JETIR.ORG ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

Trait Associations and Their Impact on Sowing Seed Quality in Soybean (*Glycine max* L.)

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ABSTRACT

The present investigation was conducted to determine the associations among various morphological, physiological, and biochemical traits and their influence on sowing seed quality in soybean (Glycine max L.). The study was carried out at the Agricultural Farm of the Faculty of Agriculture, Rabindranath Tagore University, Raisen (M.P.), during the Kharif seasons of 2021–22 and 2022–23, using 50 genotypes obtained from AICRP on Soybean, JNKVV, Jabalpur. A randomized complete block design with three replications was employed. Statistical analyses, including analysis of variance and correlation coefficients at genotypic and phenotypic levels, revealed significant variability among traits. The results indicated that seed yield per plant had significant and positive associations with number of pods per plant (0.839), plant height (0.713), germination percentage (0.591), seed vigor index-II (0.580), and 100 seed weight (0.425), suggesting these as key indicators for enhancing seed yield and quality. On the contrary, electrical conductivity exhibited strong negative associations with germination (-0.743), seed vigor (-0.703), and plant height (-0.565), reflecting its role as an indicator of seed deterioration. Traits such as swelling coefficient, hull percentage, and hydration coefficient were also negatively associated with seed quality. Positive correlations among germination, seedling length, dry matter content, and seed volume emphasized their reliability as physiological markers of seed quality. The findings highlight the importance of integrating agronomic and physiological parameters in soybean breeding programs to develop high-yielding, robust genotypes with superior seed quality suitable for storage and tropical field conditions.

Keywords: Soybean, Seed quality, Germination, Seed vigor, Trait association etc.

Introduction

Soybean [Glycine max (L.) Merrill (2n=40)] belongs to the family Leguminosae, subfamily Papilionoideae, the tribe Phaseoleae, and the subtribe Glycininea, with a genome size of approximately 1100 Mb (Walling et al., 2006). The genus Glycine is divided into two subgenera: Glycine and Soja. The subgenus Soja includes two species, Glycine max (cultivated) and Glycine soja (wild), whereas the subgenus Glycine consists of 25 wild perennial species (Hymowitz, 1995). Cytological, morphological, and molecular evidence suggests that G. soja is

the progenitor of G. max (Hymowitz, 1970).

Soybean originated in northern and central China, domesticated around the 11th century B.C., and subsequently spread to southern China, Korea, Japan, and Southeast Asia. India initiated research programs on soybean in the 1960s at Jawaharlal Nehru Krishi Vishwa Vidyalaya, Jabalpur (Madhya Pradesh), and Pantnagar in collaboration with the University of Illinois, USA, under the PL 480 project. On 1st April 1967, the Indian Council of Agricultural Research (ICAR) launched the All-India Coordinated Research Project on Soybean, with major centers at Jabalpur, Pantnagar, and Delhi, along with several sub- centers across the country (Singh, 2004). The contributions of Jabalpur have played a crucial role in making soybean one of India's most important oilseed crops.

Soybean is often regarded as a "miracle crop" due to its exceptional nutritional profile. It contains approximately 40% high-quality protein, 29% carbohydrates, and 20% oil. Its oil is composed of 85% unsaturated, cholesterol-free fatty acids with essential nutrients (Aditya et al., 2011).

The leading soybean-producing countries include the United States, Brazil, Argentina, and China (SoyStats, 2023), along with India. According to the most recent data from the Solvent Extractors' Association of India (SEA) and the Soybean Processors Association of India (SOPA, 2023), India produced approximately 13.6 million tonnes of soybean from
12.1 million hectares, with an average productivity of 1120 kg/ha. Madhya Pradesh remains the leading producer, contributing around 55% of the total national soybean output, followed by Maharashtra and Rajasthan. In Madhya Pradesh alone, soybean production reached approximately 7.5 million tonnes from 6.2 million hectares, with an average productivity of 1200 kg/ha (SOPA, 2023).

With increasing global demand for plant-based proteins and sustainable oilseeds, soybean continues to be a vital crop in food, feed, and industrial applications. Ongoing research

efforts aim to improve its yield potential, stress tolerance, and nutritional quality, ensuring its role in food security and agricultural sustainability.

Quality seed is the fundamental requirement for high productivity. The quality of sowing seed is measured by germination and vigour, which play a crucial role in the establishment of plant population and crop yield. Soybean seed has a relatively short lifespan compared to other grain crops, with germination dropping below the minimum certification standard before planting. Under cool and dry conditions, this decline occurs within 7 to 10 months, whereas under hot and moist conditions in India, it happens within 6-7 months (Khare et al., 1996). Delouche (1982) reported that almost all prevailing improved varieties inherit this deficiency. Additionally, in developing countries like India, many farmers lack proper threshing, drying, and storage facilities, which accelerates seed quality deterioration. Consequently, the non-availability of quality seed remains a major constraint in soybean cultivation, leading to significant economic losses.

Method and Materials

The experiment was carried was carried out at an agricultural farm of Faculty of Agriculture, Rabindranath Tagore University Raisan during the Kharif of 2021–22 and 2022–23 M.P. (India). Experimental material consists of 50 genotypes, obtained from All India Coordinated Research Project (AICRP) on Soybean, Department of Plant Breeding and Genetics, JNKVV, Jabalpur. The experiment was conducted in three replications under randomized complete block design.

Analysis of Variance: The data was analyzed statistically by the method described by Panse and Sukhatme (1967) to work out existing variance of observed traits (Table 1).

Table 1- Analysis of Variance

Source of variation	df	Sum of square	Mean sum of square	F value
Replication	(r-1)	RSS	RMS	RMS/ EMS
Treatment	(t-1)	TSS	TMS	TMS/ EMS
Error	(r-1)(t-1)	ESS	EMS	
Total	(rt-1)			

Where,

df = degrees of freedom

r = number of replications t = Number of treatments

EMS = Error mean sum of square ESS = Error sum of square

RMS = Replication mean sum of square RSS = Replication sum of square

TMS = Treatment mean sum of square TSS = Treatment sum of square

A significant value of F-test indicates that the test entries differ significantly among themselves, which requires for computing the critical difference (CD).

$$\text{Coefficient of variation (CV)} = \frac{\sqrt{EMS}}{G.M.} \times 100$$

Standard error of difference SE (d) = $\sqrt{\frac{2EMS}{r}}$

Critical difference (CD) = $t_{(0.01)} \times S.em_{(d)}$ Where,

G.M. = General mean

$t_{(0.01)}$ = t-value at 1% probability level r = number of replication

Result and Discussion Association analysis:

Association coefficients among observed traits were calculated at genotypic and phenotypic level (Table 3).

1. **Days to 50% flowering:** Days to 50% flowering had positive and significant association with days to maturity (0.425), number of pods per plant (0.414), pod length (0.387), seeds per pod (0.371), seed yield per plant (0.316), number of primary branches (0.312) and plant height (0.296). Whereas, it had significant negative association with hydration coefficient (-0.275) and dry matter content (-0.221).

2. Days to maturity: Days to maturity had positive and significant association with days from flowering to maturity (0.871), seed yield per plant (0.569), plant height (0.518), days to 50% flowering (0.425), germination percentage (0.344), seed vigour index –II (0.334), seedling length (0.282), seed volume (0.269) and number of primary branches (0.257). Whereas, it had significant negative association with pod length (-0.493), swelling coefficient (-0.396) and electrical conductivity (-0.285).

3. Days from flowering to maturity: Days from flowering to maturity had positive and significant association with days to maturity (0.871), number of pods per plant (0.475), seed yield per plant (0.456), plant height (0.410), seed vigour index-II (0.387), seed volume (0.332), germination percentage (0.326), seedling length (0.304), dry matter content (0.304) and 100 seed weight (0.228). The association was significant and negative with pod length (-0.333), swelling coefficient (-0.324) and electrical conductivity (-0.313).

4. Number of primary branches: Number of primary branches had positive and significant association with seed yield per plant (0.458), plant height (0.383), days to 50% flowering (0.312), germination percentage (0.285), seed vigour index-II (0.279), days to maturity (0.257), seedling length (0.254) and seed volume (0.219). The association was significant and negative with electrical conductivity (-0.380) and hull percentage (-0.216).

Table 3 Estimates of phenotypic and genotypic association among observed agronomical and physiological traits in soybean

Characters		Days to maturity	Flowering to maturity	Primary branch	Plant height	Pod/ Plant	Pod length	Seed/ Pod	Seed yield/plant	100 seed wt.	Seed coat thickness	Seed volume	Relative density	Hydration coefficient	Swelling coefficient	Seed coat cracking	Hull %	Germ%	Seedling length	Dry matter	vigor index -II	EC(µs)
Days to 50% flowering	G	0.466	0.004	0.455	0.360	0.448	0.473	0.211	0.344	0.007	0.071	-0.072	0.136	-0.324	-0.242	-0.155	-0.182	0.101	0.011	-0.253	-0.038	-0.003
	P	0.425*	-0.073	0.312*	0.296*	0.414*	0.387*	0.371*	0.316*	-0.010	0.078	-0.063	0.075	-0.275*	0.206	-0.130	-0.138	-0.096	0.012	-0.221*	-0.035	-0.001
Days to maturity	G	1.000	0.886	0.377	0.583	0.666	-0.605	-.0128	0.587	0.236	-0.004	0.288	-0.056	-0.169	-0.411	0.103	-0.088	0.353	0.321	0.211	0.358	-0.290
	P	1.000	0.871**	0.257*	0.518**	0.635	-0.493*	-0.100	0.569**	0.202	-0.0280	0.269*	-0.061	-0.156	-0.396*	0.099	-0.051	0.344*	0.282*	0.167	0.334*	-0.285*
Flowering - maturity	G		1.000	0.188	0.471	0.518	-0.437	-0.034	0.484	0.263	-0.042	0.363	-0.135	-0.022	-0.338	0.198	-0.005	0.346	0.356	0.371	0.425	-0.326
	P		1.000	0.113	0.410*	0.475*	-0.333*	-0.017	0.456*	0.228*	-0.074	0.332*	-0.108	-0.023	-0.324*	0.180	0.018	0.326*	0.304*	0.304*	0.387**	-0.313*
Primary branches	G			1.000	0.572	0.649	-0.363	0.002	0.614	0.24	0.181	0.291	-0.052	-0.131	-0.154	0.109	-0.294	0.377	0.380	0.274	0.375	-0.511
	P			1.000	0.383*	0.494	-0.203	0.038	0.458*	0.170	0.129	0.219*	-0.080	-0.128	-0.114	0.074	-0.216*	0.285*	0.254*	0.190	0.279**	-0.380*
Plant height	G				1.000	0.677	-0.554	0.268	0.793	0.472	-0.059	0.458	0.017	-0.213	-0.386	0.154	-0.357	0.668	0.591	0.411	0.667	-0.621
	P				1.000	0.592**	-0.423*	0.189	0.713**	0.391*	-0.023	0.386*	0.012	-0.163	-0.328*	0.137	-0.230*	0.608**	0.501**	0.314*	0.585**	-0.565**
Pods/plant	G					1.000	-0.641	-0.020	0.852	0.253	-0.097	0.309	-0.066	0.117	-0.382	0.087	-0.301	0.537	0.494	0.227	0.460	-0.423
	P					1.000	-0.508**	-0.305*	0.839**	-0.219*	-0.058	-0.280*	-0.061	-0.103	-0.350*	-0.079	-0.242*	0.520**	0.415*	0.203	0.437*	-0.411*
Pod length	G						1.000	0.175	-0.534	-0.033	-0.133	-0.118	0.168	-0.048	0.266	-0.035	0.101	-0.448	-0.262	-0.099	-0.344	0.186
	P						1.0000	0.287*	0.342*	-0.022	-0.113	-0.095	0.112	-0.049	0.201	-0.033	0.053	-0.370*	-0.215*	-0.048	-0.270*	0.160

Seeds/pod	G							1.000	0.375*	0.091	0.061	-0.115	0.193	-0.234	0.224	0.165	0.066	0.296	0.204	0.040	0.254	-0.375
	P							1.000	0.136	0.070	-0.018	-0.077	0.177	-0.018	0.174	0.101	-0.027	0.216*	0.106	0.049	0.188	-0.270*
Seed yield/plant	G								1.000	0.469	-0.050	0.468	-0.011	-0.079	-0.416	0.184	-0.296	0.595	0.428	0.407	0.597	-0.483
	P								1.000	0.425*	-0.034	0.439*	-0.013	-0.076	-0.386**	0.176	-0.243*	0.591**	0.389*	0.367*	0.580**	-0.476*
100 seed wt.	G									1.000	-0.024	0.778	0.406	-0.305	-0.255	0.176	-0.692	0.389	0.282	0.665	0.589	0.379
	P									1.000	-0.043	0.682**	0.459*	-0.306*	-0.235*	0.162	-0.652**	0.363*	0.226**	0.536**	0.529**	0.352*
Seed coat thickness(mm)	G										1.000	0.036	-0.047	0.251	-0.306	-0.275	0.422	0.028	-0.205	-0.110	-0.029	-0.080
	P										1.000	-0.013	-0.033	-0.444*	-0.356*	-0.353*	0.343*	0.319*	-0.134	-0.087	0.325*	-0.363*
Seed volume (mm^3)	G											1.000	-0.246	-0.022	-0.545	0.161	-0.359	0.418	0.280	0.595	0.559	0.332
	P											1.000	-0.287*	-0.028	-0.548**	0.149	-0.281*	0.395*	0.258**	0.524**	0.526**	0.363*
Relative density	G												1.000	-0.403	0.411	-0.012	-0.515	-0.071	0.038	0.174	0.056	-0.225
	P												1.000	-0.328*	0.351*	-0.002	-0.523**	-0.059	-0.022	0.084	0.021	-0.412*
Hydration coefficient	G													1.000	0.198	0.024	0.407	0.032	-0.135	0.024	0.011	0.206
	P													1.000	0.187	0.029	0.330*	0.027	-0.097	0.029	-0.317*	0.364*
Swelling coefficient	G														1.000	-0.099	0.005	-0.255	-0.196	-0.223	-0.265	0.137
	P														1.000	-0.099	0.015	-0.243	-0.172	-0.193	-0.249*	0.431*
Seed coat cracking %	G															1.000	-0.387	0.376	0.156	0.148	0.339	0.316
	P															1.000	-0.575**	-0.371*	-0.353*	-0.341*	-0.334**	0.311*
Hull%	G																1.000	-0.355	-0.248	-0.273	-0.378	0.231
	P																1.000	-0.290*	-0.160	-0.219*	-0.310*	0.186

Germination %	G																1.000	0.514	0.417	0.893	-0.719
	P																1.000	0.472*	0.373*	0.874**	-0.713**
Seedling length(cm)	G																	1.000	0.224	0.429	-0.560
	P																	1.000	0.210*	0.405*	-0.516**
Dry matter content(gm)	G																		1.000	0.774	-0.562
	P																		1.000	0.763**	-0.507**
Seed vigor index-II	G																			1.000	-0.761
	P																			1.000	-0.743**

Significant at 5% and** significant at 1%

5. Plant height: Plant height had positive and significant association with seed yield per plant (0.713), germination percentage (0.608), number of pods per plant (0.592), seed vigor index –II (0.585), days to maturity (0.518), seedling length (0.501), days from flowering to maturity (0.410), 100 seed weight (0.391), seed volume (0.386), number of primary branches (0.383), dry matter content (0.314), days to 50% flowering (0.296) and. The association was significant and negative with electrical conductivity (-0.565), pod length (-0.423), swelling coefficient (-0.328) and hull percentage (-0.230).

6. Number of pods per plant: Number of pods per plant had positive and significant association with seed yield per plant (0.839), plant height (0.592), germination percentage (0.520), days from flowering to maturity (0.475), seed vigor index –II (0.437), seedling length (0.415) and days to 50% flowering (0.414). The association was significant and negative with pod length (-0.508), electrical conductivity (-0.411), swelling coefficient (-0.350), seeds per pod (-0.305), seed volume (-0.280), hull percentage (-0.242) and 100 seed weight (-0.219).

7. Pod length: Pod length had positive and significant association with days to 50% flowering (0.387), seed yield per plant (0.342) and seeds per pod (0.287). The association was significant and negative with number of pods per plant (-0.508), days to maturity (- 0.493), seed yield per plant (-0.442), plant height (-0.423), germination percentage (- 0.370), days from flowering to maturity (-0.333), seed vigor index –II (-0.270) and seedling length (-0.215).

8. Seeds per pod: Seeds per pod had positive and significant association with days to 50% flowering (0.371), pod length (0.287) and germination percentage (0.216). The association was significant and negative with number of pods per plant (-0.305) and electrical conductivity (-0.270).

9. Seed yield per plant: Seed yield per plant had positive and significant association with number of pods per plant (0.839), plant height (0.713), germination percentage (0.591), seed vigor index –II (0.580), days to maturity (0.569), number of primary branches (0.458), days from flowering to maturity (0.456), seed volume (0.439), 100 seed weight (0.425), seedling length (0.389), dry matter content (0.367), pod length (0.342) and days to 50% flowering (0.316). The association was significant and negative with electrical conductivity (-0.476), swelling coefficient (-0.386) and hull percentage (-0.243).

10. 100 seed weight: Hundred seed weight had positive and significant association with seed volume (0.682), dry matter content (0.536), seed vigor index –II (0.529), relative density (0.459), seed yield per plant (0.425), plant height (0.391), germination percentage (0.363), electrical conductivity (0.352), days from flowering to maturity (0.228) and seedling length (0.226). The association was significant and negative with hull percentage (-0.652), hydration coefficient (-0.306), swelling coefficient (-0.235) and number of pods per plant (-0.219).

11. Seed coat thickness: Seed coat thickness had positive and significant association with hull percentage (0.343) and germination percentage (0.319). The association was significant and negative with hydration coefficient (-0.444), electrical conductivity (- 0.363), swelling coefficient (-0.356), and seed coat cracking (-0.353).

12. Seed volume: Seed volume had positive and significant association with 100 seed weight (0.682), seed vigor index-II (0.526), dry matter content (0.524), seed yield per plant (0.439), germination percentage (0.395), plant height (0.386), electrical conductivity (0.363), days from flowering to maturity (0.332), days to maturity (0.269), seedling length (0.258) and number of primary branches (0.219). The association was significant and negative with swelling coefficient (-0.548), electrical conductivity (-0.352), relative density (-0.287), hull percentage (-0.281) and number of pods per plant (-0.280).

13. Relative density: Relative density had positive and significant association with 100 seed weight (0.459) and swelling coefficient (0.351). The association was significant and negative with hull percentage (-0.523), electrical conductivity (-0.412), hydration coefficient (-0.328) and seed volume (-0.287).

14. Hydration coefficient: Hydration coefficient had positive and significant association with electrical conductivity (0.364) and hull percentage (0.330). Whereas significant negative association was recorded with seed coat thickness (-0.444), relative density (-0.328), seed vigour index-II (-0.317), 100 seed weight (-0.306) and days to 50% flowering

(-0.275).

15. Swelling coefficient: Swelling coefficient had positive and significant association with electrical conductivity (0.431) and relative density (0.351). The association was significant and negative with seed volume (-0.548), days to maturity (-0.396), seed yield per plant (- 0.386), seed coat thickness (-0.356), relative density (-0.351), number of pods per plant (- 0.350), plant height (-0.328), days from flowering to maturity (-0.324), seed vigor index- II (-0.249) and 100 seed weight (-0.235).

16. Seed coat cracking percentage: Seed coat cracking percentage had positive and significant association with electrical conductivity (0.311). The association was significant and negative with hull percentage (-0.575), germination percentage (-0.371), seed coat thickness (-0.353), seedling length (-0.353), dry matter content (-0.341) and seed vigour index-II (-0.334).

17. Hull percentage: Hull percentage had positive and significant association with hydration coefficient (0.331). Whereas the association was significant and negative with 100 seed weight (-0.652), seed coat cracking percentage (-0.575), relative density (-0.523), seed vigor index-II (-0.310), germination percentage (-0.290), seed volume (-0.281), seed yield per plant (-0.243), number of pods per plant (-0.242), plant height (-0.230), dry matter content (-0.219) and number of primary branches (-0.216).

18. Germination percentage: Germination percentage had positive and significant association with seed

vigor index-II (0.874), plant height (0.608), seed yield per plant (0.591), number of pods per plant (0.520), seedling length (0.472), seed volume (0.395), dry matter content (0.373), 100 seed weight (0.363), days to maturity (0.344), days from flowering to maturity (0.326), seed coat thickness (0.319), number of primary branches (0.285) and seeds per pod (0.216). The association was significant and negative with electrical conductivity (-0.713), seed coat cracking percentage (-0.371), pod length (-0.370) and hull percentage (-0.290).

19. Seedling length: Seedling length had positive and significant association with plant height (0.501), germination percentage (0.472), number of pods per plant (0.415), seed vigor index-II (0.405), seed yield per plant (0.389), days from flowering to maturity (0.304), days to maturity (0.282), seed volume (0.258), number of primary branches (0.254), 100 seed weight (0.226) and dry matter content (0.210). The association was significant and negative with electrical conductivity (-0.516), seed coat cracking percentage (-0.353) and pod length (-0.215).

20. Dry matter content: Dry matter content had positive and significant association with seed vigor index-II (0.763), 100 seed weight (0.536), seed volume (0.524), germination percentage (0.373), seed yield per plant (0.367), plant height (0.314), days from flowering to maturity (0.304), days from flowering to maturity (0.304), and seedling length (0.210). The association was significant and negative with electrical conductivity (-0.507), seed coat cracking percentage (-0.341), days to 50% flowering (-0.221) and hull percentage (- 0.219).

21. Seed vigour index-II: Seed vigour index-II had positive and significant association with germination percentage (0.874), dry matter content (0.763), plant height (0.585), seed yield per plant (0.580), 100 seed weight (0.529), seed volume (0.526), number of pods per plant (0.437), seedling length (0.405), days from flowering to maturity (0.387), days to maturity (0.334), seed coat thickness (0.325) and number of primary branches (0.279). The association was significant and negative with seed coat cracking percentage (-0.334), hydration coefficient (-0.317), hull percentage (-0.310), pod length (-0.270) and swelling coefficient (-0.249).

22. Electrical conductivity: Electrical conductivity had positive and significant association with swelling coefficient (0.431), hydration coefficient (0.364), seed volume (0.363), 100 seed weight (0.352) and seed coat cracking percentage (0.311). The association was significant and negative with germination percentage (-0.743), seed vigor index-II (-0.703), plant height (-0.565), seedling length (-0.516), dry matter content (- 0.507), seed yield per plant (-0.476), relative density (-0.412), number of pods per plant (- 0.411), number of primary branches (-0.380), seed coat thickness (-0.363), days from flowering to maturity (-0.313), days to maturity (-0.285) and seeds per pod (-0.270).

Conclusion

The investigation aimed to determine the associations among various morphological, physiological, and biochemical traits influencing sowing seed quality in soybean. The experiment, conducted with 50 genotypes over two kharif seasons, revealed substantial genetic variability among traits, providing valuable insights for soybean improvement programs.

The correlation and path coefficient analyses indicated that seed yield per plant was significantly and positively associated with number of pods per plant, plant height, germination percentage, seed vigor index-II, and 100 seed

weight. These traits emerged as vital determinants of both productivity and seed quality. This means that selection for these traits can lead to simultaneous improvement in seed yield and sowing quality.

Further, days to 50% flowering and days to maturity were positively correlated with seed yield and vigor-related parameters. This indicates that a longer vegetative and reproductive phase contributes positively to seed development and viability. However, traits such as hydration coefficient, electrical conductivity, and hull percentage showed negative associations with seed quality indicators like germination and seed vigor index, highlighting their detrimental impact on physiological seed health.

Notably, electrical conductivity was significantly and negatively associated with a wide array of important traits such as germination percentage, seed vigor, plant height, seedling length, seed yield, and dry matter content, implying its strong role as an indicator of seed deterioration. Higher electrical conductivity values reflect membrane leakage and reduced seed viability, making it a crucial screening parameter in seed testing.

In addition, swelling coefficient, hydration coefficient, and seed coat cracking percentage were also significantly associated with negative physiological outcomes, further emphasizing the role of seed coat integrity in maintaining seed quality. Seed coat thickness and relative density, though less influential, contributed moderately to seed viability and should be considered in combination with other traits.

The positive correlations among germination percentage, seedling length, seed vigor index, and seed volume further confirmed their role as reliable indicators of seed quality. Dry matter content was significantly correlated with seed vigor, 100 seed weight, and seed yieldper plant, suggesting that high reserve accumulation during seed development directly influences seedling establishment and crop performance.

Overall, the study underscores the importance of integrating both agronomic and physiological traits in selection indices for soybean breeding. Traits like plant height, pods per plant, 100 seed weight, and germination percentage are key contributors to superior seed yield and quality. On the contrary, traits such as high electrical conductivity, swelling coefficient, and hull percentage should be minimized to enhance seed longevity and field emergence.

The findings are pivotal for soybean breeders and seed technologists aiming to develop high-yielding, physiologically robust varieties suitable for storage and field conditions in tropical regions like India. This integrated approach can contribute significantly to seed security, farm productivity, and the overall sustainability of soybean cultivation.

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