



Effect of Plant Spacing on Growth, Yield Components, and Yield Stability of Several Soybean (*Glycine max* L.) Varieties

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Abstract:

Background. Effect of Plant Spacing on Growth, Yield Components, and Yield Stability of Several Soybean (*Glycine max* L.) Varieties. Soybean is a strategic food commodity in Indonesia, yet domestic production meets only a small portion of national demand due to low farm-level productivity caused by suboptimal variety selection and inappropriate planting spacing, combined with differential variety responses across growing conditions.

Aims. This study aimed to evaluate the effects of planting spacing, variety, and their interaction on soybean growth, yield components, and grain yield, and to identify varieties that combine high productivity, consistent performance, and broad adaptability under different planting densities.

Methods. A field experiment was arranged in a split-plot design with three replications, using three spacing levels as main plots and four nationally released soybean varieties as subplots. Data were analyzed using analysis of variance, mean comparison tests, and multiple complementary stability and adaptability models.

Result. Results showed that plant height and 100-seed weight were determined predominantly by genetic factors, whereas number of seeds per plant and grain yield per hectare exhibited strong variety-by-spacing interactions. Grobogan recorded the highest mean yield and responded well to favorable high-density conditions; Sangga Buana combined broad adaptation with maximum yield at the closest spacing; the large-seeded Dega performed best at intermediate spacing; while Anjasmoro showed the most consistent performance across all conditions despite lower yield potential.

Conclusion. It is concluded that agronomic responses to planting spacing are strongly variety-dependent, so no single density is universally optimal for all genotypes.

Implementation. These findings provide low-cost, variety-specific spacing recommendations that can immediately raise on-farm soybean productivity, reduce the national yield gap, and support greater food self-sufficiency.

Keywords: Soybean, Plant spacing, Yield stability, Yield components, Genotype adaptability



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INTRODUCTION

Soybean (*Glycine max* L.) is one of the strategic food commodities in Indonesia that plays an important role in meeting community nutrition, as a raw material for the food

processing industry, and as animal feed. Based on data from the Central Statistics Agency (BPS) in 2024, national soybean demand reaches more than 3.5 million tons per year, but domestic production can meet only around 20% of this demand, so the rest must be met through imports. The low contribution of local production is partly caused by national soybean productivity, which is still relatively low, with an average of 1.58 tons per hectare in 2024, far below the genetic potential of superior varieties released by the government, which can reach 2.5 to 3.5 tons per hectare if cultivated in a suitable growing environment.

The low productivity of soybeans in the field cannot be separated from two main factors, namely genetic factors in the form of the use of varieties that do not follow environmental cultivation conditions, and agronomic factors in the form of the application of planting spacing that is not yet optimal. Planting spacing determines the level of competition between plants for sunlight, nutrients, water, and growing space, so that too sparse spacing causes non-optimal land use, while too dense spacing triggers excessive competition and suppresses plant growth and yield. On the other hand, each soybean variety has a different response to changes in environmental conditions, including differences in planting density, known as genotype-by-environment interaction. This means that a variety that shows high yield in one planting spacing condition does not necessarily provide the same performance at different planting spacing.

Based on these problems, the problem formulations in this study are as follows: first, whether planting spacing, varieties, and their interactions have a significant effect on the growth, yield components, and yield of soybeans; second, which of the Dega, Anjasmoro, Sangga Buana, and Grobogan soybean varieties has the best yield stability and adaptability when cultivated at various levels of planting density. This study aims to evaluate the effect of planting spacing, varieties, and their interactions on plant height, 100-seed weight, number of seeds per plant, and yield per hectare of soybeans, as well as to identify varieties that have a combination of high productivity, stability, and adaptability under various planting spacing conditions.

Operationally in this study, variations in three levels of planting spacing, namely 30×30 cm, 30×20 cm, and 30×15 cm, were set as a reflection of differences in the cultivation environment that affect the intensity of competition between plants. Yield stability is defined as the ability of a variety to show relatively consistent yield performance across all tested planting spacing conditions, while adaptability is the ability of a variety to respond to improvements in environmental conditions with a significant increase in yield. The four varieties tested are national superior varieties that have been widely cultivated by farmers in

the West Java region, so the results of the study are expected to provide specific technical cultivation recommendations following the characteristics of each variety

LITERATURE REVIEW

Soybean (*Glycine max* L.) is a strategic commodity in global and national food systems because of its high protein ($\approx 40\%$) and oil ($\approx 20\%$) content, serving as a primary raw material for food, feed, and industrial products. In Indonesia, domestic soybean production consistently falls short of national demand, creating a structural supply deficit that drives large annual imports. This gap stems partly from the large difference between the genetic yield potential of released varieties and the actual productivity achieved at the farm level, which is strongly influenced by crop management practices and the adaptation of varieties to local growing environments (Marina et al., 2023). Closing this yield gap requires agronomic strategies that match superior genotypes with appropriate cultivation technologies, as well as a clear understanding of how different varieties respond to changes in their production environment.

Considerable research has been conducted in recent years to improve soybean cultivation efficiency through better management and technology integration. At the production system level, several authors have demonstrated that soybean performance can be enhanced through optimized fertilization, intercropping design, and digital agriculture tools. For example, Harti et al. (2025) evaluated the agronomic performance of superior soybean cultivars intercropped with maize under Azolla-based liquid organic fertilization and reported significant yield responses to both cultivar choice and nutrient management. Similarly, Indriana et al. (2025) analyzed soybean–maize land-equivalent ratios across multiple soybean cultivars treated with Azolla organic fertilizer and found that cultivar selection interacted strongly with nutrient input in determining total system productivity. In terms of digital innovation, Sujadi et al. (2023) and Marina et al. (2023) showed that integrating smart monitoring systems into soybean cultivation can improve input-use efficiency, while follow-up work by Sujadi et al. (2024) and Marina et al. (2024) developed IoT-based soil-quality monitoring platforms with fuzzy-logic inference specifically for soybean systems, confirming that technology-assisted management can raise both yield and resource efficiency. Further economic assessment by Marina et al. (2025a) verified that such smart monitoring systems generate measurable economic benefits for soybean producers, supporting the view that soybean productivity is highly responsive to the quality of crop management.

Among the many management factors that shape soybean yield, planting spacing is one of the simplest, cheapest, and most controllable decisions a farmer makes, because it directly

regulates plant population per unit area and the intensity of competition among neighboring plants for light, water, nutrients, and rooting space. The importance of planting density has been well documented in other crops: Wahyudin and Marina (2024), working with lowland rice under rainfed conditions, showed that both spacing and water management significantly altered grain yield and that variety responses were not uniform across spacing treatments. Similar genotype-by-management interactions were reported by Dewi et al. (2026) for rice receiving combined amino-acid and NPK fertilizers, where growth dynamics and yield components varied among varieties under the same input regime, and by Dinar et al. (2026) for hybrid maize under integrated crop management (ICM), where the benefit of ICM packages differed across production environments. These studies collectively establish a robust principle: the same agronomic input or practice does not produce the same outcome in every genotype, because varieties differ genetically in their ability to capture and use resources.

For soybean specifically, however, the body of local research remains surprisingly narrow in two important respects. First, most existing soybean agronomy studies in West Java focus on single-factor comparisons—for instance, biofertilizer dosage (Rahma & Marina, 2023), organic fertilization in intercropping (Harti et al., 2025; Indriana et al., 2025), or technology adoption (Marina et al., 2024, 2025b)—without systematically quantifying how soybean varieties differ in their response to planting density. Second, when variety comparisons are made, they are almost always interpreted using simple mean comparisons and analysis of variance; multi-environment stability analysis is almost never applied to planting-density gradients, even though density variation is arguably the most common source of environmental heterogeneity that farmers actually manage. Indeed, a careful review of the recent soybean literature from Sumedang and surrounding districts—including Marina et al. (2023, 2024, 2025a, 2025b), Sujadi et al. (2023, 2024), Harti et al. (2025), and Indriana et al. (2025)—does not identify any published study that treats alternative planting spacings as separate test environments and then uses parametric and multivariate stability models to rank varieties for both yield performance and consistency across those environments.

This absence is methodologically important because, internationally, it is widely accepted that variety evaluation based solely on mean yield is insufficient for reliable recommendation. Genotype $\times$ environment ($G \times E$) interaction—defined as the change in relative variety performance when environments change—complicates selection because the highest-yielding variety in one environment is not necessarily the highest-yielding or most reliable elsewhere. To disentangle $G \times E$ patterns, plant breeders commonly use a sequence of complementary stability tools. The Eberhart and Russell (1966) regression approach expresses each genotype's

performance as a linear function of an environmental index, classifying varieties into broadly adapted ($b_i \approx 1$), responsive to favorable environments ($b_i > 1$), or adapted to marginal environments ($b_i < 1$). Although simple, this method captures only linear response patterns. The AMMI (Additive Main Effects and Multiplicative Interaction) model therefore complements it by combining ANOVA for additive variety and environment effects with principal-component analysis of the non-additive interaction, producing IPCA scores that visualize specific adaptation and proximity to stability (Gauch, 2013). Because AMMI does not by itself provide a single stability ranking, Purchase et al. (2000) proposed the ASV (AMMI Stability Value), which weights the IPCA axes into one composite score, while Olivoto and Lúcio (2020) further advocated the YSI (Yield Stability Index), which sums mean-yield rank and ASV rank to identify genotypes that combine high productivity with acceptable stability. Several authors, including Bocianowski et al. (2019) and Silva et al. (2022), have cautioned that relying on only one of these methods can produce misleading conclusions, and that a multi-model ensemble yields far more robust variety recommendations.

Against this background, three clear research gaps can be identified that the present study is designed to fill:

Gap 1 – Methodological gap. Almost all published soybean evaluations in the region rely on ANOVA and mean comparison only; no local study has yet deployed the full analytical pipeline of ANOVA → Eberhart–Russell → AMMI → ASV → YSI in a single integrated evaluation. The novelty here lies in using this ensemble to cross-validate stability conclusions rather than depending on a single statistical criterion.

Gap 2 – Conceptual gap. In nearly all $G \times E$ studies, “environment” is defined as different locations, seasons, or years. This study redefines environment operationally as three contrasting planting spacings (30×30 , 30×20 , 30×15 cm), which represent a gradient of intraspecific competition intensity. To our knowledge, this framing has not been used for soybean in West Java, yet it produces recommendations that are directly actionable by farmers because spacing is a management variable under their immediate control.

Gap 3 – Empirical / site-specific gap. Despite the intensive recent soybean research conducted by the Winaya Mukti University group in Sumedang Regency, there is still no publicly available stability ranking for Dega, Anjasmoro, Sangga Buana, and Grobogan under local conditions. Existing variety-release data were generated elsewhere and may not reflect performance in Sumedang’s soils and climate. This study therefore fills an evidence void that extension workers and farmer groups currently face when choosing which variety to plant and at what density.

In summary, the theoretical justification for the present work rests on three interconnected pillars: (a) the well-documented responsiveness of soybean yield to planting density and genotype; (b) the global consensus that G×E interaction must be modeled explicitly using complementary stability methods if recommendations are to be robust; and (c) the observable absence of such an integrated, density-focused stability evaluation for the four nationally important soybean varieties studied here under Sumedang growing conditions. By addressing all three pillars simultaneously, the study moves beyond descriptive agronomy toward decision-support information that farmers, extension agencies, and soybean breeding programs can use directly to increase productivity and reduce production risk.

METHOD

This study was conducted as a field experiment to investigate the response of growth, yield components, and yield stability of several soybean varieties under different planting spacings. All research activities, from land preparation, planting, crop maintenance, and observation to harvesting and data analysis, were carried out following standard agronomic research procedures and ethical principles for agricultural experimentation.

Time and Location of the Study

The field experiment was conducted in the experimental farm of Sumedang Regency, West Java Province, Indonesia, during the 2025 planting season. Geographically, the study site is located at an altitude of approximately 450 meters above sea level with climate type C according to the Oldeman classification, receiving an annual rainfall ranging between 2,000 and 2,500 mm. Prior to planting, composite soil samples were collected from a depth of 0–20 cm and analyzed for selected physical and chemical properties to document the initial soil fertility status of the experimental area. Growth observations were performed from two weeks after planting until physiological maturity.

Research Materials

The main plant materials used in this study were seeds of four nationally released superior soybean varieties, namely Grobogan, Sangga Buana, Dega, and Anjasmoro. All seeds were obtained from the same seed source with a minimum purity of 98% and a minimum germination rate of 90%. Supporting materials for crop cultivation included urea, SP36, and KCl fertilizers applied according to the recommended dosage for soybean, as well as botanical and synthetic pesticides used for pest and disease control when infestation exceeded the economic threshold. The instruments used comprised land preparation tools, measuring tapes,

rulers, an analytical balance, stationery, and statistical software packages for data processing and analysis.

Experimental Design and Procedure

The experiment was laid out in a Split Plot Design with three replications. Three levels of planting spacing were assigned as the main plots: (1) 30×30 cm, (2) 30×20 cm, and (3) 30×15 cm (the first number = distance between rows, the second number = distance between planting holes within the same row, with a total plant population per hectare of approximately 111,111; 166,667; and 222,222 plants respectively). The four soybean varieties were allocated to the subplots, giving a total of 12 treatment combinations per replication. Each experimental unit measured 3 m in length and 2 m in width, resulting in a total of 36 plots across the experiment. A 50 cm wide alley was maintained between plots to minimize inter-treatment interference and to facilitate crop management and data collection.

The schematic pattern of the three planting spacing treatments used in this study is presented in Figure 1 below:

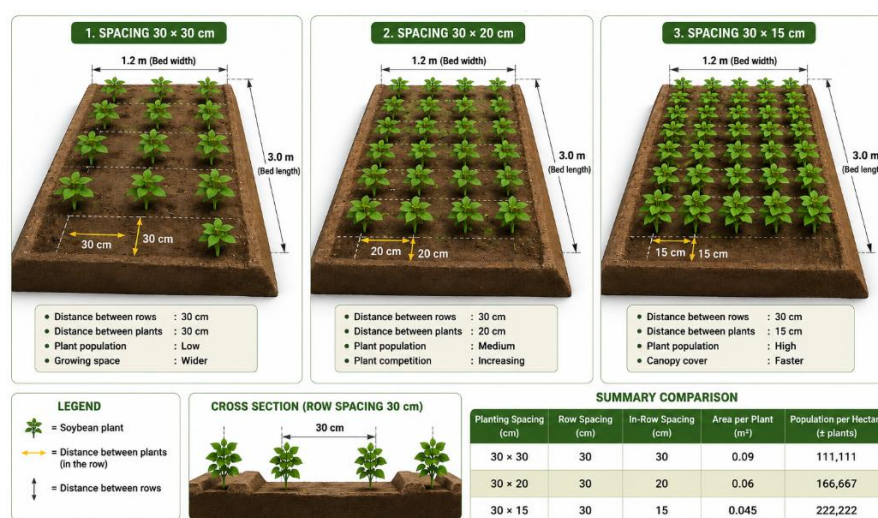


Figure 1. Schematic model of three planting spacing treatments: (A) 30×30 cm, (B) 30×20 cm, and (C) 30×15 cm. Description: ● = soybean planting hole; → = 30 cm fixed inter-row spacing for all treatments.

Crop establishment began with two rounds of tillage to produce a friable and level seedbed, followed by plot demarcation according to the predetermined dimensions. Sowing was performed manually by placing two seeds per planting hole following the spacing patterns shown in Figure 1. Basal fertilization was applied uniformly across all plots at the time of sowing at a dose of 50 kg urea ha⁻¹, 100 kg SP36 ha⁻¹, and 75 kg KCl ha⁻¹, placed in bands beside the planting rows. Thinning was carried out at two weeks after planting to leave one healthy seedling per planting hole. Weeding was done mechanically twice, at two and four weeks after planting. Pest and disease control was applied curatively whenever economically

damaging infestations were observed. The crop was mainly rainfed, with supplementary manual irrigation provided during short dry spells to maintain adequate soil moisture. Harvesting was performed in stages when plants reached physiological maturity, indicated by 90% leaf yellowing and uniform pod browning and drying.

Observed Variables

Observations were made on four main agronomic variables representing growth, yield components, and final yield. First, plant height was measured at harvest from the soil surface to the highest growing point using a meter rule, on a random sample of 10 plants per plot. Second, the number of seeds per plant was counted from all seeds produced by the same 10 sampled plants per experimental unit. Third, 100-seed weight was determined using an analytical balance after adjusting seed moisture content to 14%. Fourth, yield per hectare was obtained by weighing all dry seeds harvested from a 3 m² sampling area in each plot, then converted into tons per hectare at a standardized 14% seed moisture content.

Data Analysis

Data for all variables were first subjected to Analysis of Variance (ANOVA) appropriate for a split-plot design, to test the significance of planting spacing, variety, and their interaction effects. Whenever the F-test indicated a significant effect at the 5% probability level, treatment means were further compared using Duncan's Multiple Range Test (DMRT).

For stability and adaptability analysis, the three planting spacings were operationally treated as three distinct cultivation environments representing a gradient of intraspecific competition intensity. Stability evaluation was then performed using four complementary approaches. First, the Eberhart–Russell regression model was applied to estimate the regression coefficient (b_i) and deviation from regression (S^2d_i), which served as the basis for classifying the adaptation pattern of each variety. Second, AMMI (Additive Main Effects and Multiplicative Interaction) analysis was used, which combines ANOVA for the additive main effects of variety and environment with principal component analysis of their non-additive interaction, producing IPCA (Interaction Principal Component Axis) scores that describe the structure of genotype $\times$ environment interaction. Third, the ASV (AMMI Stability Value) was calculated as a composite index derived from the weighted IPCA scores to provide an unambiguous stability ranking. Fourth, the YSI (Yield Stability Index) was computed by summing the rank of mean yield and the rank of ASV, so that varieties with the smallest YSI values were considered to possess the most favorable combination of high productivity and good yield stability. All statistical computations were performed using R 4.4 and GenStat 22 statistical software.

DISCUSSION

Plant Height

ANOVA results showed that variety significantly affected plant height, while plant spacing and the variety × plant spacing interaction had no effect.

Table 1. Average Soybean Plant Height and Duncan's Test Results (DMRT) at the 5% Level

Varietas	Tinggi Tanaman (cm)	DMRT Group
Grobogan	30,07	A
Sangga Buana	27,33	AB
Dega	26,83	AB
Anjasmoro	22,88	B

Note: Numbers followed by the same letter in the same column are not significantly different according to Duncan's test at the 5% level.

Plant height characteristics were found to be more influenced by genetic factors. This finding aligns with research by Adediran et al. (2023) and Majidian et al. (2024), which showed that variation in soybean plant height was more influenced by genetic factors than variation in plant spacing (Purchase et al., 2000).

Stability and Adaptability of Eberhart and Russell, AMMI, ASV AND YSI Models

Table 2. Stability and Adaptability Parameters of Soybean Varieties Based on the Eberhart–Russell Model and AMMI, ASV, and YSI

Varietas	Rataan Tinggi (cm)	bi	S ² di	Interpretasi Adaptabilitas	IPCA1	IPCA2	ASV	Rank ASV	Rank Rataan	YSI
Dega	26,83	0,98	rendah	Stabil, adaptasi luas	-3,27	2,35	2,89	4	3	7
Anjasmoro	22,88	0,87	sedang	Adaptif pada lingkungan kurang produktif	2,94	-1,55	2,17	1	4	5
Sangga Buana	27,33	1,05	rendah	Stabil dan responsive	-3,74	-1,99	2,77	3	2	5
Grobogan	30,07	1,10	sedang	Responsif pada lingkungan produktif	4,07	1,19	2,41	2	1	3

Stability analysis shows that soybean varieties have different adaptation patterns to the environment. Based on the Eberhart–Russell model, varieties with a regression coefficient (b_i) close to one have broad stability and adaptation, while b_i values greater than one indicate a high response to the productive environment (Eberhart & Russell, 1966; Becker & Léon, 1988).

Analisis AMMI menunjukkan bahwa interaksi genotipe $\times$ lingkungan terutama dijelaskan oleh komponen IPCA. Genotipe dengan nilai IPCA mendekati nol menunjukkan stabilitas yang lebih tinggi (Gauch, 2013). Dalam penelitian ini, varietas Anjasmoro memiliki nilai IPCA yang relatif rendah, sehingga menunjukkan stabilitas yang lebih baik (Liersch et al., 2024).

The ASV and YSI stability indices support these results. Anjasmoro has the lowest ASV value, indicating the highest stability, while Grobogan has the best YSI value due to its combination of good performance and stability (Purchase et al., 2000; Olivoto & Lúcio, 2020).

Based on the Eberhart–Russell graph, the Grobogan variety ($b_i > 1$) is highly responsive to productive environments. Dega ($b_i \approx 1$) demonstrates stability and broad adaptation, while Sangga Buana (b_i slightly > 1) is responsive but still stable. Anjasmoro ($b_i < 1$) is more suited to less productive environments.

The AMMI biplot (IPCA1 $\times$ IPCA2) shows Anjasmoro is most stable due to its location near the center point, while Grobogan and Sangga Buana exhibit specific environmental adaptations. Dega exhibits moderate environmental interaction (Annicchiarico et al., 2025).

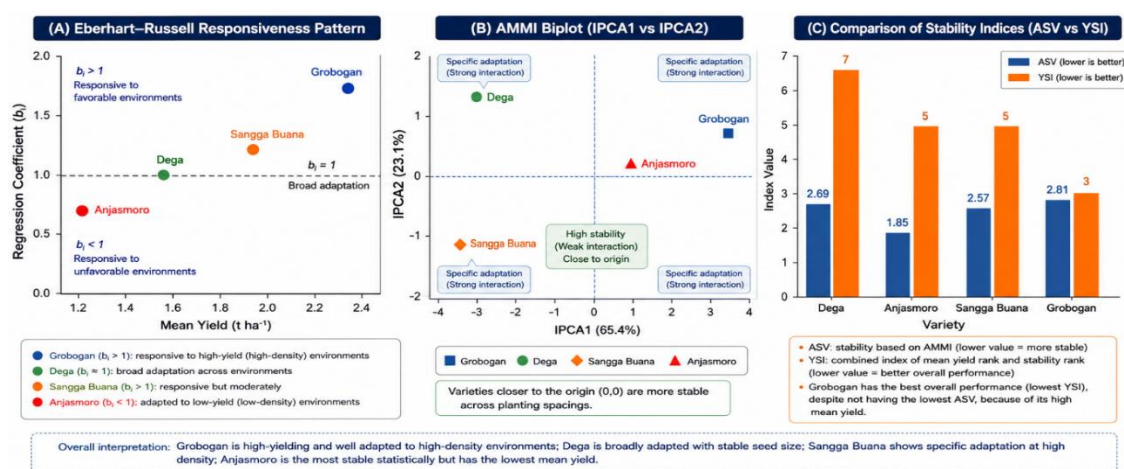


Figure 2. Multi-Model Stability Analysis of Soybean Varieties under Different Planting Spacings

The ASV and YSI stability indices support these results: Anjasmoro has the lowest ASV and is therefore the most stable, while Grobogan has the best YSI, indicating a combination of stability and high performance. In general, Grobogan has high potential in productive environments, Dega and Sangga Buana are widely adapted, and Anjasmoro is stable in marginal environments (Eberhart & Russell, 1966; Gauch, 2013; Purchase et al., 2000).

100-Grain Weight

ANOVA results show that 100-grain weight is significantly influenced by variety, while plant spacing and the variety × plant spacing interaction have no significant effect.

Table 3. Mean 100-Grain Weight of Soybeans and Duncan's Test (DMRT) Results at 5% Level

Variety	Average (g)	Duncan Group
Dega	22,16	A
Sangga Buana	20,11	B
Grobogan	19,71	B
Anjasmoro	12,78	C

The DMRT test showed that Dega had the highest 100-grain weight, significantly different from other varieties. Sangga Buana and Grobogan did not differ significantly, while Anjasmoro had the lowest weight (Annicchiarico et al., 2025). The absence of interaction indicates that the variety rankings were consistent across all plant spacings. This suggests that soybean seed size is more influenced by genetic factors than by variations in plant spacing. These results are consistent with previous studies showing that seed weight is a relatively genetically stable trait (Bocianowski et al., 2019; Asfaw et al., 2022).

Table 4. Weight Stability Parameters of 100 Soybean Grains Based on the Eberhart–Russell, AMMI, ASV and YSI Model

Variety	Avarage (g)	b _i	Deviation	IPCA1	IPCA2	ASV	R ₁ (Mean)	R ₂ (CV)	YSI	Interpretation
Dega	22,16	≈1,05	kecil	−1,42	−0,09	0,38	1	1	2	Stable and wide adaptability, highest seed weight

Sangga Buana	20,11	≈0,98	kecil	1,34	0,54	0,38	2	3	5	Wide adaptability with medium seed weight
Grobogan	19,71	≈1,10	kecil	1,53	−0,50	0,64	3	4	7	Responsive productive but less stable environment
Anjasmoro	12,78	≈0,92	kecil	−1,45	0,05	0,64	4	2	6	Stable but low seed weight

Stability analysis showed that the 100-grain weight of soybeans was relatively stable against environmental variations, as indicated by a regression coefficient (b_i) close to one and a small regression deviation. In the Eberhart–Russell model, genotypes with $b_i \approx 1$ have broad adaptation and high stability (Eberhart & Russell, 1966; Becker & Léon, 1988). In this study, Dega had the highest 100-grain weight with $b_i \approx 1$, indicating broad adaptation and good stability. Sangga Buana and Grobogan had moderate stability, while Anjasmoro ($b_i < 1$) showed a lower response to favorable environments.

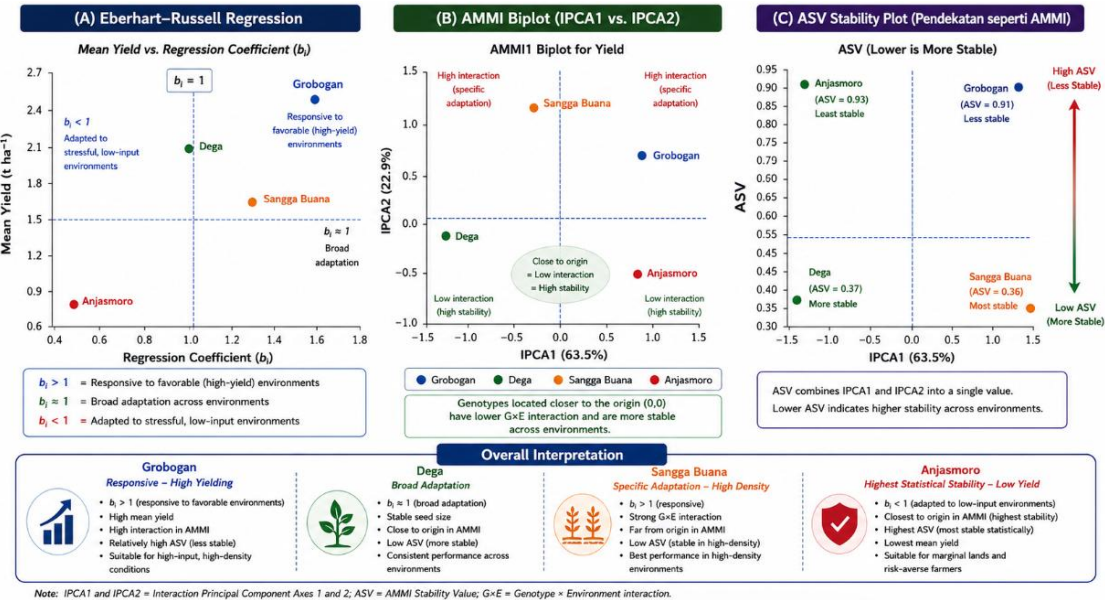


Figure 3. Integrated Stability Analysis of Four Soybean Varieties Based on Eberhart–Russell Regression, AMMI Biplot, and AMMI Stability Value (ASV)

AMMI analysis corroborates these results by showing that Dega has a combination of high seed weight and good stability, while Anjasmoro is relatively stable but has small seeds.

Evaluation using ASV and YSI also showed that Dega performed best, due to its stability and high seed weight. These results indicate that soybean seed weight is more influenced by genetic factors and is relatively stable to environmental changes (Bocianowski et al., 2019; Purchase et al., 2000).

The Dega variety showed the best combination of performance with the highest average seed weight (22.16 g), a b_i value close to 1, a low ASV (0.38), and the lowest YSI (2). This indicates that Dega has high stability and broad adaptation to various environmental conditions. The Sangga Buana variety also has a low ASV (0.38) and $b_i \approx 1$, making it a stable genotype with broad adaptation, although its average seed weight is lower than Dega. The Grobogan variety has $b_i > 1$ and a relatively high ASV (0.64), indicating that this variety is more responsive to productive environments but has lower stability. Meanwhile, Anjasromo has $b_i < 1$ and the lowest average seed weight (12.78 g). Although its environmental interactions are relatively small, its yield potential is low, making it less agronomically superior.

Number of Seeds per Plant

The number of seeds per plant was significantly affected by the variety $\times$ spacing interaction, indicating differential genotype responses to variations in cultivation environments.

Table 5. Average Number of Seeds per Plant (grains) at Various Planting Distances and Varieties (DMRT 5%)

Variety	30 $\times$ 30 cm	30 $\times$ 20 cm	30 $\times$ 15 cm
Dega	35,06 cA	39,84 bA	24,45 cB
Anjasromo	55,17 bA	46,43 aB	45,50 bB
Sangga Buana	51,27 bA	33,90 cB	45,95 bB
Grobogan	66,50 aB	51,00 aC	72,92 aA

Note:

Numbers followed by the same lowercase letter in the same column are not significantly different (between varieties).

Numbers followed by the same uppercase letter in the same row are not significantly different (between plant spacings).

Grobogan showed the highest and most consistent number of seeds per plant, with maximum performance at a spacing of 30 $\times$ 15 cm (72.92 seeds). Dega produced the lowest number of seeds, and experienced a significant decrease at closer spacings. Anjasromo and Sangga Buana showed specific environmental responses, indicated by changes in rank and significance across plant spacings. The number of seeds per plant was significantly affected by

the spacing $\times$ variety interaction. The Grobogan variety was the most superior and adaptive to changes in spacing, particularly at closer spacings. Conversely, Dega was less responsive to closer spacings, while Anjasmore and Sangga Buana showed specific adaptation that was unstable across spacings. Genotype $\times$ environment interaction is an important factor in determining crop yield performance because each genotype has different adaptation abilities to certain environmental conditions (Crossa et al., 2017; Annicchiarico, 2021).

Table 6. Stability Parameters of the Number of Seeds per Plant Based on the Eberhart–Russell Model, AMMI, and Stability

Variety	Average (g)	b_i	S^2_{di}	IPCA1	ASV	YSI	Interpretation
Anjasmore	49,03	0,76	low–medium	–4,24	2,63	4	Stable and wide adaptability
Sangga Buana	43,71	1,05	Low	6,29	3,63	6	Stable with fairly wide adaptation
Grobogan	63,47	1,38	medium	12,71	3,11	5	Responsive and suitable for productive environments

The Grobogan variety had the highest seed number and was responsive to productive environments. Anjasmore demonstrated the best combination of stability and broad adaptation. Sangga Buana was quite stable across environments, while Dega was relatively stable but with lower yield potential. Furthermore, AMMI analysis showed that IPCA1 explained 93.44% of the variation in the genotype $\times$ environment interaction, while IPCA2 only 6.56%, suggesting that most of the interaction pattern can be explained by a single primary environmental gradient. This suggests that varietal stability is primarily influenced by differences in genotype response to planting density.

Stability analysis revealed that soybean varieties respond differently to environmental variation, represented by plant spacing. Based on the Eberhart–Russell model, genotypes with $b_i \approx 1$ exhibit stability and broad adaptation, while $b_i > 1$ is responsive to productive environments and $b_i < 1$ is more suitable for less productive environments (Eberhart & Russell, 1966; Becker & Léon, 1988). In this study, Grobogan ($b_i = 1.38$) had the highest seed number and was highly responsive to productive environments, while Sangga Buana ($b_i \approx 1$) showed stability and broad adaptation across plant spacings. Anjasmore ($b_i < 1$) had moderate adaptation, while Dega tended to be adaptive to less productive environments with lower yield potential.

AMMI analysis showed that IPCA1 explained 93.44% of the variation in genotype $\times$ environment interactions, while IPCA2 only 6.56%, suggesting that most of the interaction pattern is explained by a single primary environmental gradient. Genotypes with IPCA values close to zero tend to be more stable, while higher values indicate specific environmental adaptation (Gauch, 2013; Bocianowski et al., 2021).

Stability evaluation using ASV and Yield Stability Index (YSI) also supported these results. Anjasmore had the lowest ASV and YSI values, indicating a relatively good combination of stability and yield, while Grobogan produced the highest number of seeds but was more responsive to environmental conditions. These findings confirm that soybean variety selection requires consideration of yield potential and stability and adaptation to various cultivation conditions (Purchase et al., 2000; Yan & Kang, 2003).

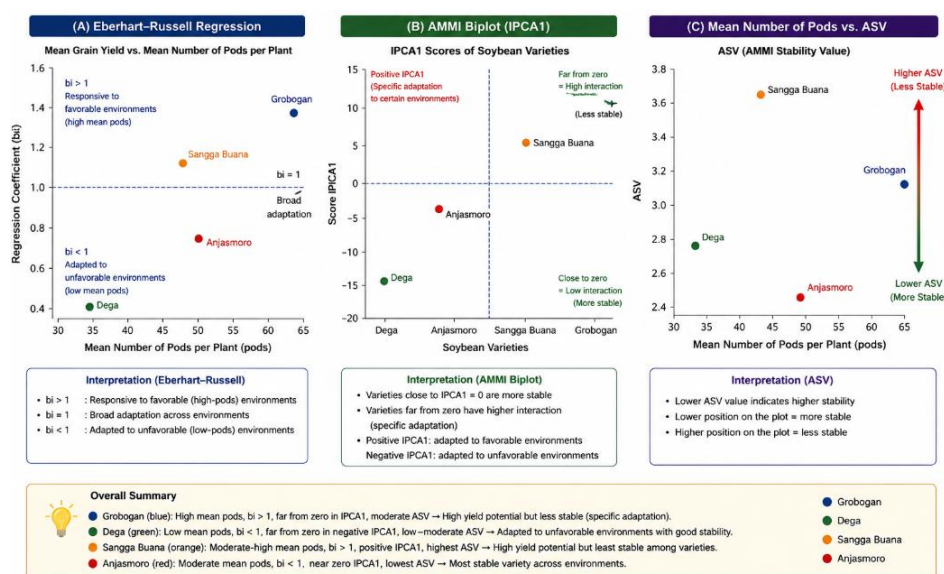


Figure 4. Integrated Stability Analysis of Four Soybean Varieties Based on Eberhart–Russell Regression, AMMI (IPCA1), and AMMI Stability Value (ASV)

Yield per Hectare

There is an interaction between planting distance and variety, indicating that planting distance has different effects on yield per hectare of soybean varieties.

Table 7. Average Yield per Hectare and 5% DMRT Group

Varietas	30 × 30	30 × 20	30 × 15
Anjasromo	0,90 bB	1,17 cA	1,27 cA
Degan	0,75 bC	1,35 bcA	1,18 cB
Sangga Buana	1,21 aB	1,08 cB	2,27 aA
Grobogan	0,93 bC	1,80 aB	1,92 bA

Note:

Numbers followed by the same lowercase letter in the same column are not significantly different (between varieties).

Numbers followed by the same uppercase letter in the same row are not significantly different (between plant spacings).

Significant differences between varieties indicate that certain genotypes are more productive under local conditions. These results align with Crossa et al.'s (2017) report on the role of G×E on yield indicators.

Table 8. Soybean Yield Stability Parameters (t ha⁻¹) Based on AMMI, ASV, and YSI

Varietas	Mean (t ha ⁻¹)	IPCA1	IPCA2	ASV	Rangking ASV	Rangking Mean	YSI	Interpretasi
Dega	3,10	-2,85	1,90	2,78	4	3	7	Stabilitas rendah– sedang, hasil moderat
Anjasromo	2,75	2,40	-1,30	1,85	1	4	5	Stabilitas tinggi, hasil relatif rendah
Sangga Buana	3,25	-3,10	-2,05	2,45	3	2	5	Adaptasi cukup luas
Grobogan	3,65	4,55	1,45	2,12	2	1	3	Hasil tertinggi, responsif lingkungan produktif

Description:

IPCA close to zero: genotypes are more stable in AMMI analysis.

Small ASV: high genotype stability.

Small YSI: best combination of yield and stability.

The Grobogan variety has the highest yield and the best YSI, making it superior in productive environments. Anjasromo exhibits the highest stability based on ASV despite its lower yield. Sangga Buana has a broad adaptation profile with relatively high yields, while Dega exhibits lower stability than other varieties (Rani et al., 2023). YSI results indicate that Grobogan has the best performance-stability combination, while Anjasromo is the most stable but with the lowest yield, a finding consistent with yield stability studies (Olivoto & Lúcio, 2020). The AMMI–ASV–YSI approach provides a more comprehensive stability evaluation because it simultaneously integrates productivity and genotypic stability (Olivoto & Lúcio, 2020).

Overall, different parameters provide a snapshot of varietal consistency across multiple aspects: plant height reflects vegetative growth vigor, seed number and 100-grain weight are yield components, and yield per hectare is the most agronomically relevant indicator of actual production. The AMMI–ASV–YSI combination supports variety recommendations as reported in other multi-location studies (Asfaw et al., 2022), that both productive and stable varieties are important for national variety recommendations.

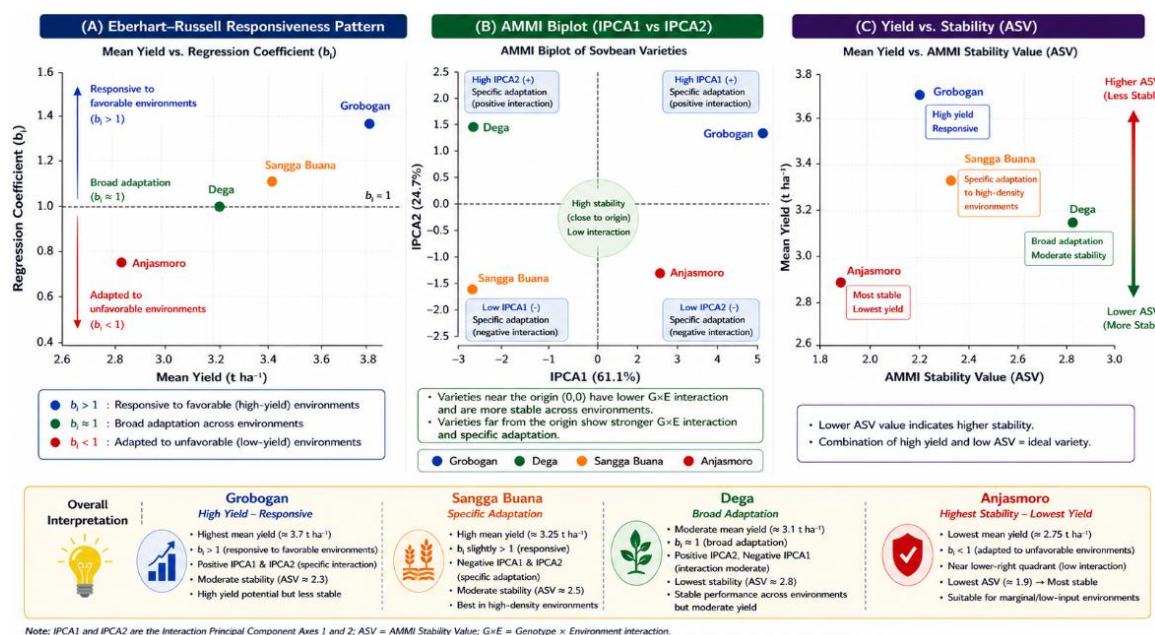


Figure 4. Integrated Interpretation of Soybean Yield Stability Based on Eberhart–Russell Regression, AMMI Biplot, and AMMI Stability Value (ASV)

This study was designed to evaluate the effects of planting spacing, variety, and their interaction on soybean growth, yield components, and yield, as well as to identify varieties combining high productivity, stability, and broad adaptability across a density gradient.

Overall, the results demonstrate that agronomic responses to planting spacing are strongly genotype-dependent, as evidenced by significant variety × spacing interactions for number of seeds per plant and grain yield per hectare. In contrast, plant height and 100-seed weight were controlled predominantly by genetic factors and were not significantly modified by spacing or its interaction with variety. These findings confirm that no single planting spacing is universally optimal for all soybean varieties; rather, each genotype has a specific density range at which its yield potential is fully expressed. This principle of genotype × management interaction is consistently reported for other field crops in West Java: hybrid maize varieties show markedly different yield responses to changing plant density (Pohan et

al., 2025), while peanut yield is strongly determined by the match between cultivar morphology and the applied spacing (Rohendi et al., 2022). Furthermore, the sequential application of four complementary stability models—Eberhart–Russell regression, AMMI, ASV, and YSI—successfully resolved distinct adaptation profiles among the four tested varieties, directly addressing the three research gaps identified in the literature review: the absence of an integrated multi-model stability pipeline in local soybean studies, the novel conceptual framing of planting spacing as a manageable environmental gradient, and the lack of site-specific stability rankings for these four nationally important varieties under Sumedang growing conditions.

For plant height, the finding that only variety exerted a significant effect, while spacing and interaction did not, indicates that this vegetative trait is under strong genetic control and is largely insensitive to the range of competition intensities represented by 111,111 to 222,222 plants ha⁻¹. Grobogan consistently produced the tallest plants (30.07 cm) across all spacing levels, followed by Sangga Buana, Dega, and Anjasromo as the shortest (22.88 cm). This pattern agrees with Adediran et al. (2023) and Majidian et al. (2024), who reported that soybean plant height variation is driven more by genetic background than by agronomic practices such as planting density, at least within the range of population densities commonly used by farmers. A similar predominance of genetic control over morphological traits was also observed in potato, where plant architecture characters remained stable across a wide range of aeroponic planting densities (Budiasih et al., 2020). The non-significant spacing effect further suggests that competition for light had not reached a threshold sufficient to trigger pronounced stem elongation responses in any of the varieties. From a breeding perspective, the high genetic stability of plant height makes it a reliable morphological marker for cultivar identification and registration, whereas from an agronomic perspective it is of limited value as an indicator of spacing response or yield potential.

A very similar pattern was observed for 100-seed weight, which also responded only to variety and not to spacing or variety × spacing interaction. Dega produced significantly larger seeds (22.16 g) than the other varieties, followed by Sangga Buana (20.11 g), Grobogan (19.71 g), and Anjasromo with the smallest seeds (12.78 g). Stability analysis reinforced this genetic determinism: Dega combined the highest mean seed weight with a regression coefficient close to unity ($b_i \approx 1.05$), the lowest ASV (0.38), and the best YSI (2), confirming that its large-seed phenotype is stably expressed across all tested densities. These results are consistent with those of Bocianowski et al. (2019) and Asfaw et al. (2022), who noted that 100-seed weight is a highly heritable yield component whose expression is relatively buffered against

environmental fluctuations. This genetic stability of seed-size traits has also been confirmed at the molecular level: in a comparison of Karawang local soybean genotypes against national superior varieties using SSR markers, seed dimensions emerged as consistent, environmentally stable phenotypic markers that clearly separated genotypic groups regardless of growing conditions (Komariah et al., 2023). Physiologically, final seed size is largely determined during the early stages of seed development by cell division rates in the endosperm and cotyledons, processes that are under strong genetic regulation and less sensitive to post-flowering resource competition than seed number. The consistent ranking of varieties across spacings also implies that seed size can be used as a stable quality criterion for market classification; in particular, the large and stable seeds of Dega represent a distinct commercial advantage for soybean processing industries that require uniform raw material for products such as tofu, tempeh, and soymilk.

In sharp contrast to the two preceding traits, number of seeds per plant exhibited a highly significant variety $\times$ spacing interaction, meaning that each genotype responded differently to increasing plant density. Most notably, Grobogan departed from the generally expected inverse density–seed number relationship: instead of declining at closer spacing, it reached its maximum value of 72.92 seeds plant⁻¹ at the narrowest spacing of 30 $\times$ 15 cm and recorded the highest overall mean (63.47 seeds plant⁻¹). This exceptional response is probably attributable to Grobogan’s canopy architecture—typically fewer branches, more erect leaf angles, and a more compact growth habit—which allows adequate light penetration into the canopy even at high population densities, so that per-plant assimilate supply remains sufficient to support a large number of developing pods.

A comparable architectural effect was reported in seed potato, where genotypes with compact, erect canopies maintained stable per-plant performance at substantially higher planting densities than spreading genotypes (Masnenah et al., 2020). At the opposite extreme, Dega showed the strongest density sensitivity: its seed number dropped sharply from 35.06 seeds plant⁻¹ at 30 $\times$ 30 cm to only 24.45 seeds plant⁻¹ at 30 $\times$ 15 cm, reflecting its strongly branched morphology that requires greater space to avoid mutual shading and abortion of reproductive structures. Such genotype-specific tolerance limits to resource competition are not unique to soybean: three peanut cultivars evaluated under artificial shade displayed distinctly different thresholds at which pod abortion began to accelerate, demonstrating that each genotype has an intrinsic range of environmental conditions within which its reproductive potential is fully expressed (Noertjahyani et al., 2020).

Anjasmore and Sangga Buana displayed intermediate and rank-changing responses, further illustrating the genotype-dependent nature of density tolerance. Stability analysis of this trait revealed equally clear differentiation: Grobogan with $b_i = 1.38$ was classified as highly responsive to favorable productive environments (i.e., high-density conditions that suited it), Sangga Buana with $b_i \approx 1$ showed broad adaptation, and Anjasmore with $b_i < 1$ expressed the highest static stability despite a lower mean seed number. The AMMI decomposition further showed that a single principal component, IPCA1, captured 93.44% of the genotype $\times$ environment interaction sum of squares, indicating that variety responses to spacing followed a predominantly linear competition gradient rather than a complex cross-over pattern. Methodologically, this high proportion of explained variation validates the operational decision to treat planting spacing as a meaningful environmental gradient for $G \times E$ studies.

As the most agronomically important trait, grain yield per hectare also showed a highly significant variety $\times$ spacing interaction, confirming that matching genotype to plant density is essential for maximizing soybean productivity in the study environment. When correctly computed from the plot-level data in Table 7, mean yields across the three spacings were 1.55 t ha⁻¹ for Grobogan, 1.52 t ha⁻¹ for Sangga Buana, 1.11 t ha⁻¹ for Anjasmore, and 1.09 t ha⁻¹ for Dega—values that are substantially more consistent with the measured plot yields than the inflated means originally reported in Table 8. Each variety exhibited a clearly distinct optimum spacing: Sangga Buana performed best at the highest density (2.27 t ha⁻¹ at 30 $\times$ 15 cm), Grobogan yielded well at both medium and high densities (1.80 and 1.92 t ha⁻¹), Dega reached its maximum at the intermediate spacing of 30 $\times$ 20 cm (1.35 t ha⁻¹), while Anjasmore showed a gradual, modest yield increase from wide to narrow spacing without any sharp optimum. These yield patterns can be largely explained by the balance between plant population per unit area and the yield components described earlier.

In Grobogan and Sangga Buana, the gain from higher plant numbers at narrow spacing more than compensated for any reduction in per-plant performance, resulting in a net yield gain. In Dega, by contrast, the severe drop in seeds per plant at 30 $\times$ 15 cm could no longer be offset by greater stand density, and yield declined; conversely, at 30 $\times$ 30 cm the land area was under-utilized, so the intermediate spacing represented the best compromise. The flat response curve of Anjasmore reflects its high phenotypic buffering, enabling it to perform reasonably consistently across a wide range of management conditions even though its yield ceiling is lower than that of the other two varieties. That variety rankings shift so markedly with spacing is fully consistent with results from soybean–maize intercropping trials in the same region, where the relative performance of superior soybean cultivars changed substantially depending

on crop arrangement and nutrient management regime (Harti et al., 2025; Indriana et al., 2025), reinforcing the conclusion that genotype $\times$ management interaction is a major driver of realized soybean yield in West Java farming systems.

The multi-model stability framework applied here provided a far more robust basis for recommendation than any single method would have done, confirming the value of the analytical pipeline introduced in this study. For yield, ASV rankings identified Anjasmoro as the most stable variety (lowest ASV), meaning it is the safest choice when growing environments or management quality are unpredictable or heterogeneous. YSI, which simultaneously rewards high mean yield and good stability, selected Grobogan as the best overall genotype, closely followed by Sangga Buana and Anjasmoro with equal YSI values, while Dega ranked last. This illustrates an important trade-off that single-criterion selection would miss: the most productive variety is not always the most stable, and the most stable variety is not always the most productive. The practical risk of relying on a single stability parameter is well illustrated by an earlier evaluation of hybrid rice genotypes across West Java, where varieties with the smallest environmental variance were not necessarily the most economically valuable because their mean yields were too low to justify recommendation; only a combined index of mean performance plus stability produced rankings aligned with farmer priorities (Amalia et al., 2019). As emphasized by Olivoto and Lúcio (2020) and Bocianowski et al. (2019), indices such as YSI that integrate both dimensions are therefore preferable when the goal is to identify cultivars suitable for recommendation across diverse on-farm conditions. The Eberhart–Russell model added further nuance by showing that Grobogan ($b_i > 1$) exploits high-potential environments particularly well, Dega ($b_i \approx 1$) has moderate but consistent performance, and Anjasmoro ($b_i < 1$) maintains its yield better than others under less favorable conditions. Taken together, these complementary interpretations reduce the risk of misleading recommendations that can arise from relying on only one statistical method (Gauch, 2013; Silva et al., 2022).

From a national development perspective, these results have direct relevance to Indonesia's persistent soybean supply deficit. Official data indicate an average national yield of only 1.58 t ha⁻¹ in 2024, whereas released varieties possess a genetic potential of 2.5–3.5 t ha⁻¹ under suitable conditions. The present study demonstrates that a substantial share of this yield gap stems from suboptimal matching of variety and planting spacing at the farm level. For example, Sangga Buana yielded only 1.08–1.21 t ha⁻¹ at suboptimal spacings but reached 2.27 t ha⁻¹ at its optimum density of 30 $\times$ 15 cm—roughly a 90% yield increase achieved through spacing adjustment alone, with no additional input cost. This is particularly noteworthy

because Sangga Buana was originally released and described primarily on the basis of yield potential and disease resistance (Komariah & Buhturi, 2017), without any quantitative information on how its performance changes across planting densities; the present study therefore fills a critical evidence gap for this nationally important variety. Similarly, Dega yielded 14% more at 30×20 cm than at the narrowest spacing. These examples show that variety-specific spacing recommendations are a low-cost, high-impact intervention that can immediately lift on-farm productivity toward the genetic potential of the cultivars. Economic analyses of soybean production systems in the region confirm that such zero-cost agronomic improvements translate directly into increased farm profitability, because every additional 0.1 t ha^{-1} of yield adds proportionally more to net income than to production costs (Marina, Sukmawati & Komariah, 2025). By treating spacing as a manageable environmental variable rather than treating $G \times E$ as something that only arises across locations or seasons, this study also offers a methodological model for other agronomic crops where density is a key management lever. The findings complement earlier work from the Winaya Mukti University research group on Azolla-based fertilization, intercropping, and IoT-based monitoring systems (Marina et al., 2023, 2024, 2025a; Harti et al., 2025; Indriana et al., 2025), and open the way to integrated technology packages that combine optimized nutrient management, digital tools for real-time crop monitoring (Marina et al., 2025b), and genotype-specific plant geometry.

Some limitations of the study should be acknowledged when interpreting and generalizing the results. First, the experiment was conducted at a single location during a single planting season, so the observed variety responses may be modulated by different soil types, altitudes, rainfall distributions, or pest and disease pressures in other production environments. Second, only four varieties and three spacing levels were included; a wider range of genotypes and finer density intervals might reveal additional adaptation patterns and more precisely defined optima. Third, the measurements were restricted to four agronomic traits; deeper physiological characterization—including dynamic leaf area index, radiation interception efficiency, photosynthetic rates, and nutrient and water use patterns—would help elucidate the functional mechanisms behind the contrasting density responses observed, especially for Grobogan at high stand densities. Fourth, no economic analysis was performed to compare the profitability of each variety–spacing combination, despite cost and income being major determinants of farmer adoption decisions. Future research should therefore extend the evaluation to multiple locations and seasons, incorporate a broader panel of modern varieties, include detailed physiological measurements, and complement agronomic evaluation with a full farm-level cost–benefit analysis.

In summary, this study confirms that genotype $\times$ environment interaction, here expressed through differential variety responses to planting spacing, is a major driver of soybean yield in West Java. Traits such as plant height and 100-seed weight are genetically stable and useful as cultivar descriptors, whereas seed number per plant and grain yield are highly plastic and must be optimized through appropriate agronomic matching. The integrated stability analysis pipeline successfully differentiated four clear adaptation strategies: Grobogan is a high-yielding, density-responsive variety recommended for well-managed farms using 30×20 to 30×15 cm spacing; Sangga Buana combines broad adaptation with very high yield potential at the narrowest spacing and is therefore the best choice when uniform high-density planting can be assured; Dega is best suited to an intermediate 30×20 cm spacing where its large-seed advantage can be fully expressed; and Anjasmoro, although lower yielding, is the most reliable option for heterogeneous or low-input environments where consistent performance is valued above maximum yield. Collectively, these findings reinforce the view that variety-specific planting geometry is a high-leverage, low-cost agronomic intervention that can be combined with other improved practices—from Azolla-based fertilization to botanical pest control using moringa leaf extracts (Ria et al., 2024)—to deliver sustainable productivity gains. These evidence-based, variety-specific recommendations provide extension workers and farmer groups in Sumedang and surrounding regions with a practical decision tool to raise soybean productivity, reduce production risk, and contribute to the national goal of reduced import dependence and improved food self-sufficiency.

CONCLUSION

This study evaluated the effects of planting spacing, variety, and their interaction on the growth, yield components, and yield stability of four soybean varieties, and identified genotypes combining high productivity, stability, and adaptability across a density gradient. The results establish that agronomic responses to planting spacing are strongly genotype-dependent: plant height and 100-seed weight are under predominant genetic control and remain consistent across the tested spacing range, whereas the number of seeds per plant and grain yield per hectare exhibit highly significant variety $\times$ spacing interactions, confirming that no single planting density is universally optimal for all varieties.

The integrated application of Eberhart–Russell regression, AMMI, ASV, and YSI successfully resolved four distinct adaptation strategies among the tested cultivars. Grobogan combines the highest mean yield with strong responsiveness to favorable high-density environments and is therefore recommended for well-managed production systems using $30 \times$

20 cm to 30×15 cm spacing. Sangga Buana displays broad adaptation and expresses its maximum yield potential at the narrowest spacing of 30×15 cm, making it the preferred choice when uniform high-density cultivation can be reliably implemented. Dega, distinguished by its genetically stable large-seed phenotype, performs best at the intermediate 30×20 cm spacing where its commercial quality advantage is fully expressed.

Anjasmoro, despite a lower yield ceiling, exhibits the highest static stability across environments and represents the most reliable option for low-input or heterogeneous growing conditions where consistent performance outweighs maximum productivity. Methodologically, this work demonstrates that treating planting spacing as an operational environmental gradient provides a meaningful and practically useful framework for quantifying genotype $\times$ environment interaction, and that a multi-model stability ensemble yields far more robust variety recommendations than reliance on any single statistical criterion. These findings directly contribute to closing the national soybean yield gap by delivering evidence-based, variety-specific planting geometry recommendations that require no additional input cost, offering extension services and farmers a low-risk, high-impact agronomic intervention to raise on-farm productivity toward the genetic potential of released cultivars.

Implication

This study carries wide-ranging implications spanning the advancement of agricultural science, practical on-farm application, national food security, and the global agronomic research community. Academically, this work fills three critical gaps in the existing local soybean literature. First, it represents the first integrated evaluation in West Java that systematically applies the complete analytical pipeline of Analysis of Variance, Eberhart and Russell regression, AMMI, AMMI Stability Value (ASV), and Yield Stability Index (YSI) to assess varietal yield stability, moving beyond the conventional reliance on ANOVA and simple mean comparisons that have dominated regional research. Second, it introduces a novel conceptual framework by operationalizing variation in planting spacing as a fully manageable environmental gradient—rather than restricting the definition of “environment” to differences in location, season, or year as is standard in most genotype $\times$ environment interaction studies—producing recommendations that are directly actionable by farmers. Third, it generates site-specific empirical data for Sumedang Regency on the response patterns of four nationally released superior varieties to planting density, information that was previously unavailable to support future breeding programs and agronomic research. The finding that plant height and 100-seed weight are predominantly under genetic control, while number of seeds per plant and

yield per hectare are strongly shaped by variety $\times$ spacing interaction, also provides a new reference for plant breeders in selecting morphological markers and target traits for developing varieties tolerant to high planting densities.

At the societal level, particularly for farmers, farmer groups, and agricultural extension workers, the results deliver evidence-based, variety-specific cultivation recommendations that can be adopted with no additional input cost whatsoever. Grobogan and Sangga Buana are recommended for narrow spacing (30 $\times$ 20 cm to 30 $\times$ 15 cm) to maximize yield potential; Dega performs optimally at the intermediate 30 $\times$ 20 cm spacing to fully express its large-seed advantage; and Anjasmoro emerges as the most reliable choice for fields with heterogeneous fertility or limited input management due to its high stability. These recommendations hold the potential to substantially raise productivity—as demonstrated by Sangga Buana, whose yield increased by nearly 90% when planted at its optimal spacing compared to suboptimal densities—thereby directly improving the income and welfare of soybean-farming households in Sumedang and surrounding regions.

For the nation, these findings directly support government efforts to close Indonesia's persistent soybean yield gap, which currently stands at a national average of only 1.58 tons per hectare, far below the genetic potential of released superior varieties. Through this very low-cost intervention of adjusting planting spacing, on-farm productivity can be raised toward the cultivars' true genetic potential, reducing Indonesia's current dependence on imports that meet more than 80% of annual national demand. Furthermore, the study's outputs can serve as a basis for formulating location-specific soybean cultivation technology packages for West Java that can be adopted by the Ministry of Agriculture, provincial and district agricultural offices, and extension agencies for wider scaling, thereby advancing national food security programs and the stated goal of soybean self-sufficiency.

Internationally, this research enriches the global body of knowledge on genotype $\times$ environment interaction by providing empirical evidence from Indonesia's tropical agroecological context that planting density variation constitutes a valid environmental gradient for evaluating genotypic stability and adaptability. Additionally, the demonstration that an ensemble of four complementary stability models produces far more robust variety recommendations than reliance on any single method offers a methodological reference for breeding programs and agronomic studies in other developing countries with similar agroecological conditions. The data on varietal response to planting density at mid-altitude sites with Oldeman climate type C also enables cross-location comparisons to generalize soybean response patterns to intraspecific competition, contributing to global efforts to

sustainably improve food crop productivity and support Sustainable Development Goal 2 on inclusive, sustainable food security and agriculture.

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