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MULTIVARIATE ANALYSIS OF SOYBEAN AGRONOMIC TRAITS UNDER DIFFERENT PLANT STRUCTURE MANAGEMENT PRACTICES

ANÁLISE MULTIVARIADA DO DESEMPENHO AGRONÔMICO DA SOJA SOB DIFERENTES MANEJOS DE ESTRUTURA DE PLANTAS

ANÁLISIS MULTIVARIADO DE RASGOS AGRONÓMICOS DE LA SOJA BAJO DIFERENTES PRÁCTICAS DE MANEJO DE LA ESTRUCTURA DE LA PLANTA

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Abstract

Soybean is a major crop in global agriculture, and the application of plant growth modulators offers a promising approach to improve yield; this study aimed to evaluate their effects on agronomic traits and yield components to identify the most effective management strategy and the primary determinants of grain yield using multivariate analytical techniques. The experiment was conducted in Mineiros, Goiás, Brazil, using a randomized block design with eight treatments and four replications under field conditions. Treatments involved the application of plant growth modulators PR136 (Prime), StoppingGo (Valence), Equaliza (Master), Stimulate (Stoller), Biozyme (UPL), MaxCel (Sumitomo), and StartStop (Blucorp) at the V4 growth stage, plus an untreated Control, and agronomic traits related to vegetative and reproductive growth were analyzed using multivariate analysis of variance (MANOVA), principal component analysis (PCA), linear mixed models, path analysis, and the Multi-Trait Genotype-Ideotype Distance Index (MGIDI). MANOVA detected significant differences among treatments ($p < 0.05$), PCA revealed consistent covariance patterns among traits with the first two principal components explaining a substantial portion of the total variance, and path analysis identified the number of pods per plant and stem base diameter as the main positive direct determinants of grain yield, whereas plant height and the number of lateral branches had negative effects. The MGIDI, applied with a 15% selection intensity, exclusively selected the Stimulate treatment as the closest to the ideal ideotype. Multivariate techniques proved effective for synthesizing information from multiple traits and supporting management decisions in soybean, highlighting Stimulate as the treatment with the most balanced multivariate performance and StoppingGo as particularly effective in optimizing plant architecture and yield components.
Keywords: Foliar fertilization; MGIDI; multivariate analysis; plant growth modulators; soybean yield.

Resumo

A soja é uma das culturas mais importantes do agronegócio mundial, e a otimização de seu manejo através de reguladores de crescimento representa estratégia promissora para incrementar a produtividade. Este estudo objetivou avaliar o desempenho agronômico da soja sob diferentes manejos de reguladores de crescimento utilizando técnicas de análise multivariada. O experimento foi conduzido em Mineiros-GO, com delineamento em blocos casualizados com oito tratamentos e quatro repetições. Os tratamentos consistiram na aplicação de diferentes produtos comerciais (Prime-PR136, Valence-StoppingGo, Master-Equaliza, Stoller-Stimulate, UPL-Biozyme, Sumitomo-MaxCel e Blucorp-StartStop) no estádio V4, além de uma testemunha. Foram avaliadas características agronômicas relacionadas ao crescimento vegetativo e reprodutivo, submetidas à análise MANOVA, PCA, modelos lineares mistos, análise de trilha e MGIDI. A MANOVA detectou diferenças significativas entre tratamentos ($p < 0,05$), validando a abordagem experimental. A PCA revelou padrões consistentes de covariação entre as variáveis, com os dois primeiros componentes explicando proporção significativa da variância total. A análise de trilha inclui o número de vagens por planta e o diâmetro de caule como principais determinantes diretos do rendimento de grãos, enquanto altura de planta e número de ramos laterais apresentaram efeitos negativos. O MGIDI, aplicado com ponto de corte de 15% de intensidade, selecionou exclusivamente o tratamento StoppingGo como mais próximo ao ideótipo praticado. Os resultados demonstram a eficácia das técnicas multivariadas para integrar informações de múltiplas variáveis e orientar decisões de manejo, evidenciando a superioridade do StoppingGo na otimização da arquitetura de plantas e componentes de rendimento da soja.
Palavras-chave: Produtividade da soja; reguladores de crescimento; nutrição foliar; análise multivariada; MGIDI.

Resumen

La soja es una de las culturas más importantes del agronegocio mundial, y la optimización de su manejo a través de reguladores de crecimiento representa una estrategia prometedora para

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incrementar la productividad. Este estudio objetivo es evaluar el desarrollo agronómico de la soja con diferentes manejos de reguladores de crecimiento utilizando técnicas de análisis multivariado. El experimento realizado en Mineiros-GO, con delineamiento en bloques casualizados con oito tratamentos y cuatro repeticiones. Los tratamientos consisten en aplicaciones de diferentes productos comerciales (Prime-PR136, Valence-StoppingGo, Master-Equaliza, Stoller-Stimulate, UPL-Biozyme, Sumitomo-MaxCel y Blucorp-StartStop) en el estación V4, además de una prueba. Foro evaluado características agronómicas relacionadas con el crecimiento vegetativo y reproductivo, submetidas en análisis MANOVA, PCA, modelos lineales mistos, análisis de trilha y MGIDI. A MANOVA detectó diferencias significativas entre tratamientos ($p < 0,05$), validando un abordaje experimental. A PCA revela padrões consistentes de covariación entre las variables, con los dos primeros componentes explicando la proporción significativa de la variación total. A análise de trilha include o número de vagens por planta y o diâmetro de caule como principais determinantes diretos do rendimento de grãos, enquanto altura de planta y número de ramos laterales apresentaram efeitos negativos. O MGIDI, aplicado con un punto de corte de 15% de intensidad, seleccione exclusivamente el tratamiento StoppingGo como más próximo al ideótipo practicado. Los resultados demuestran la eficacia de las técnicas multivariadas para integrar información de múltiples variantes y orientar las decisiones de manejo, evidenciando la superioridad de StoppingGo en la optimización de la arquitectura de plantas y componentes de rendimiento de la soja.
Palabras clave: Produtividade da soja; reguladores de crecimiento; nutrición foliar; análisis multivariado; MGIDI.

1. Introduction

Soybean (*Glycine max* L. Merrill) is a major crop in global agriculture, contributing significantly to food security and economic stability. Soybean is a primary source of plant-derived protein and oil for human and animal consumption, as well as a raw material for various industrial products, having increasing strategic importance amid climate change and population growth (Mishra et al., 2024). Brazil is the world's largest soybean producer, with a cultivated area exceeding 40 million hectares, contributing approximately 38% of global production, placing the country in a prominent position in international supply chains (Krenchinski et al., 2024).

Despite technological and genetic advancements, soybean cultivation faces challenges in maximizing its yield potential. Nutritional deficiencies, abiotic stresses, and suboptimal plant architecture limit the ability to fully realize genetic potential under actual field conditions (Mishra et al., 2024). In this context, the application of plant growth modulators has emerged as a promising approach to manage plant development, enhancing the allocation of photoassimilates and improving crop yield.

Recent studies indicate that plant growth modulators significantly alter soybean morphophysiological traits, including plant height, stem base diameter,

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number of branches, and yield components (Rajadhivya, Macwan & Bhanvadia, 2024; Tigga et al., 2024). These compounds modify the endogenous hormonal balance, influencing processes such as cell elongation, tissue differentiation, and phenological transitions (Zamarian & Battistus, 2024). The strategic application of these compounds, combined with foliar fertilization programs, can result in plants with a more efficient architecture, increased resistance to lodging, and improved resource utilization.

The complexity of agronomic responses to varying plant growth modulator management practices requires analytical methods that concurrently evaluate multiple plant traits. Traditional univariate analyses, while informative, fail to fully capture the interrelationships among traits and the multivariate response patterns characteristic of complex biological systems (Vasconcelos, Silva & Santos, 2024). Consequently, multivariate analytical techniques have become increasingly prevalent in agronomic research, facilitating the integration of data from multiple traits and the identification of patterns that inform evidence-based management decisions.

Principal component analysis (PCA) is widely used to reduce the dimensionality of complex agricultural datasets, revealing latent structures and aiding the interpretation of variation patterns (Vasconcelos, Silva & Santos, 2024). This method identifies linear combinations of original variables that account for most of the data variance, simplifying analysis and elucidating relationships among seemingly independent traits. Complementarily, multivariate analysis of variance (MANOVA) provides a robust framework for simultaneously testing the effects of treatments on multiple correlated traits, controlling Type I error rates associated with multiple univariate comparisons.

The Multi-Trait Genotype-Ideotype Distance Index (MGIDI) is a recent methodological advancement developed to integrate multiple traits into a single selection metric (Pham et al., 2023; Al-Ashkar et al., 2023b). This index computes the Euclidean distance between genotypes or treatments and a defined ideotype, facilitating the identification of materials that exhibit an optimal balance of desirable traits. The MGIDI demonstrates higher efficacy than traditional indices by

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accounting for the correlation structure among traits and allowing the assignment of specific weights to each trait based on its relative importance.

Path analysis is a useful method for elucidating causal relationships among agronomic traits, decomposing correlations into direct and indirect effects on a dependent variable, such as grain yield. This method identifies traits with the greatest direct influence on yield and those contributing primarily through indirect effects, supporting more efficient selection and management strategies.

Given the significance of soybean in Brazilian agriculture, the need to optimize management practices, and the capacity of multivariate analytical techniques to clarify complex response patterns, this study evaluated the effects of plant structure management practices on the agronomic traits and yield components of soybean to identify the most effective management strategy and the primary determinants of yield using multivariate analytical techniques. MANOVA, linear mixed models, PCA, path analysis, and MGIDI were applied to characterize response patterns, identify primary determinants of grain yield, and rank treatments based on their proximity to the ideotype, thereby supporting recommendations for more efficient management practices.

2. Material and methods

The experiment was conducted at Fazenda Invernadinha, located in the rural region of Mineiros, Goiás, Brazil (17°23'07.3"S, 52°16'54.3"W, and 800 m average altitude). The region has a mean annual temperature of 22.7 °C and a mean annual rainfall of 1695 mm, with rainfall concentrated during the spring and summer seasons. The local climate is classified as Aw (tropical savanna with a dry winter), according to the Köppen and Geiger classification (1936).

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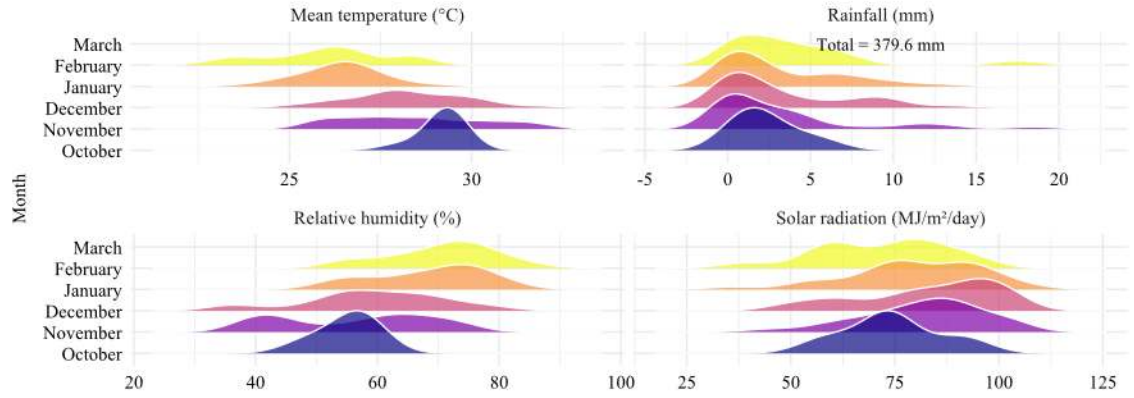
Figure 1. Monthly variations in mean temperature, rainfall, solar radiation, and relative humidity from October 2023 to February 2024 in Mineiros, Goiás, Brazil.



Soil chemical analyses, conducted on the 0–20 cm layer, revealed the following results: pH = 5.7; Ca = 5.62 cmolc dm^{-3}; Mg = 1.77 cmolc dm^{-3}; Al = 0.0 cmolc dm^{-3}; H+Al = 2.4 cmolc dm^{-3}; CEC = 9.9 cmolc dm^{-3}; K = 105 mg dm^{-3}; P = 5.5 mg dm^{-3}; Cu = 1 mg dm^{-3}; Fe = 54 mg dm^{-3}; Mn = 17.9 mg dm^{-3}; Zn = 2 mg dm^{-3}; Na = 2.4 mg dm^{-3}; clay = 46.5%; silt = 10%; sand = 43.5%; organic matter = 4.07%; and organic carbon = 2.36%. Soil analyses were performed following the methodology described by Embrapa (2009).

A randomized block experimental design with four replications was used, comprising eight treatments corresponding to different plant structure management practices using plant growth modulators PR136 (Prime) at 300 mL ha^{-1}, StoppingGo (Valence) 300 mL ha^{-1}, Equaliza (Master) at 1000 mL ha^{-1}, Stimulate (Stoller) at 250 mL ha^{-1}, Biozyme (UPL) at 250 mL ha^{-1}, MaxCel (Sumitomo) 250 mL ha^{-1}, and StartStop (Blucorp) at 300 mL ha^{-1} and a Control with water at 300 mL ha^{-1}. The treatments were applied on November 30, 2023, when the soybean was in the V4 phenological stage. Each experimental plot consisted of eight rows, 5 m in length, spaced 0.45 m apart, with an evaluation area of 18 m^2. Sowing was carried out on October 23, 2023, and harvesting on February 15, 2024.

Field preparation involved pre-planting desiccation, following the recommendations of Cobucci et al. (1999). Soil fertilization consisted of MAP (9% N, 52% P) at 173 kg ha^{-1} applied in the sowing furrow and KCl at 150 kg ha^{-1} as

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topdressing, split equally between planting and 20 days after emergence, following the recommendations of Souza (2004). Phytosanitary management, addressing pests, diseases, and weeds, was conducted based on crop requirements and in accordance with integrated pest management practices (Ávila et al., 2018).

At the end of the crop cycle, 30 plants were randomly collected from the evaluation area of each plot and evaluated for agronomic traits representative of plant architecture and yield potential. The measured traits included: number of lateral branches; number of nodes on the main stem; the number of pods with one grain, two grains, three grains, and four grains; total number of pods per plant; total number of grains per plant; average number of grains per pod; stem base diameter; plant height from soil to apex; and grain yield. These traits enabled the concurrent characterization of vegetative architecture and the yield potential of the treatments.

The data were initially analyzed using multivariate analysis of variance (MANOVA) with the Roy test, considering treatments as a fixed effect and blocks as a random effect. The significance of effects was assessed with degrees of freedom adjusted using the Kenward–Roger method. The statistical model is expressed as:

$$Y_{ij} = \mu + \tau_i + \beta_j + \varepsilon_{ij}$$

Subsequently, principal component analysis (PCA) was performed to examine the correlation structure among agronomic traits and reduce data dimensionality. The PCA was based on the standardized correlation matrix:

$$Z = X\Lambda$$

Posterior marginal means of the principal components were estimated using multivariate linear mixed models, considering block as a random effect and parameters estimated via restricted maximum likelihood (REML). The adopted model was:

$$y = Xb + Zu + \varepsilon$$

Path analysis was performed to decompose correlations between agronomic variables and grain yield, to estimate direct effects. The matrix model is expressed as:

$$r_{yx} = R_{xx} P$$

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Multi-Trait Genotype-Ideotype Distance Index (MGIDI) was applied to integrate multiple traits into a single selection metric. The index is calculated as:

$$MGIDI_i = \sqrt{(\Sigma (\gamma_{ij} - \gamma^*_j)^2)}$$

where $MGIDI_i$ = index of genotype i; γ_{ij} = factorial score of genotype i on factor j; γ_j = ideal score in factor j; and f = number of factors retained in the analysis.

All analyses were conducted in the R software (R Core Team, 2025), using the packages lme4, emmeans, ggridges, ggplot2, ggh4x, metan, and their dependencies.

3. Results

Multivariate analysis of variance (MANOVA) using the Roy test revealed significant effects for both blocks and treatments (Table 1). For blocks, the Roy value was 4.69498, with an approximate F-value of 6.573 and $p < 0.001$, indicating significant differences among experimental blocks. Similarly, treatments exhibited significant effects (Roy = 3.94529; F = 7.1015; p < 0.001), confirming multivariate variation among the evaluated treatments. These results, obtained with degrees of freedom adjusted using the Kenward–Roger method, confirm the robustness of the analysis and demonstrate that the observed differences are not attributable to random variation.

Table 1. Results of multivariate analysis of variance (MANOVA) using the Roy test and complementary analyses with REML linear mixed models, with degrees of freedom adjusted by the Kenward–Roger method.

Effect	Value	NDF	DDF	AFV	*p*-value	Significance
Blocks	4.69498	10	14	6.573	0.00087432	p < 0.001
Treatments	3.94529	10	18	7.1015	0.00018153	p < 0.001

Treatments were considered as a fixed effect and blocks as a random effect. NDF = numerator degrees of freedom; DDF = denominator degrees of freedom; AFV = approximate F-value.

Given the significance of multivariate effects, principal component analysis (PCA) was performed to examine the correlation structure among agronomic traits and the distribution of treatments in multivariate space (Figure 2a). PCA revealed that the first two principal components, PC1 (33.5%) and PC2 (20.1%), accounted for 53.6% of the total variance, effectively distinguishing the treatments. The

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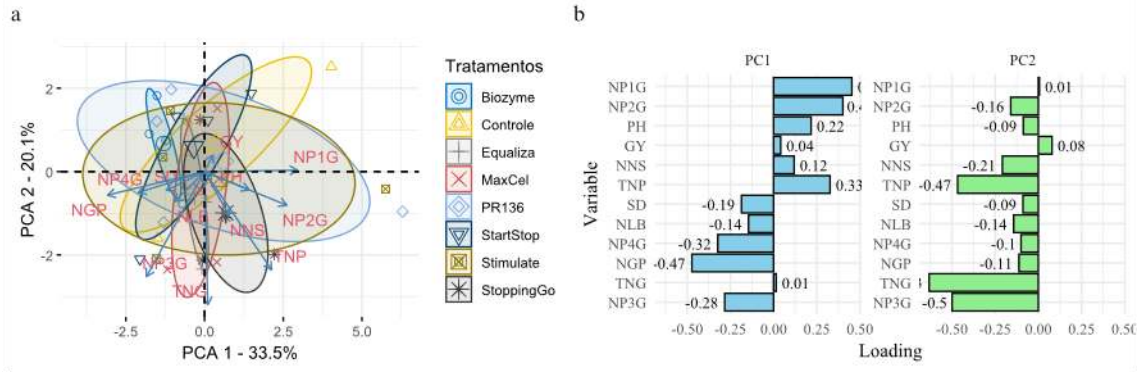
treatments Stimulate, StoppingGo, Equaliza, and MaxCel were associated with a higher total number of pods and greater number of pods with one to two grains, suggesting higher yield potential. The Control and PR136 exhibited more limited reproductive traits, while Biozyme and StartStop showed intermediate responses. These findings suggest that increases in pods with 1 to 2 grains contribute more significantly to yield than increases in the number of grains per pod.

The variable contribution plot (Figure 2b) supports this interpretation by showing that the number of pods with one grain (0.40), number of pods with two grains (0.40), and total number of pods per plant (0.33) exhibited the highest positive loadings on PC1, whereas average number of grains per pod (–0.47), number of pods with four grains (–0.32), and number of pods with three grains (–0.28) had negative loadings, confirming that PC1 represents a gradient of pod prolificacy contrasted with the number of grains per pod. The highest loadings in PC2 were observed for the total number of grains per plant (–0.63) and number of pods with three grains (–0.50), indicating that this component captures variation related to the number of grains per plant and pods with three grains.

Figure 2. Principal component analysis (PCA) of soybean agronomic traits. (a) Distribution of treatments in the plane formed by the first two principal components (PC1 and PC2) with 95% confidence ellipses. (b) Loadings of original traits on principal components PC1 and PC2.



In addition to the exploratory PCA, a mixed model analysis was conducted on PC1 and PC2 scores, considering block as a random effect, to estimate posterior marginal means and their corresponding 95% credible intervals (Table 2). This analysis assessed the statistical robustness of the treatment separations observed

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in the biplot. All credible intervals included zero, indicating that although some treatments exhibited tendencies toward positive scores (StoppingGo, PR136, and Stimulate in PC1; Control and StartStop in PC2), none differed significantly from the multivariate centroid. Thus, these findings confirm that the differences observed in the PCA represent non-significant trends, highlighting the need for cautious agronomic interpretation and further studies to substantiate these observations.

Table 2. Posterior marginal means of PC1 and PC2 by treatment from multivariate mixed models considering block as a random effect, including point estimates and 95% **credible** intervals (CrI).

Treatment	PC1 Mean	PC1 Lower 2.5%	PC1 Upper 97.5%	PC2 Mean	PC2 Lower 2.5%	PC2 Upper 97.5%
Biozyme	-0.49	-2.44	1.43	0.38	-1.41	2.22
Controle	0.14	-2.12	2.4	0.67	-1.31	2.62
Equaliza	-0.4	-2.69	1.86	-0.43	-2.36	1.54
MaxCel	-0.26	-2.51	1.95	-0.32	-2.22	1.63
PR136	0.34	-1.97	2.57	0.31	-1.63	2.26
StartStop	-0.42	-2.7	1.83	0.6	-1.34	2.59
Stimulate	0.21	-2.05	2.42	-0.07	-1.96	1.85
StoppingGo	0.38	-1.92	2.58	-0.82	-2.74	1.09

Path analysis based on direct effects revealed that the average number of grains per pod (–0.62) and the number of pods with one grain (–0.42) exerted the largest negative direct effects on grain yield, suggesting that, under similar experimental conditions, increases in these traits may be associated with reduced yield (Figure 3). In contrast, stem base diameter (0.19) and the number of pods with two grains (0.15) exhibited the largest positive direct effects, indicating that these traits contribute directly to yield increases. Other traits exhibited direct effects of low magnitude (≤ |0.10|), including total number of pods per plant (–0.18), number of pods with four grains (0.10), and plant height (0.06), indicating limited direct influence on grain yield. These findings suggest that reproductive architecture, particularly number of pods with two grains and stem base diameter, contributes more significantly to grain yield increases than increasing the number of grains per pod.

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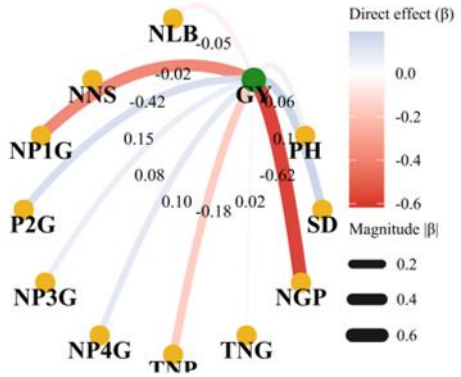
Figure 3. Radial plot of path analysis depicting direct effects of agronomic traits on grain yield. The thickness of the arrows is proportional to the magnitude of the effect (|β|), and the color indicates positive (blue) or negative (red) values.



The Multi-Trait Genotype-Ideotype Distance Index (MGIDI) integrated multiple traits into a single selection metric (Figure 4). This index ranked treatments based on their proximity to the ideotype, defined as the theoretical combination of optimal trait values, establishing a selection threshold at Z = 15% intensity to identify treatments closest to this standard. The analysis revealed that only the Stimulate treatment remained within the selection threshold, demonstrating the closest alignment with the ideotype and, therefore, superior multivariate performance under the experimental conditions. Other treatments exceeded the selection threshold, falling outside the elite group and indicating lower potential when morphoagronomic and yield traits were evaluated concurrently. These findings confirm the efficacy of MGIDI in synthesizing complex data and guiding the selection of treatments with balanced agronomic traits.

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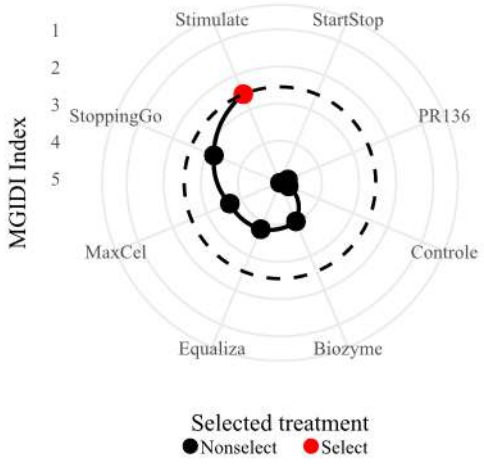
Figure 4. Classification of treatments by the Multi-Trait Genotype-Ideotype Distance Index (MGIDI) in soybean under plant structure management practices. Dashed circle = Z threshold (15% intensity).



The integrated application of multivariate analytical techniques (MANOVA, PCA, mixed models, path analysis, and MGIDI) provided a comprehensive assessment of treatment effects on agronomic traits. The results revealed consistent multivariate response patterns, demonstrating that only Stimulate exhibited optimal trait combinations under the evaluated conditions, although specific traits such as average number of grains per pod and stem base diameter significantly influenced grain yield.

4. Discussion

Multivariate analysis of variance (MANOVA) confirmed significant differences among treatments, validating the experimental design. Vasconcelos et al. (2024) noted that multivariate techniques in agriculture enable the identification of efficiency patterns in management practices that are not detectable by univariate analyses. In this study, the detection of multivariate differences suggests that the tested plant growth modulators induced coordinated changes in multiple agronomic traits, reflecting modifications in underlying physiological processes.

Principal component analysis (PCA) revealed that the first two principal components accounted for a substantial proportion of the total data variance, indicating consistent covariation patterns among the evaluated agronomic traits.

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This multivariate approach aligns with recent studies demonstrating the efficacy of PCA in identifying clusters of agronomic traits, facilitating the simplification of complex datasets and the detection of treatment response patterns (Vasconcelos, Silva & Santos, 2024). Additionally, Ferreira et al. (2025a) confirmed in a field study that foliar fertilization with magnesium enhances soybean yield, highlighting the importance of nutritional management in optimizing yield, as evidenced by PCA-based analysis.

Posterior marginal means (Table 2) indicated that, although trends of separation among treatments were observed in the first two principal components, none exhibited statistically significant deviation from the multivariate centroid. In PC1, most treatments exhibited positive scores, suggesting a common response gradient associated with overall plant development. In PC2, distinct patterns were observed, with Stimulate and Control treatments exhibiting positive scores, in contrast to Equaliza and StoppingGo with negative scores. These findings suggest that PC2 captures qualitative variations among plant growth modulators, associated with specific traits of plant architecture or grain yield. However, as the credible intervals included zero, these differences should be interpreted as trends, highlighting the need for further studies to substantiate these observations.

Path analysis revealed that stem base diameter and the number of pods with two grains exhibited the largest positive direct effects on grain yield. These findings are consistent with studies identifying structural traits and specific reproductive components as primary determinants of soybean yield (Khoi, 2024; Krenchinski et al., 2024). The positive effect of stem base diameter may be associated with enhanced photoassimilate transport capacity and increased resistance to lodging, whereas the contribution of number of pods with two grains highlights the importance of balanced reproductive architecture for yield increases.

The most pronounced negative direct effects were observed for the average number of grains per pod and the number of pods with one grain, suggesting that increases in these traits may reduce yield by decreasing the efficiency of converting reproductive structures into grain yield. This interpretation is supported by studies demonstrating that plant growth modulators optimize the source-sink relationship,

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enhancing grain filling relative to less efficient reproductive patterns (Zamarian & Battistus, 2024).

The application of the Multi-Trait Genotype-Ideotype Distance Index (MGIDI) provided an effective method for integrating multiple traits into a single selection metric. Recent studies have demonstrated the efficacy of MGIDI in selecting ideotypes for crops such as maize and wheat, due to its ability to balance multiple traits simultaneously (Pham et al., 2023; Al-Ashkar et al., 2023a). Ferreira et al. (2025b) reported that multivariate analysis, including MGIDI, facilitated the classification of genotypes and treatments based on physiological and yield-related patterns, demonstrating the efficacy of the multi-trait approach for enhancing soybean resistance. This approach, aligned with other multivariate analyses such as PCA and MANOVA, validated the importance of coordinated changes in agronomic traits induced by the applied treatments.

The exclusive selection of the Stimulate treatment by MGIDI, using a 15% intensity threshold, indicates that this treatment exhibited the most balanced combination of desirable agronomic traits. Pham et al. (2023) reported comparable results for waxy purple maize, where MGIDI identified elite hybrids that optimally combined growth and yield traits. The specificity of this selection suggests that other treatments, although possibly exhibiting superior individual traits, did not achieve the necessary balance across all evaluated traits.

The superior multivariate response of the Stimulate treatment, identified by the MGIDI analysis, can be attributed to the specific mechanisms of action of plant growth modulators on plant architecture and carbohydrate allocation. Recent studies indicate that plant growth modulators alter the hormonal balance of plants, affecting internode elongation, number of leaves, and flowering time (Rajadhivya, Macwan & Bhanvadia, 2024; Tigga et al., 2024). Tigga et al. (2024) observed that intermediate concentrations of triazole-based plant growth regulators increased stem dry weight and promote early flowering, resulting in an optimal balance between plant height and grain yield.

The dose-dependent responses observed across treatments align with the findings of Rajadhivya et al. (2024), who reported that plant growth modulators in

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soybean induce more pronounced architectural changes at higher rates, whereas intermediate rates often optimize reproductive biomass. This hormonal modulation explains the observed differences in vegetative and reproductive traits among treatments, as reflected in the separation patterns of the principal components.

These findings have direct implications for the management of plant growth modulators in soybean cultivation. The superior multivariate response of Stimulate suggests that its formulation promotes an optimal balance between vegetative and reproductive traits, likely through coordinated modulation of multiple hormonal pathways. This result indicates that soybean producers should select plant growth modulators considering not only effects on individual traits but also their integrated impact on overall crop yield.

The application of plant growth modulators at the soybean V4 stage aligns with literature recommendations identifying this stage as critical for interventions targeting plant architecture (Amoanimaa-Dede et. al., 2022; Zamarian & Battistus, 2024). Recent studies indicate that applications at the V4 stage enable plant growth modulators to influence both vegetative development and reproductive differentiation, maximizing agronomic benefits (Krenchinski et al., 2024).

The integrated application of multivariate techniques principal component analysis (PCA), multivariate analysis of variance (MANOVA), path analysis, and the Multi-Trait Genotype-Ideotype Distance Index (MGIDI) proved effective in evaluating plant growth modulators in soybean, facilitating the identification of response patterns not detectable by univariate analyses. The treatment with Stimulate (Stoller) was identified as the closest to the ideotype, achieving an optimal balance of vegetative and reproductive traits and demonstrating superior multivariate yield potential. Path analysis identified stem base diameter and the number of pods with two grains as the primary positive determinants of grain yield, whereas traits associated with excessive vegetative growth exhibited negative effects. The MGIDI index demonstrated its efficacy as a robust selection tool for the simultaneous evaluation of multiple traits. These findings provide practical implications for soybean management and contribute methodologically to agronomic research,

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highlighting the need for validation across diverse environments and cultivation conditions.

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