

Modulators of apical dominance and seeding density alter the vegetative and productive development of soybean

Moduladores de dominância apical e densidade de semeadura alteram o desenvolvimento vegetativo e produtivo da soja

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ABSTRACT

Soybean cultivation (*Glycine max* (L.) Merrill) faces challenges due to excessive vegetative growth. Therefore, this study aimed to evaluate the effect of mechanical apical meristem removal and the application of three herbicides and one biostimulant at two vegetative development stages, under different sowing densities. The study was conducted during the 2019/20 and 2020/21 cropping years using a randomized complete block design with a split-plot arrangement and four replications. Main plots consisted of two sowing densities (300,000 and 400,000 seeds ha⁻¹), and subplots comprised eight combinations of apical dominance modulators and application timings (1. lactofen at V4; 2. lactofen at V6; 3. lactofen at V4+V6; 4. 2,4-D at V6; 5. imazethapyr at V4+V6; 6. mechanical apical bud removal at V6; 7. biostimulant at V4+V6; and 8. control without application). Plant height, number of branches and pods per plant, weight of 100 grains, and grain yield were evaluated. Plants grown at the highest sowing density (400,000 seeds ha⁻¹) exhibited greater height and higher weight of 100 grains, but fewer lateral branches. At the highest sowing density, chemical treatments reduced grain yield during the 2019/20 cropping year; however, lactofen applied at V4 significantly increased grain yield in the 2020/21 cropping year. Although lactofen application shows potential under specific conditions, it still lacks consistent results to support a reliable recommendation. In this study, no growth modulation effects were observed from the herbicides 2,4-D, imazethapyr, or the biostimulant.

Index terms: Plant architecture; *Glycine max*; herbicides; plant population; growth regulators.

RESUMO

O cultivo da soja (*Glycine max* (L.) Merrill) enfrenta desafios devido ao crescimento vegetativo excessivo. Portanto, objetivou-se avaliar o efeito do corte mecânico do meristema apical e da aplicação de três herbicidas e um bioestimulante em dois estádios de desenvolvimento vegetativo da soja, implantada em diferentes densidades de semeadura. Nas safras 2019/20 e 2020/21 o estudo foi conduzido em delineamento de blocos casualizados, esquema de parcelas subdivididas, com quatro repetições. As parcelas principais foram duas densidades (300.000 e 400.000 sementes ha⁻¹), e as subparcelas oito combinações de moduladores de dominância apical e estágio fenológico para aplicação (1. lactofen em V4; 2. lactofen em V6; 3. lactofen em V4+V6; 4. 2,4-D em V6; 5. imazetapir em V4+V6; 6. corte mecânico da gema apical em V6; 7. bioestimulante em V4+V6 e 8. controle sem aplicação). Foi avaliada a altura, número de ramificações e de vagens por planta, peso de 100 grãos e produtividade de grãos. As plantas cultivadas com a maior densidade (400.000 sementes ha⁻¹) apresentaram maior altura e peso de 100 grãos, mas menor número de ramificações laterais. Na maior densidade de semeadura, a aplicação dos produtos químicos reduziu a produtividade na safra 2019/20, porém o lactofen (V4) aumentou significativamente a produtividade de grãos na safra 2020/21. Embora a aplicação de lactofen mostre potencial em situações específicas, ainda carece de resultados consistentes que sustentem uma recomendação segura. Neste estudo, não foi observado efeito de modulação do crescimento pelos herbicidas 2,4-D, imazetapir ou pelo bioestimulante.

Termos para indexação: Arquitetura vegetal; *Glycine max*; herbicidas; população de plantas; reguladores de crescimento.

Introduction

Soybean (*Glycine max* (L.) Merrill) is a key crop for global food and energy security. Brazil leads global production with 169 million metric tons, followed by the United States (118 million t) and Argentina (51 million t) for the 2024/25 cropping year (United States Department of Agriculture - USDA, 2025). The crop's socioeconomic relevance is marked by its contribution to job creation and trade surplus in producing countries (Toloi et al., 2021).

However, soybean production still faces challenges related to lodging and self-shading, caused by excessive vegetative growth in some cultivars. This reduces light incidence on the leaves of the lower third of the plants, causing premature senescence, which can result in the abortion of flowers and pods (Pereira et al., 2018; Xu et al., 2021). In this context, controlling vegetative

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development emerges as an alternative to mitigate these effects through the adjustment of sowing density and the management of plant architecture, aiming to regulate height growth and stimulate lateral branching to favor the formation of reproductive structures (Silva et al., 2019; Martins et al., 2020).

Altering plant architecture through the use of biostimulants, herbicides, and mechanical apical meristem cutting may represent an effective agronomic strategy to modulate soybean vegetative development and increase grain yield. The application of plant extract-based biostimulants to soybean shows potential for improving the plant's productive characteristics (Szparaga et al., 2023). Regarding herbicides and mechanical apical meristem cutting, studies demonstrate significant alterations in vegetative development and crop yield (Gallon et al., 2016; Martins et al., 2020; Rosa et al., 2020; Pereira et al., 2022; Rosa et al., 2021).

However, the positive effect of herbicides is the most questioned due to the injuries they cause to plants, especially in locations more prone to environmental stresses, such as low-altitude regions in Brazil. Lactofen, an inhibitor of the PROTOX (protoporphyrinogen oxidase) enzyme, stands out as one of the most used herbicides for modulating soybean architecture, although it may reduce its productive potential (Gallon et al., 2016; Rosa et al., 2020; Pereira et al., 2022). Due to its low mobility, lactofen exerts its effects primarily at the application sites, with a more pronounced action on the apical bud and leaves of the upper third, promoting the formation of reactive oxygen species, altering essential physiological processes, and consequently, potentially reducing final grain yield (Hess, 2000; HRAC, 2025). However, this response may vary depending on the region's climatic characteristics, applied dose, soybean cultivar, and the vegetative stage of the plants at the time of spraying, which justifies further investigation into its use as a vegetative management tool.

Sowing density is also a determining factor for soybean performance, as it simultaneously regulates plant architecture and productive efficiency (Silva et al., 2021; Paraginski et al., 2022; Xu et al., 2021; Xu et al., 2024). Sowing density management has contrasting effects on the soybean crop: high populations favor canopy closure and light interception but increase the risk of etiolation and lodging (Xu et al., 2021; Wang et al., 2023). Conversely, at low densities, soybean exhibits greater vegetative stability and activates phenotypic plasticity mechanisms (such as increased lateral branching and pods per plant) to compensate for the population reduction (Paraginski et al., 2022); however, this can still result in yield losses per area (Xu et al., 2024). Thus, a sowing density adjusted to regional sowing conditions can optimize plant architecture, promoting a greater emission of productive branches and increasing the number of pods per plant (Silva et al., 2021; Xu et al., 2021; Xu et al., 2024).

Given the above, we hypothesize that the interaction between plant architecture-modulating agents and sowing density positively affects soybean crop yield. Therefore, the objective

of this study was to evaluate the effect of mechanical apical meristem cutting and the application of three herbicides and one biostimulant at two vegetative development stages of soybean, established under sowing densities.

Material and Methods

The study was conducted during the 2019/20 and 2020/21 cropping years at the Scientific and Technological Development Center in Agriculture of UFLA, at Muquém Farm (21° 14' 43" S and 44° 59' 59" W), in Lavras, Minas Gerais. The local soil is classified as a Red-Yellow Latosol (Oxisol), with a clayey texture (Santos et al., 2018) and as a Typic Hapludox according to US Soil Taxonomy (Soil Survey Staff, 2014). The climate under the Köppen classification is Cwa, with an average annual temperature of 20°C and average annual rainfall of 1460 mm (Alvares et al., 2013).

Sowing was carried out on October 28, 2019, and November 5, 2020, for the 2019/20 and 2020/21 cropping years, respectively. The meteorological conditions during the experimental period are shown in Figure 1. Harvesting for the 2019/20 and 2020/21 cropping years were performed on March 16, 2020, and March 23, 2021, respectively.

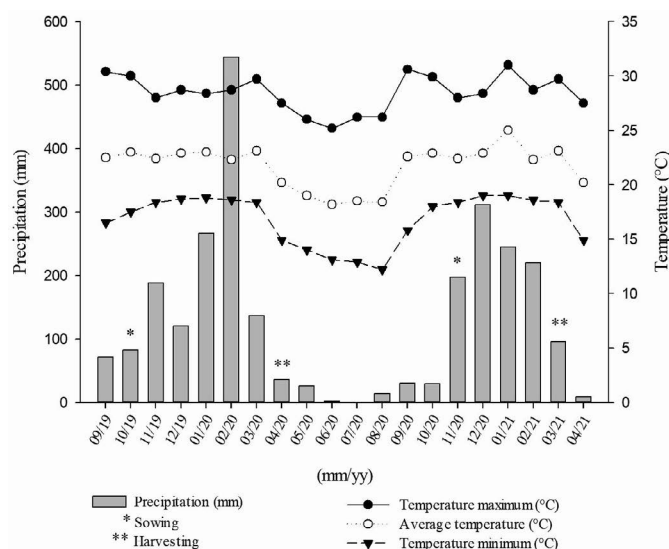


Figure 1: Temperature and cumulative precipitation (mm) during the course of the experiments in the 2019/20 and 2020/21 cropping years, Muquém Farm, Lavras, Minas Gerais. Source: INMET (2025) Conventional Meteorological Station in Lavras, MG, Brazil.

Soil chemical characterization was performed for the 2019/20 cropping year by collecting samples from the 0-20 cm depth layer. The results of the chemical analyses are as follows: pH (H₂O) 5.7; 2.6 dag kg⁻¹ O.M. (organic matter); 7.4

mg dm⁻³ P (P-Mehlich); 130 mg dm⁻³ K; 3.2 cmol_c dm⁻³ Ca; 1.1 cmol_c dm⁻³ Mg; 0.1 cmol_c dm⁻³ Al; 2.3 cmol_c dm⁻³ H+Al; 4.7 cmol_c dm⁻³ SB (sum of bases); 7 cmol_c dm⁻³ CEC (cation exchange capacity at pH 7); 67% BS (base saturation); 2.1% m of aluminum saturation. The average soil physical composition was: 24% sand, 25% silt, and 50% clay.

The experiments were set up in a randomized block design with a split-plot arrangement and four replications, totaling 64 plots per experiment. The main plots consisted of two sowing densities: 300,000 and 400,000 seeds ha⁻¹ of the cultivar Brasmax Desafio RR (indeterminate growth habit, relative maturity group = 7.4, average cycle in microregion 302 South MG = 128 days). The subplots consisted of the apical dominance modulators, described in Table 1.

At the time the experiments were conducted, the Desafio cultivar was among the most widely planted in Brazil and remains commercially available to this day. Among the herbicides tested (Table 1), lactofen is the most used for this purpose; however, its effectiveness has shown inconsistent results due to its response being influenced by multiple factors, notably the phenological stage and application rate (Gallon et al., 2016; Martins et al., 2020; Rosa et al., 2020; Rosa et al., 2021). For this reason, three out of the eight treatments evaluated in this study involved this molecule, involving the commercial dose (144 g a.i. ha⁻¹) applied at two distinct phenological stages, as well as the split application of this dose twice on the same plants. In contrast, 2,4-D, imazethapyr, and the biostimulant have been less extensively studied by the scientific community (Pereira et al., 2022), yet they exhibit potential for use as modulators of apical dominance. Branching in soybean plants begins to occur between the V3 and V5 developmental stages (Zanon et al., 2015), which justifies the selection of these phenological stages in the present study.

The experimental units consisted of four rows, each 6.0 m long, with 0.6 m spacing between rows, totaling an area of 14.4 m². The useful area comprised the two central rows, each 5 meters long (discounting 0.5 m from each end, totaling 1 m per row).

Fertilization was based on soil analysis and recommendations by Sousa and Lobato (2004) for target yields of 4.0 to 5.0 t ha⁻¹, applying 82 kg ha⁻¹ P₂O₅ and 40 kg ha⁻¹ K₂O. Six doses of a *Bradyrhizobium* sp. inoculant (strains SEMIA 587, SEMIA 5019, SEMIA 5079, and SEMIA 5080) were used, corresponding to 7.2 million viable cells per 50 kg of soybean seeds and 600 mL of commercial product per 50 kg of seeds, applied in the seeding furrow. Manual weed management was conducted at the V3 growth stage of soybean, while pest and disease control measures were applied based on monitoring and necessity.

The apical dominance modulators were applied post-emergence using a motorized backpack sprayer. The application boom contained four nozzles with AD 11002 flat fan tips (spaced 0.6 m apart). All sprays were applied at a volume of 200 L ha⁻¹ and at the respective phenological stages described in Table 1. Removal of the apical meristem was performed mechanically using a manual grass cutter, cutting 0.5 m below the apical meristem.

Evaluations were carried out before harvest at stage R8 (physiological maturity). Five soybean plants were randomly selected from the useful area of each plot to measure plant height and count the number of lateral branches, and the number of pods per plant.

At harvest, yield was estimated from the useful area. Plants were mechanically threshed, and grains from each plot were separated for weighing and moisture determination. After obtaining the moisture content of each sample, the total grain mass per plot was corrected to 13% moisture. The weight of 100 grains was also evaluated based on three replicates of 100 grain each, followed by calculation of the average.

Table 1: Apical dominance modulators and application timings according to the phenological stage of the soybean crop. Muquém Farm, Lavras, Minas Gerais.

Apical dominance modulators		Dose (g ha ⁻¹) ²	Phenological stage of application ³
Common name/a.i. or a.e. ¹	Trade name		
Control	-	-	-
Mechanical cutting of apical buds	-	-	V6
Biostimulant ⁴	Grain Set®	250 + 250 mL	V4 + V6
2,4-D	2,4-D Nortox®	50	V6
Lactofen	Naja®	72 + 72	V4 + V6
Lactofen	Naja®	144	V4
Lactofen	Naja®	144	V6
Imazethapyr	Imazetapir Nortox®	60	V6

¹a.i. active ingredient; a.e. acid equivalent ²2,4-D and imazethapyr doses expressed as a.e.; lactofen doses expressed as a.i. ³Soybean phenological stage (Fehr & Caviness, 1977). ⁴Biostimulant composition: plant extracts and nutrients complexed by amino acids (1% S + 0.8% Mn + 1.2% Zn).

Statistical analysis was performed separately for each cropping year using analysis of variance (ANOVA). The F-test was used to detect significant effects after prior checking of its assumptions and confirmation of normality and homoscedasticity. Treatment means were compared by Tukey's test at a 5% probability level using the statistical software SISVAR, version 5.6 (Ferreira, 2019).

Results and Discussion

The factors apical dominance modulators × sowing densities resulted in an isolated effect on plant height, the number of lateral branches and weight of 100 grains in the 2019/20 and 2020/21 cropping years (Tables 2, 3 and 5). The number of pods per plant (2020/21 cropping year) was affected by the interaction of the factors in only one cropping year, while in the 2019/20 cropping year they were affected in isolation without a significant interaction effect (Tables 4). The soybean grain yield was altered due to the interaction of the factors in both cropping years (Tables 6).

Plant height was not significantly altered by sowing density in the 2019/20 cropping year; however, a 14.93% increase in height was observed at the density of 400 thousand seeds ha⁻¹ in the 2020/21 cropping year (Table 2).

The increase in plant height under higher sowing density may be related to the intensification of competition for essential resources, primarily light, which can induce etiolation, an

excessive stem elongation in search of luminosity, altering plant architecture (Martins et al., 1999; Mauad et al., 2010). Xu et al. (2024) observed that increased planting density in soybean resulted in a significant increment in plant height and internode length, accompanied by a reduction in stem diameter, highlighting structural changes that can affect plant performance. Such responses are triggered in soybean plants as an adaptive strategy to maximize light capture, reallocating carbon toward stem elongation at the expense of stem diameter and mechanical properties, such as lignin and cellulose accumulation, which may increase the risk of lodging (Wang et al., 2023).

Apical bud cutting resulted in the lowest plant heights in both the 2019/20 (57.55 cm) and 2020/21 (55.93 cm) cropping years (Table 2). This was likely due to its early removal, performed when plants had only six nodes on the main stem, leading to a premature cessation of height growth. Martins et al. (2020) also observed that plants subjected to apical bud cutting exhibited reduced height development. The removal of the apical bud, the primary source of auxin in the plant, significantly reduces longitudinal growth, as this phytohormone is essential for cell elongation in the stem (Taiz et al., 2017).

The application of lactofen at the V4 (83.93 cm) and V6 stage (79.84 cm) increased plant height by 14.48% and 8.9% in the 2020/21 cropping year, respectively, compared to the control (Table 2). Pereira et al. (2022) also observed an increase in M8372 IPRO soybean plant height following the application of a subdose (96 g a.e. ha⁻¹) of lactofen at V4.

Table 2: Plant height (cm) of soybean as a function of apical dominance modulator application and sowing density in the 2019/20 and 2020/21 cropping years

Apical dominance modulators	Cropping year/sowing density (seeds ha ⁻¹)			
	2019/20		2020/21	
	300,000	400,000	300,000	400,000
	70.94 A ¹	77.12 A	69.71 B	80.12 A
Control	75.62 ab		73.31 c	
Cutting the apical buds (V6)	57.55 c		55.93 d	
2,4-D (V6)	71.62 b		78.21 bc	
Biostimulant (V4 + V6)	77.32 ab		73.15 c	
Lactofen (V4 + V6)	72.72 b		76.84 bc	
Lactofen (V4)	77.40 ab		83.93 a	
Lactofen (V6)	78.00 ab		79.84 ab	
Imazethapyr (V4 + V6)	82.02 a		78.12 bc	
Overall Average	74.03		74.92	
C.V. 1(%)	15.75		4.64	
C.V. 2(%)	5.91		4.76	

¹Uppercase letters (row) and lowercase letters (column) compare different treatments within each sowing density for the respective cropping year using Tukey's test at a 5% probability level.

Table 3: Number of lateral branches per soybean plant as a function of apical dominance modulator application and sowing density in the 2019/20 and 2020/21 cropping years

Apical dominance modulators	Cropping year/sowing density (seeds ha ⁻¹)			
	2019/20		2020/21	
	300,000	400,000	300,000	400,000
	2.95 A ¹	2.98 A	4.06 A	3.06 B
Control		3.02 ab		3.90 ²
Cutting the apical buds (V6)		3.92 a		3.87
2,4-D (V6)		2.77 b		3.57
Biostimulant (V4 + V6)		3.12 ab		3.92
Lactofen (V4 + V6)		2.87 ab		3.95
Lactofen (V4)		2.91 ab		2.67
Lactofen (V6)		2.55 b		2.77
Imazethapyr (V4 + V6)		2.55 b		3.85
Overall Average		2.96		3.56
C.V. 1(%)		23.08		13.52
C.V. 2(%)		22.38		23.49

¹Uppercase letters (row) and lowercase letters (column) compare different treatments within each sowing density for the respective cropping year using Tukey's test at a 5% probability level. ²In the 2020/21 cropping year, the effects of apical dominance modulators were not significant according to the F-test ($p \leq 0.05$).

Table 4: Number of pods per plant as a function of apical dominance modulator application and sowing density in the 2019/20 and 2020/21 cropping years

Apical dominance modulators	Cropping year/sowing density (seeds ha ⁻¹)			
	2019/20		2020/21	
	300,000	400,000	300,000	400,000
	61.03 ¹	54.00	-	-
Control	55.37		62.95 Aab ²	53.40 Aab
Cutting the apical buds (V6)	59.47		59.55 Aab	47.00 Aab
2,4-D (V6)	55.80		62.90 Aab	65.95 Aa
Biostimulant (V4 + V6)	60.67		64.15 Aab	37.90 Bc
Lactofen (V4 + V6)	56.02		71.95 Aa	51.80 Bab
Lactofen (V4)	57.47		50.35 Aab	47.70 Aab
Lactofen (V6)	58.80		43.30 Bc	64.50 Aa
Imazethapyr (V4 + V6)	56.50		63.00 Aab	51.75 Aab
Overall Average	57.51		56.13	
C.V. 1(%)	25.64		9.84	
C.V. 2(%)	19.48		19.95	

¹In the 2019/20 cropping year, the effects of apical dominance modulators and sowing density were not significant according to the F-test ($p \leq 0.05$). ²Uppercase letters (row) and lowercase letters (column) compare different treatments within each sowing density for the respective cropping year using Tukey's test at a 5% probability level.

The absence of significant differences between lactofen treatments and the control in the 2019/20 cropping year, in contrast to the increased plant height observed in 2020/21 for lactofen V4 and lactofen V6, can be primarily attributed

to differing environmental conditions between the two years, particularly in terms of temperature and precipitation (Figure 1). In 2020/21, more favorable environmental conditions - characterized by higher rainfall and stable average temperatures

after the period of growth regulator application - enabled greater physiological plasticity and compensatory growth, thereby enhancing the hormetic effect of lactofen.

The phenomenon of hormesis - where low doses of herbicides stimulate plant growth - has been described by Pereira et al. (2022),

and is highly dependent on the interaction among dose, phenological stage, cultivar, and environment. Thus, in 2020/21 cropping year, lactofen applied at the V4 and V6 stage under favorable metabolic and photosynthetic conditions stimulated stem elongation and internode growth, resulting in taller plants (Table 2).

Table 5: Weight of 100 grains as a function of apical dominance modulator application and sowing density in the 2019/20 and 2020/21 cropping years.

Apical dominance modulators	Cropping year/sowing density (seeds ha ⁻¹)			
	2019/20		2020/21	
	300,000	400,000	300,000	400,000
	17.81 ¹	17.87	17.54 B ²	18.41 A
Control		18.41		18.11 ab
Cutting the apical buds		16.91		17.48 ab
2,4-D (V6)		18.08		17.28 b
Biostimulant (V4 + V6)		17.98		18.36 ab
Lactofen (V4 + V6)		17.93		18.65 a
Lactofen (V4)		17.57		17.85 ab
Lactofen (V6)		17.71		18.16 ab
Imazetapir (V4 + V6)		18.16		18.03 ab
Overall Average		17.84		17.98
C.V. 1(%)		6.49		4.18
C.V. 2(%)		5.43		4.34

¹In the 2019/20 cropping year, the effects of apical dominance modulators and sowing density were not significant according to the F-test ($p \leq 0.05$). ²Uppercase letters (row) and lowercase letters (column) compare different treatments within each sowing density for the respective cropping year using Tukey's test at a 5% probability level.

Table 6: Grain yield as a function of apical dominance modulator application and sowing density in the 2019/20 and 2020/21 cropping years

Apical dominance modulators	Cropping year/sowing density (seeds ha ⁻¹)			
	2019/20		2020/21	
	300,000	400,000	300,000	400,000
Control	4006.84 Bab ¹	5697.61 Aa	3151.68 Aab	3392.76 Ab
Cutting the apical buds (V6)	3366.23 Bb	5182.28 Aab	2648.99 Bb	3796.67 Aab
2,4-D (V6)	3747.05 Aab	3551.04 Ad	3982.81 Aa	4151.35 Aab
Biostimulant (V4 + V6)	3624.51 Aab	4365.39 Abcd	2690.79 Bb	4169.90 Aab
Lactofen (V4 + V6)	3640.52 Bab	4579.32 Abc	3798.44 Aab	3967.18 Aab
Lactofen (V4)	3600.74 Aab	3937.41 Acd	4015.18 Aa	4642.73 Aa
Lactofen (V6)	4362.72 Aa	4374.96 Abcd	4281.83 Aa	3800.83 Aab
Imazethapyr (V4 + V6)	4217.98 Aab	4123.13 Acd	4208.37 Aa	3566.08 Aab
Overall Average		4148.61		3766.60
C.V. 1(%)		22.46		21.17
C.V. 2(%)		9.41		13.72

¹Uppercase letters (row) and lowercase letters (column) compare different treatments within each sowing density for the respective cropping year using Tukey's test at a 5% probability level.

In summary, the variation between cropping years is explained by the interaction among genotype, environment, dose, and application timing, with a more pronounced positive response in 2020/21 cropping year due to climatic conditions that favored recovery and vegetative growth following herbicide-induced stress.

The number of lateral branches was highest following mechanical apical meristem cutting (3.92 lateral branches plant⁻¹) compared to the application of 2,4-D at V6, lactofen at V4, and lactofen at V4 + V6 (Table 3). Thus, the removal of the apical bud, the primary source of auxin, reduces apical dominance and can result in an increased number of lateral branches per plant. This effect occurs both through a reduction in auxin inhibition of lateral buds and a possible stimulation of cytokinin flow to these buds in the main stem of soybean plants (Noodén & Letham, 1993; Nonokawa et al., 2007). As in the present study, no chemical product was able to increase the number of lateral branches compared to the control (Martins et al., 2020).

In the 2020/21 cropping year, the number of lateral branches observed was 4.06 and 3.06 lateral branches plant⁻¹, for the sowing densities of 300,000 and 400,000 seeds ha⁻¹, respectively (Table 3). The average number of lateral branches per soybean plant was reduced with the increase in sowing density. Martins et al. (1999) described that competition among plants, caused by denser plantings, results in lower availability of photoassimilates for the growth of lateral branches, as they are preferentially allocated to the growth of the soybean's main axis.

However, the use of a sowing density lower than recommended can result in shorter plants with a greater number of branches (Fiss et al., 2018), which corroborates the findings of this study. Furthermore, some soybean genotypes exhibit high phenotypic plasticity in response to plant spatial arrangement, being capable of adjusting traits such as height and number of lateral branches based on population density (Argenta et al., 2001; Xu et al., 2024).

The number of pods per plant did not differ statistically in the 2019/20 cropping year (Table 4). In the 2020/21 cropping year, there was a reduction of 31.22% and 40.89%, respectively, due to the application of lactofen at V6 at the density of 300,000 seeds ha⁻¹ and the biostimulant at V4 + V6 at the higher sowing density when compared to the control.

The lower efficacy of lactofen at V6 may be attributed to the late single application reducing the plant's recovery capacity before floral pre-differentiation under the study's environmental conditions. Lactofen can interfere with apical dominance by inhibiting the apical meristem, but its severe phytotoxic effects, such as leaf necrosis and membrane peroxidation, can also compromise the plant's physiological recovery (Marafon & Muller, 2020; Rosa et al., 2020). Furthermore, its effect as a single dose can vary depending on the application stage and cultivar. Pereira et al. (2022), evaluating herbicide application at the V4 stage on

six soybean cultivars (M8644 IPRO, M8372 IPRO, M8349 IPRO, M8766 RR, NS7901 RR, and CD251 RR), observed both increases and decreases compared to the control in the number of pods per plant following lactofen application.

The biostimulant, while it did not increase the number of pods per plant, possibly optimized the allocation of photoassimilates for the development and filling of grains in the existing pods (Table 4), suggesting a mechanism prioritizing quality over quantity. Thus, the reduction observed at the higher population density was likely due to excessive stimulation of vegetative growth at the expense of reproductive structure formation, exacerbated in a high population where competition for light and resources intensifies apical dominance.

Szparaga et al. (2023) reported greater efficiency when the application of a plant extract-based biostimulant occurred at V4 and R1 of the Abelina cultivar. At this stage, the biostimulant promoted a balance between primary (growth) and secondary (reproductive responses) metabolism, increasing pods and yield. Therefore, the application window (V4+V6) used in the present study may require adjustments in population density to avoid imbalances in assimilate partitioning, whereas applications at R1 appear more suitable for harmonizing vegetative and reproductive development (Szparaga et al., 2023).

The lower sowing density provided an increase of 69.26% and 38.90% in the number of pods per plant compared to the higher density, for the biostimulant and lactofen applied at V4 + V6 in the 2020/21 cropping year, respectively (Table 4). Therefore, a lower plant population per area can provide better light penetration into the canopy, which increases the partitioning of total dry matter to branches and decreases it to the main stem, consequently favoring the number of pods per plant (Board, 2000). However, it is worth emphasizing that soybean has high phenotypic plasticity and, even under variations in plant population, is capable of adjusting flower and pod production to maintain productive potential (Rambo et al., 2004; Peixoto et al., 2000; Ribeiro et al., 2017).

Furthermore, it is important to note that the split application of lactofen (V4+V6) may enhance both the vegetative and reproductive development of soybean. At the V4 stage, the action of lactofen is more efficient due to the high concentration of auxin in the apex of the main stem, which facilitates the modulation of plant architecture and growth patterns (Rosa et al., 2020). At the V6 stage, the greater cuticular thickness and detoxification capacity of the plants, associated with the subdose of lactofen, may reduce oxidative stress, preserving reproductive potential (Gallon et al., 2016; Lima et al., 2011). Therefore, the lower sowing density associated with the split application of lactofen or the biostimulant may promote a more efficient plant response due to better hormonal and architectural modulation, optimizing light interception and the partitioning of assimilates to productive branches, respectively.

During the 2019/20 cropping year, the 100-grain weight was not significantly affected by either sowing density or the application of apical dominance modulators (Table 5). In contrast, the 2020/21 cropping year revealed statistically significant effects from both factors independently. The highest 100-grain weight was observed at a sowing density of 400,000 seeds per hectare (Table 5).

In the 2020/21 cropping year, increasing the sowing density to 400,000 seeds ha^{-1} led to taller soybean plants (Table 2) with fewer lateral branches (Table 3), a typical morphophysiological response to intensified light competition. Under greater intraspecific shading, the crop reallocates resources to elongate the main stem and suppress branch development, a strategy known as shade avoidance (Xu et al., 2021). This architectural adjustment results in a shift in assimilate distribution with enhanced biomass accumulation in the main stem and reproductive organs (Xu et al., 2021). Such reallocation favors grain filling due to lower internal competition among reproductive structures, which explains the observed increase in 100-seed weight at higher plant density (Table 5). Despite a reduction in the number of branches, investment in heavier individual seeds helps sustain overall yield (Xu et al., 2024).

Thus, higher density modifies plant architecture and assimilate partitioning. This reflects physiological compensation among yield components, where increased seed weight offsets reduced branches number, prioritizing seed quality and filling under competitive conditions.

Regarding the application of apical dominance modulators, all treatments exhibited performance comparable to the untreated control, indicating no differential impact on grain weight (Table 5). No influence of lactofen on the weight of 100 grains was observed in other studies involving different cultivars (Martins et al., 2020; Pereira et al., 2022).

Grain yield in the 2019/20 cropping year following the application of lactofen at V6 (4362.72 kg ha^{-1}) was higher than mechanical apical bud cutting at the density of 300,000 seeds ha^{-1} but was statistically similar to the other treatments (Table 6). However, when the density of 400,000 seeds ha^{-1} was used in the 2019/20 cropping year, only mechanical apical bud cutting (5182.28 kg ha^{-1}) achieved a yield statistically similar to the control (5697.61 kg ha^{-1}).

The herbicide lactofen, by inhibiting the PROTOX enzyme, activates the production of reactive oxygen species in the presence of light (HRAC, 2025), causing plant injury such as necrosis and cell death symptoms at the contact sites (Graham, 2005). The herbicide imazethapyr, also registered for soybean, interferes with cellular metabolism (HRAC, 2025) and, by inhibiting the enzyme acetolactate synthase (ALS), causes damage to the plant's active growth points (apical meristem), leading to chlorosis and necrosis due to the blockage of branched-chain amino acid biosynthesis (valine, leucine, and isoleucine) and consequent disruption of protein synthesis and

meristematic cell division (Devine & Shukla, 2000). The 2,4-D herbicide acts as an auxin mimic, directly affecting cell division and growth in broadleaf weeds (HRAC, 2025). Its action induces hormonal imbalance in sensitive plants, such as conventional soybean, even at low doses (Nunes et al., 2023; Brochado et al., 2023). The mode of action of these three herbicides - by damaging the apical meristem and/or causing direct or indirect hormonal imbalance - makes them promising candidates as modulators of apical dominance. However, any phytotoxic effect caused by herbicides, whether visible or hidden, may lead to yield reduction when the plant lacks the ability to metabolize them (Brochado et al., 2023; Nunes et al., 2023), which may have occurred in this cropping year.

In the 2020/21 cropping year at the density of 300,000 seeds ha^{-1} , yields from the application of lactofen at V6 (4281.83 kg ha^{-1}), imazethapyr at V4 + V6 (4208.37 kg ha^{-1}), lactofen at V4 (4015.18 kg ha^{-1}), and 2,4-D at V6 (3982.81 kg ha^{-1}) were higher than mechanical cutting of apical bud and the application of the biostimulant at V4 + V6 and were statistically equal to the control. At the density of 400,000 seeds ha^{-1} in the 2020/21 cropping year, the application of lactofen at V4 promoted the highest result (4642.73 kg ha^{-1}), superior to the control (36.84%) and statistically equal to the other treatments (Table 6).

Rosa et al. (2021) also reported increased soybean yield following the application of lactofen (140 g a.i. ha^{-1}) at the V3 growth stage, although this effect was observed in only one cropping year. Similar to the findings of the present study, this response may be attributed to the higher rainfall volume occurring after herbicide application, which likely facilitated the rapid recovery of soybean plants from the stress induced by lactofen. In the study by Martins et al. (2020), a yield increase induced by lactofen was observed in two of the three locations evaluated. On the other hand, Pereira et al. (2022) reported an increase in the number of grains per plant caused by lactofen in the cultivars NS7901 RR and M8644 IPRO, and by 2,4-D and imazethapyr in the cultivar M8644 IPRO, all applied at subdoses.

Most yields at the higher sowing density were above the national average of 3,560 kg ha^{-1} (Companhia Nacional de Abastecimento - CONAB, 2025). Thus, lactofen treatments promoted high yields across different sowing densities and cropping years. Gallon et al. (2016) and Martins et al. (2020) found similar results using lactofen at V6 on long-cycle soybean cultivars.

Therefore, the increase in sowing density provided higher average grain yields for mechanical apical bud cutting (2019/20 and 2020/21 cropping years), the biostimulant (2020/21 cropping year), and lactofen (V4 + V6, 2019/20 cropping year) (Table 6). In this context, high sowing densities can increase the leaf area exposed to solar radiation, enhancing light interception efficiency and photosynthesis, which contributes to yield increases (Sobko et al., 2019; Xu et al., 2021; Xu et al., 2024). However, the impact of density on yield varies

according to environmental conditions, the cultivar used, and the management practices adopted (Martins et al., 2020; Rosa et al., 2021; Silva et al., 2021).

Conclusions

The interaction between sowing density and apical dominance modulators influenced soybean plant architecture and yield components. Higher plant density increased plant height and reduced lateral branching, demonstrating morphological adaptation to light competition. Although lactofen application shows promise in specific situations, it still lacks consistent results to support a safe recommendation. In this study, no growth modulation effect was observed from the herbicides 2,4-D, imazethapyr, or the biostimulant. Further studies are required to define optimal management strategies for the safe use of apical dominance modulators in soybean.

Author contribution

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Data availability statement

Data available upon request to authors.

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