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Stability Analysis of Mungbean [*Vigna radiata* (L.) Wilczek] Genotypes under Late Sown Conditions

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Abstract

A field study was conducted to evaluate genotype × environment interaction and yield stability of 14 mungbean genotypes sown at three different late-season dates (mid-July, late July, mid-August) in a randomized block design with three replications. Agronomic traits included flowering time, maturity, plant height, primary branches, number of pods, pods per cluster, seeds per pod, 100-seed weight, seed yield, and protein content. Analysis of variance revealed highly significant effects of genotype, sowing date (environment), and their interaction for most traits. Regression-based stability analysis (Eberhart and Russell model) identified that the earliest sowing (19th July) was the most favourable environment, whereas the latest sowing (9th August) was most stressful. Genotypes IPM-604-16, Pusa M-1971 and Phule Suvarn combined high mean seed yield with regression coefficients near unity and low deviation from regression, indicating broad adaptation and stability across environments. No genotype was simultaneously stable for all traits. These results highlight promising mungbean lines for late-sown cultivation and the importance of G x E analysis in breeding. The identified stable genotypes merit further multi-location testing to confirm their suitability for cultivation under delayed sowing.

Key words : Mungbean, genotype x environment interaction, yield stability, Eberhart and Russell model, delayed sowing.

Mungbean (*Vigna radiata*), also called green gram or moong, is an important short-duration pulse crop in asian agriculture. It matures in about 60 days and can yield over 2.4 t ha^{-1} under optimal conditions (Singh and Singh, 1992). Due to its short growth period, low water requirement and ability to enhance soil fertility through nitrogen fixation, it plays a crucial role in sustainable agriculture (Pandey and Gopalakrishnan, 2021). Its high digestibility and low flatulence potential also make it a preferred dietary component (Dahiya *et al*., 2013; USDA, 2020).

In Indian cuisine, green gram is used in wide range of traditional dishes. It is consumed as dal primarily, sprouted for salads, or its flour is used for making dosa and other preparations. Popular dishes like moong dal khichdi, pesarattu and kosambari highlight its versatility in different regional cuisines. Due to its high demand in both domestic and international markets, green gram cultivation offers economic advantages to farmers, contributing to rural livelihoods.

The average production of mungbean is 721 kg ha^{-1}, and there are around 7.3 million hectares planted worldwide. 30% of the 5.3 million tonnes of production produced globally is split between India and Myanmar. Other significant producers are China, Indonesia, Thailand, Kenya, and Tanzania. Mungbean alone accounts for 10% of production and 16% of area for all pulses (Nair and Schreinemachers, 2020).

Adaptability of genotypes to environmental fluctuations is important for stabilization of crop production both temporally and spatially. Assessment of phenotypic stability which entails regression analysis has become a beneficial drive in the estimation of varietal adaptability. Stability analysis is useful in the identification of adaptable genotypes and in predicting the responses of various genotypes over changing environments. It is generally agreed that the more stable genotypes adjust their phenotypic responses to provide some measure of uniformity in spite of environmental fluctuations (Basford and Cooper, 1998).

Late sowing is a critical agronomic factor that can drastically reduce crop yields across various species and environments. The primary reasons for yield losses associated with delayed sowing conditions include shortened growing periods, reduced thermal time accumulation, and increased exposure to terminal heat stress during sensitive growth stages. A comprehensive global meta-analysis revealed that late sowing significantly decreased plant biomass by approximately 21% and yield by about 24% compared to normal sowing dates. These reductions were especially evident when sowing was delayed by more than three weeks and when average minimum temperatures during the growing season exceeded 13°C. (Dadrasi *et al*., 2024).

Climate variability and erratic monsoon often delay sowing of *Kharif* crops. Late-season planting exposes mungbean to higher temperatures and shorter rainy periods, which can reduce growth duration and yield. Under such stress, genotypic differences and genotype-by-environment (G x E) interactions critically influence performance. Genotype x environment interaction complicates selection of broadly adapted varieties. Stability analysis methods, such as the regression method of Eberhart and Russell (1966) are widely used to quantify how genotypes perform across diverse environments. These methods help distinguish broadly adapted genotypes (stable yield across environments) from those suited to specific conditions. Previous stability analyses in mungbean and related pulses have demonstrated the utility of this approach (Kumar *et al*. 2024; Arunkumar and Konda 2014).

This study focuses on mungbean genotypes under late-sown conditions. The objectives of this research were to analyze genotype × environment interaction and estimate stability parameters for yield and yield-related traits; and to identify high-yielding genotypes with stable performance under late-sown conditions. This information can guide breeder for selection of late-season mungbean genotypes.

Material and Methods

A field experiment was carried out during the 2024 *Kharif* season at the Agriculture Botany Research Farm, Mahatma Phule Krishi Vidyapeeth, Rahuri, India. Three late-sowing dates were imposed: 19th July (Environment E1), 29th July (E2), and 9th August (E3). Fourteen mungbean genotypes (including three released varieties) were evaluated in each environment. The experiment laid out in randomized block design with three replications. Each plot (1.20 m x 3.00 m) consisted of four rows with 30 cm x 10 cm spacing. All plots received standard agronomic management and recommended fertilization.

From each plot, data were recorded for ten traits *viz*. days to 50% flowering, days to maturity, plant height, number of primary branches plant^{-1}, number of pods plant^{-1}, number of seeds pod^{-1}, number of pods cluster^{-1}, 100-seed weight, seed yield plant^{-1}, and grain protein content. Protein content was estimated from dried seed samples using standard methods.

The data were subjected to pooled analysis of variance (ANOVA) to test the effects of genotype (G), environment (E), and G x E interaction for each trait. For stability analysis of yield per plant, we applied the regression method of Eberhart and Russell. For stability analysis, the regression method given by Eberhart and Russell was applied. The mean seed yield of each genotype across environments was regressed on the environmental index (mean yield of all genotypes in that environment). All statistical computations were performed using the window-stat software.

Results and Discussion

Pooled analysis of variance showed highly significant differences among environments and among genotypes for the majority of the traits, as shown in Table 1. Importantly, the G x E interaction mean square was highly significant for most characters, indicating considerable differential response of genotypes to the three sowing dates. The significance of the environmental (linear) component for all traits implies substantial differences among the sowing environments in their effect on crop performance. In general, the earliest sowing (July 19th) yielded the highest grain, while the latest sowing (August 9th) had the lowest yields and lowest mean values for yield components. Such marked environmental effects on yield components have been noted in previous mungbean studies, confirming that environment and G x E must be considered in breeding.

Estimates of environmental indices (Ij) for different characters of mungbean across three environments (E_1, E_2, E^3) are presented in Table 1. The data revealed that environment E_1 (19th July) was favourable for days to 50% flowering (-0.71), days to maturity (-1.02), plant height (5.55), number of pods plant^{-1} (3.79), number of seeds pod^{-1} (0.22), number of primary branches plant^{-1} (0.26), number of pods cluster^{-1} (0.28), 100 seed weight (0.08), seed yield plant^{-1} (1.48), and protein content (0.25). Environment E_2 (29th July) and Environment E_3 (9th August) did not show favourability for any traits based on the indices provided. It indicated that as the date of sowing increased, the yield and yield contributing characters showed drastic reduction in their magnitude.

The stability analysis using the Eberhart and Russell (1966) model identified genotypes with broad adaptability, specific adaptability to favourable or unfavourable environments, and those lacking stability. Genotypes IPM-604-16, Pusa M-1971, and Phule Suvarn consistently recorded high mean seed yields, regression coefficients (bi) near unity, and non-significant deviations from regression (S^2di), indicating average stability and wide adaptability across late-sown environments.

Phule Suvarn demonstrated stability for multiple traits including days to 50% flowering, days to maturity, plant height, number of pods cluster^{-1}, seed yield plant^{-1}, and protein content. Similarly, Pusa-9531 showed average stability for traits such as flowering, maturity, number of pods plant^{-1}, seeds pod^{-1}, pods cluster^{-1}, primary branches, and 100-seed weight. Pusa M-1971 exhibited consistent performance for plant height, pods per plant, seeds per pod, and seed yield.

Genotypes such as TPMD-601-7 and Pusa BM-09 showed bi< 1 for certain traits, indicating

Table 1. Estimates of Environmental index of three environments for ten characters of mungbean

Characters	Environmental Index (Ij)		
	E_1	E_2	E_3
Days to 50% flowering	-0.71	0.20	0.51
Days to maturity	-1.02	-0.11	1.13
Plant height (cm)	5.55	0.63	-6.18
No. of pods plant^{-1}	3.79	-0.96	-2.83
No. of seed pod^{-1}	0.17	-0.01	-0.16
No.of Primary branches plant^{-1}	0.26	-0.05	-0.21
No. of pods cluster^{-1}	0.28	-0.07	-0.21
100 seed weight (g)	0.08	0.00	-0.08
Seed yield plant^{-1} (g)	1.48	-0.36	-1.12
Protein content (%)	0.25	0.03	-0.28

better performance under stress. TPMD-601-7 was stable under poor conditions for number of pods per cluster and primary branches, while Pusa BM-09 demonstrated above-average stability for flowering. These lines are potentially valuable for resource-limited or stress-prone environments.

On the other hand, genotypes like IPM-1604-1, Pusa BM-3, and Pusa M-1971 exhibited bi> 1 for days to 50% flowering, reflecting sensitivity and better performance under favourable environments. Phule Chetak and Pusa-9531 also showed higher seed yield under favorable conditions, suggesting specific

Table 2. Stability ANOVA for ten yield and yield contributing characters of fourteen mungbean genotypes

Character	Genotypes	Environ-ments	Env.+ (G x E)	Gen. x Env.	Env. (L)	G x E (L)	Pooled Dev.	Pooled error
DF	**13**	**2**	**28**	**26**	**1**	**13**	**14**	**78**
Days to 50% flowering	1.233##+**	5.574##++**	0.783**	0.415**	11.148++**	0.355	0.440*	0.203
Days to maturity	8.115##++**	16.201##++**	1.447##++**	0.312**	32.402++**	0.348**	0.257*	0.130
Plant height (cm)	13.848##++**	486.359##++**	38.688##++**	4.252**	972.717++**	4.286**	3.917**	0.380
No. of pods plant^{-1}	3.513**	162.740##++**	13.570##++**	2.095**	325.480++**	1.419*	2.574**	0.758
No. of seed pod^{-1}	2.277##++**	0.385##++**	0.064+**	0.039**	0.770+**	0.051**	0.025**	0.010
No. of primary branches	0.042**	0.812##++**	0.081##++**	0.025**	1.624+**	0.025**	0.023**	0.005
No. of pods cluster^{-1}	0.018**	0.921##++**	0.082##++**	0.017**	1.843+**	0.015**	0.018**	0.005
100 seed weight (g)	0.468##++**	0.089##++**	0.020**	0.017**	0.178++**	0.020**	0.013**	0.005
Seed yield plant^{-1} (g)	0.573#+*	25.101##++**	1.987##++**	0.209**	50.202++**	0.127*	0.270**	0.059
Protein content (%)	17.681##++**	1.005##++**	0.113##++**	0.045**	2.010++**	0.057**	0.030*	0.015

#, ## significant at 5 and 1% level of significance when tested at G x E
+, ++ significant at 5 and 1% level of significance when tested at pooled deviation
*,** significant at 5 and 1% level of significance when tested at pooled error

Table 3. Stability parameters of mungbean for days to 50% flowering, days to maturity and plant height (cm)

Genotype	Days to 50% flowering			Days to maturity			Plant height (cm)		
	Mean	**bi**	**s^2di**	**Mean**	**bi**	**s^2di**	**Mean**	**bi**	**s^2di**
MJH-1703	40.56	0.67	-0.05	62.00	1.41**	-0.08	35.35	1.30**	0.18
SML-1933	40.56	0.67	-0.05	62.22	1.07	-0.05	33.87	1.10	0.92
IPM-1604-1	41.33	2.03*	0.06	64.22	1.51	0.44*	36.28	1.28	3.06**
Pusa-9531	41.11	1.74	0.13	62.67	0.93	-0.11	35.15	0.61**	-0.38
PM-1520	41.56	1.69	-0.18	62.11	0.60	0.00	37.11	0.75	-0.25
Pusa-BM-9	41.33	0.51**	-0.19	64.56	1.20	0.38	36.60	1.24	1.68*
TPMD-601-7	42.44	0.08**	-0.13	64.22	0.94	-0.11	38.00	0.94	-0.25
BM-2003-2	42.11	0.47	1.03*	66.33	0.53	1.21**	35.59	0.90	3.49**
Pusa-BM-3	41.33	2.03*	0.06	64.56	0.63**	-0.09	36.20	0.90	0.28
IPM-604-16	41.33	1.01	1.88**	66.00	0.44*	0.09	33.39	0.93	-0.22
Pusa-M-1971	40.78	1.10**	-0.20	61.78	1.58**	-0.02	39.75	0.77	3.35
Phule Chetak	42.33	0.26	0.63*	66.22	1.07	-0.05	35.15	0.90**	-0.36
Phule Suvarn	40.44	1.35	0.42	63.44	0.65	0.08	36.33	0.89	0.16
Virat	41.00	0.38	-0.09	62.22	1.43	0.11	30.68	1.50	37.86**

*,** significant at 5 and 1% level of significance, respectively

adaptation. MJH-1703 and SML-1933 demonstrated below-average stability for protein content, indicating that their protein performance was more environment-dependent.

Protein content showed significant variability, ranging from 17.49% to 24.30% with a population mean of 21.45%. Genotypes PM-1520 (23.89%), Pusa BM-9 (23.83%), and Phule Suvarn (23.52%) exhibiting high protein

Table 4. Stability parameters of mungbean for no. of pods plant^{-1}, no. of seeds pod^{-1} and no. of primary branches

Genotype	No. of pods plant^{-1}			No. of seeds pod^{-1}			No. of primary branches		
	Mean	bi	s^2di	Mean	bi	s^2di	Mean	bi	s^2di
MJH-1703	13.22	1.14	5.23**	8.57	2.25*	0.007	3.23	1.64	0.046**
SML-1933	10.62	1.19	1.24	9.23	0.91	-0.009	3.06	1.73**	0.002
IPM-1604-1	11.82	1.09	1.90	10.58	-0.70	0.108**	3.12	1.56	0.050**
Pusa-9531	12.32	0.96	-0.71	10.39	1.48	0.003	3.20	0.81	0.000
PM-1520	12.61	0.78	15.55**	8.33	1.23	-0.006	3.20	0.40	0.116**
Pusa-BM-9	11.29	1.18	0.52	9.31	-0.03*	0.002	3.09	1.10	0.002
TPMD-601-7	12.53	1.15**	-0.74	9.23	0.42*	-0.004	3.17	0.72*	-0.004
BM-2003-2	10.32	0.37	2.53*	8.54	1.62**	-0.009	3.07	0.37*	0.006
Pusa-BM-3	13.27	0.89	-0.15	8.96	2.44**	-0.005	3.27	0.68	0.002
IPM-604-16	11.38	0.79	0.20	10.77	2.49	0.074**	3.12	1.01	0.001
Pusa-M-1971	12.87	0.87	0.55	9.62	0.34	0.011	3.30	0.49	0.013
Phule Chetak	9.81	1.19**	-0.70	10.34	0.51**	-0.010	2.82	1.47**	-0.005
Phule Suvarn	11.67	1.07	-0.14	8.56	0.63	0.062**	3.21	1.25**	-0.005
Virat	12.53	1.34	0.14	8.30	0.40**	-0.010	3.18	0.76	0.020*

*,** significant at 5 and 1 % level of significance, respectively

Table 5. Stability parameters of mungbean for no. of pods cluster^{-1}, 100 seed weight, yield plant^{-1} and protein content

Genotype	No. of pods cluster^{-1}			100 seed weight			Seed yield plant^{-1}			Protein content		
	Mean	bi	s^2di	Mean	bi	s^2di	Mean	bi	s^2di	Mean	bi	s^2di
MJH-1703	3.16	1.06	0.007	3.97	1.26	0.001	4.68	1.21	0.287*	23.11	2.34**	0.005
SML-1933	3.04	1.26**	-0.005	3.86	1.67**	-0.005	3.83	1.20	0.212*	23.86	1.18*	-0.014
IPM-1604-1	2.99	0.97	0.016*	3.43	0.62	0.010	4.40	1.01	0.556**	18.50	1.09	0.000
Pusa-9531	3.18	1.03	0.012	3.68	1.26	-0.003	4.79	1.12**	-0.059	19.84	1.37**	-0.015
PM-1520	3.17	1.12	0.125**	3.72	2.50	-0.002	3.94	0.85	1.444*	23.89	0.07	0.023
Pusa-BM-9	2.99	0.77*	-0.003	3.13	0.61	0.036**	3.31	0.87*	-0.042	23.83	1.04	-0.009
TPMD-601-7	3.11	0.76**	-0.004	3.13	-0.01	0.001	3.58	0.86**	-0.059	22.18	1.17	-0.012
BM-2003-2	3.11	1.08	0.002	4.36	1.89	0.016*	3.90	0.55	0.365**	19.53	0.46*	-0.004
Pusa-BM-3	3.16	0.40**	-0.005	3.34	3.57	0.025*	4.09	1.11	0.164	19.63	0.54	0.006
IPM-604-16	3.12	0.72	0.010	3.76	0.21**	-0.005	4.66	0.96	0.054	17.49	0.69	0.032
Pusa-M-1971	3.21	0.60	0.003	3.57	0.62	-0.004	4.47	0.87	0.115	18.43	0.45	0.018
Phule Chetak	2.97	1.77*	0.013	4.22	-1.46**	-0.005	4.13	1.16**	-0.058	24.30	2.12*	0.028
Phule Suvarn	3.06	1.28	0.003	4.24	-0.20	0.026*	4.28	1.01	0.004	23.52	0.75	0.039
Virat	3.06	1.19	0.010	3.43	1.45	0.010	3.79	1.22*	-0.029	22.12	0.72	0.112**

*,** significant at 5 and 1 % level of significance, respectively

levels coupled with stable performance.

The linear component of G x E interaction (bi) was significant for almost all traits, while the non-linear (deviation) component (S^2di) was also significant, showing complex responses among genotypes under stress. The earlier workers, Imrie and Butler (1982), Pathak *et al*., (1990), Gupta *et al*., (1991), Renganayaki (1995), Raje and Rao (2004), Abbas *et al*., (2008), Singh *et al*., (2009), Akhtar *et al*., (2010), Arunkumar and Konda (2014), Kyaw *et al*., (2018) also observed significant differences among the genotypes, environments and G x E interaction for all the characters studied in mungbean. Overall, significant G x E interaction suggests that selection for yield stability must account for environmental conditions. The genotypes identified as most stable here such as IPM-604-16, Pusa M-1971, Phule Suvarn performed better for late-sown mungbean cultivation, but they should be further tested multilocationally. These results highlight the utility of stability analysis in selecting mungbean genotypes with reliable performance under varying sowing dates.

Conclusion

Delayed sowing significantly reduced mungbean performance, with the first late-sowing date (19th July) giving substantially higher growth and yield than later dates. Genotypic differences and G x E interactions were significant for most agronomic traits. The stability analysis identified three genotypes (IPM-604-16, Pusa M-1971, Phule Suvarn) that combined high yield with average stability across all late-sown environments. Two other genotypes (Phule Chetak, Pusa-9531) performed best only under the most favourable late-sowing condition. No genotype was specifically adapted to the most stressful environment. These results suggest that breeding for late-sowing adaptation should focus on genotypes with stable performance across environments. The promising lines identified here warrant multi-location trials to confirm their adaptability before release. Overall, this study provides insights into selecting mungbean genotypes for stable yield under late-season planting, which is important for climate-resilient agriculture.

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