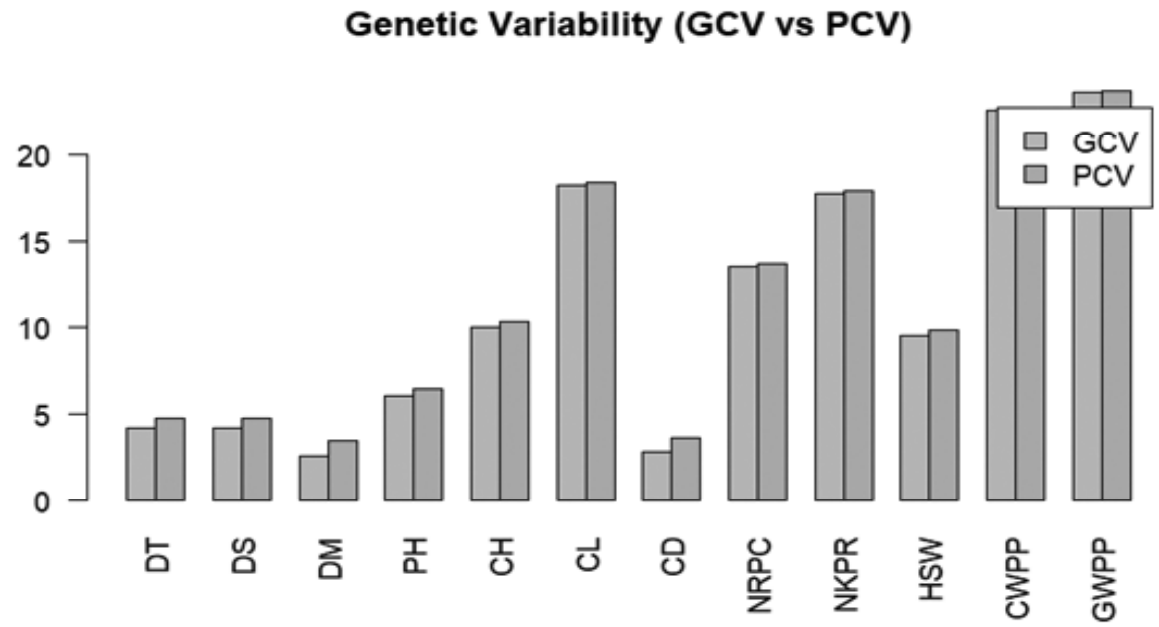

Figure 1 : Genetic variability comparison between genotypes

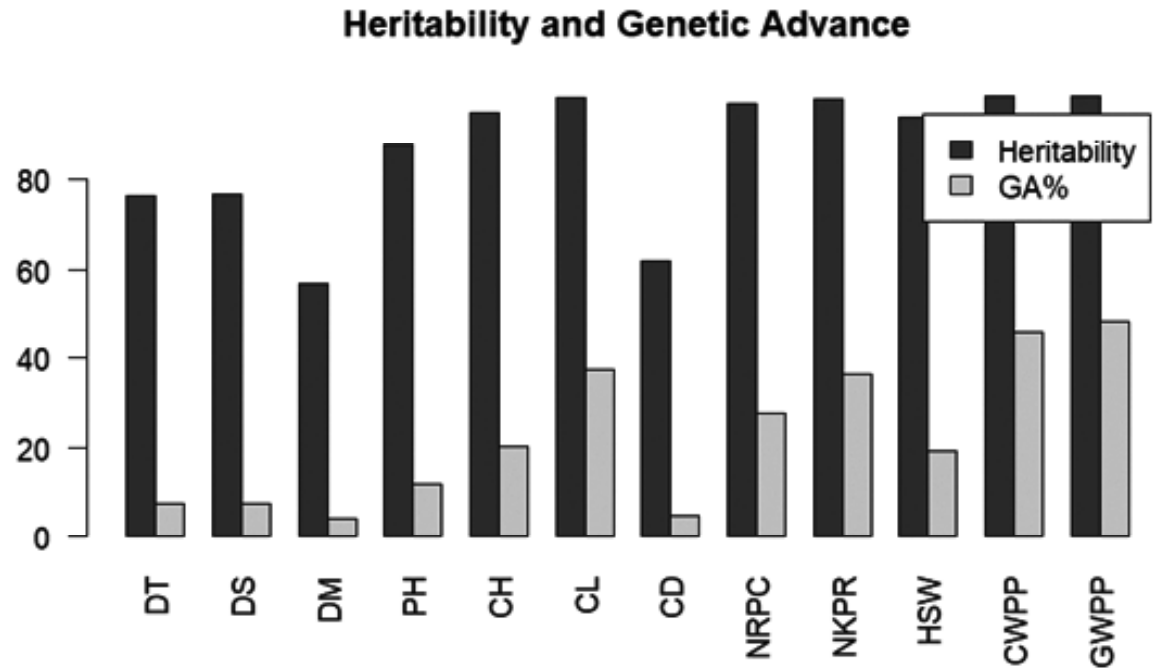

Figure 2 : Heritability and Genetic Advance comparison between genotypes

seed weight at both phenotypic and genotypic levels. These relationships indicate that improvement in these component traits would directly contribute to improve grain yield. Similar associations have been reported by Singh et al. (2018) highlighting the importance of yield contributing traits in maize improvement.

The heatmap visualization further substantiated the clear clustering of yield-related traits in contrast to the phenological traits such as days to tasseling, days to silking and days to maturity which exhibited weaker associations with grain yield, suggesting early maturity may confer yield advantages under Rabi conditions (**Figure 3**).

Path coefficient analysis provided deeper insights into cause-and-effect relationships among traits. Cob weight per plant revealed the highest positive direct effect on grain yield, followed by 100-seed weight and number of kernels per row, indicating their influence on yield (**Figure 4**). Similar conclusions have been drawn in maize by Dewey and Lu (1959).

Therefore, key traits such as cob weight, kernel number and seed weight have been identified as major contributors to yield improvement and can definitely be considered as effective selection indices for future breeding programs.

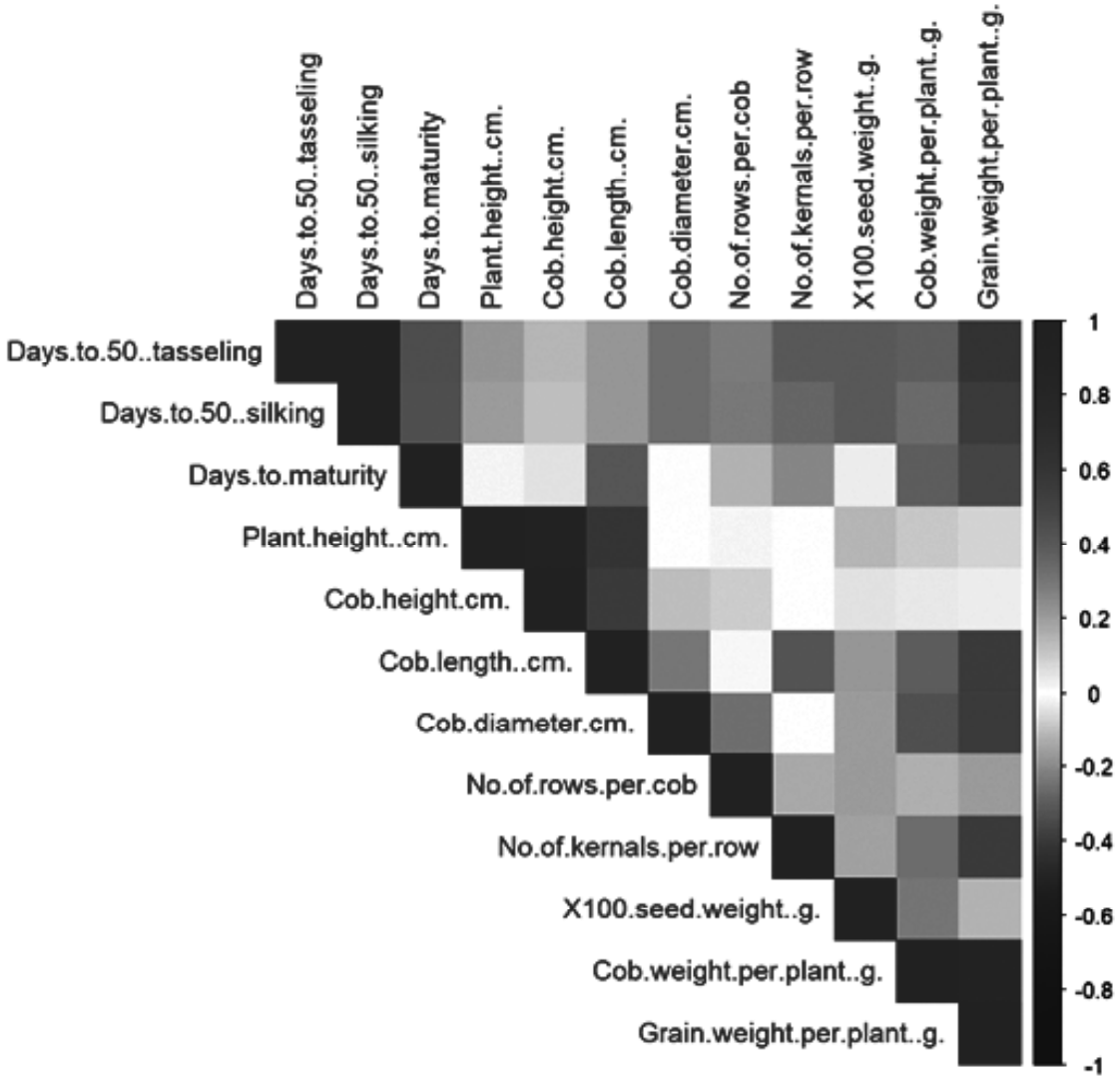

Figure 3 : Correlation heatmap visualization

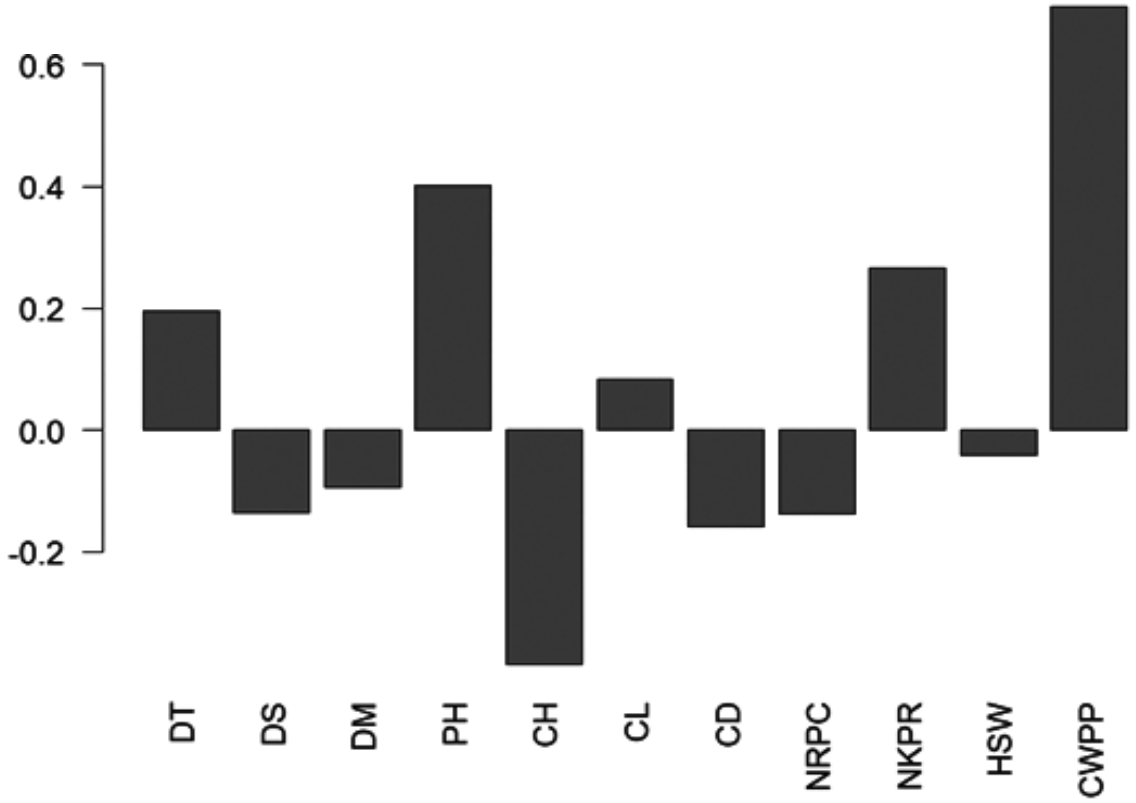

Figure 4 : Path coefficient analyses of yield attributing traits

3.4 Economic Heterosis

Economic heterosis is an important evaluating parameter to judge the practical utility of hybrids under field conditions. In the present study, substantial variation in economic heterosis was observed among the evaluated hybrids showing potential hybrid vigour.

Among the hybrids, 64×T1 exhibited the highest economic heterosis (33.47%) over the standard check variety (DMRH1308), followed by 62×T2 (33.27%) and 38×T3 (31.06%). The superior performance of these hybrids can be attributed to their optimal expression to key yield contributing traits such as cob weight, kernel number and seed weight (**Figure 5**).

The prevalence of high economic heterosis suggests predominance of non-additive gene action, including dominance and epistatic interactions that contributed to genetic gain. Similar findings have been reported by Prasad *et al*. (2017) who emphasized the importance of heterosis in enhancing maize productivity and by Badu-Apraku *et al*. (2021) in tropical maize where economic heterosis has been identified as key factor in maize yield enhancement.

The identification of hybrids with high economic heterosis is considerably important as it directly translates increased productivity and profitability. These hybrids hold strong potential for commercial cultivation under Rabi conditions in Eastern India.

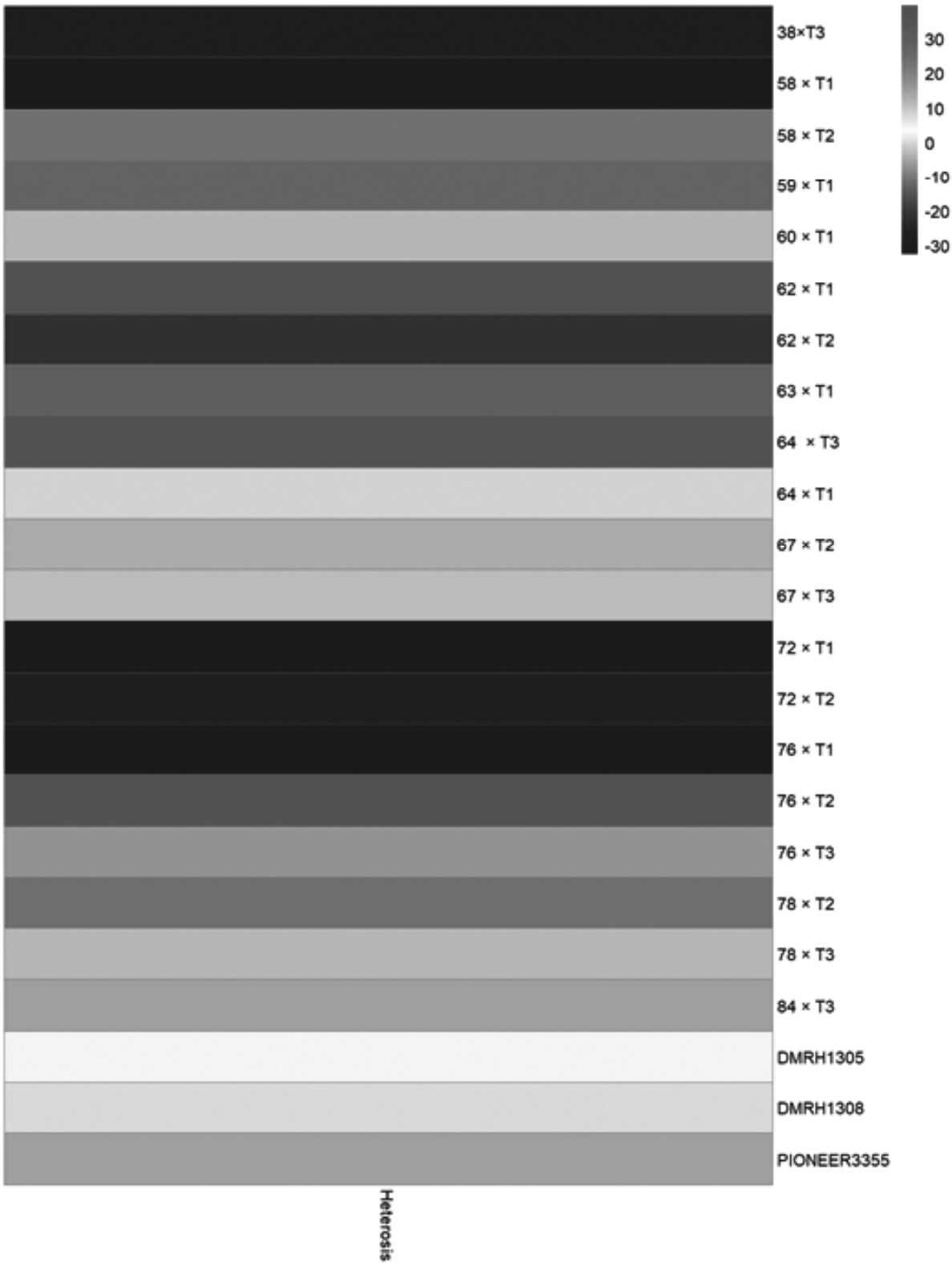

Figure 5: Visualization of Heterosis heatmap among genotypes

3.5 Principal Component Analysis (PCA)

Principal component analysis provided a comprehensive analysis of multivariate relationships among concerned traits. The first two principal components described approximately 54% of the total variation, reflecting a substantial contribution of these components in exploiting variability.

The PCA biplot revealed a clear clustering of yield-related traits such as grain yield, cob weight, kernel number and cob length along with positive axis of PC1, depicting strong positive associations among these traits (**Figure 6**). This observation justifies the results of correlation and path analysis, confirming the central role of these traits in yield determination.

Conversely, phenological traits were positioned along the negative axis of PC1, suggesting an inverse relationship with yield (**Figure 6**). This eventually indicates early maturing genotypes may have yield advantage under Rabi conditions in Eastern India.

The distribution of hybrids further enabled the identification of promising high yielding genotypes located in proximity of yield –related traits. These findings clearly showcase the usefulness of PCA in identifying key traits and superior genotypes for selection, as also reported by Falconer and Mackay (1996). The effectiveness of PCA in identifying key traits and superior genotypes has been widely demonstrated in crop improvement studies, where multivariate understanding provides a comprehensive insight of trait interactions (Wang *et al*., 2020).

4. Conclusion

The present study demonstrated substantial genetic variability among maize hybrids evaluated under Rabi conditions of Eastern India, reflecting significant scope for genetic improvement through selection and hybrid evaluation. The assessment of variability parameters revealed that key yield contributing traits, particularly cob weight per plant, number of kernels

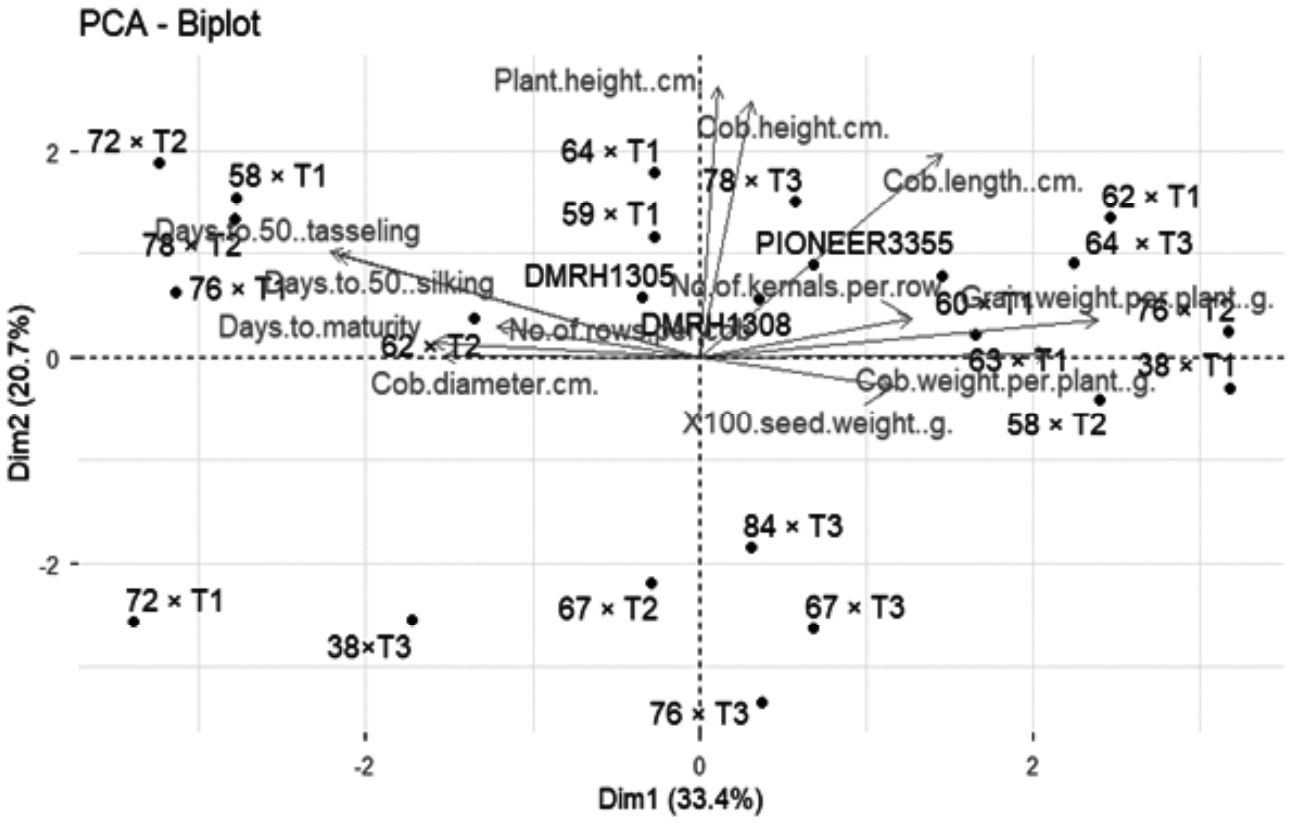

Figure 6 : Principal Component Analysis of experimental genotypes

per row and 100-seed weight exhibited high heritability coupled with high genetic advance indicating the predominance of additive gene action proving them as effective selection indices.

The combined analysis of correlation and path coefficient analysis provided deeper insight into trait interrelationships, affirming that cob weight per plant exerts most pronounced direct influence on yield, followed by kernel number and seed weight. These traits have been identified as promising through multiple analytical approaches thus proving their robustness as reliable selection indices for yield improvement.

Economic heterosis estimation further highlighted significant hybrid vigour, with hybrids such as 64×T1, 62×T2, and 38×T3 exhibiting substantial yield advantage over standard commercial check variety. The high performance hybrids underscored the importance of non-additive gene action in enhancing their productivity and potential of commercial exploitation.

Multivariate analysis further complemented by effective grouping of traits and genotypes based on performance. The convergence of results across univariate and multivariate approaches strengthened the reliability of the findings and facilitates the identification of superior and genetically diverse hybrids.

Overall, the study provides a useful analytical framework integrating genetic variability, trait association, heterosis along with multivariate analysis like PCA and Cluster analysis to identify high-performing and genetically superior maize hybrids. These findings are in line with recent advances in maize breeding that emphasizes the integration of variability, trait association and heterosis for the development of high yielding hybrids (Badu-Apraku *et al.*, 2020). Therefore, potential deployment of these superior hybrids could significantly increase maize productivity and farmers' income narrowing the existing yield gap in Eastern India.

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Author Contributions

Debojyoti Modak conceived and designed the study, conducted the field experiment, performed data analysis, and prepared the manuscript. Ashutosh Sawarkar contributed to data refinement, provided technical guidance, and critically reviewed the manuscript.

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this manuscript.

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