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Plant Hormones as Mitigators of the Defoliation at the Reproductive Stage of Soybean Plants

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ABSTRACT

Soybean defoliation reduces grain yield, but its effects can be mitigated with products that help maintain crop productivity. This study aimed to evaluate the efficiency of plant growth regulators in mitigating the effects of defoliation on the morphometric characteristics, yield, and germination of soybean seeds. Three field trials were conducted: one in the 2022/23 and two in the 2023/24 growing seasons in Brunópolis-SC Brazil, using the cultivars NS_5000_IPRO and M_5917_IPRO. The experiments were carried out with 17 treatments arranged of two stages of defoliation (R1-beginning bloom and R3-beginning pod), three levels of defoliation: 0 (Control = D0%), 50 (D50%) and 100% (D100%) of leaf area removal, and six plant growth regulators: IBA; mepiquat; etephon; AVG; ASA; kinetin + gibberellic acid + indole-butyric acid; the regulator were applied only on plant defoliated at level of 50% (D%50%) with four replicates. Data underwent analysis of variance, and the means were compared with Dunnett tests ($p<0.05$). In general, D100% defoliation reduced plant height (PH), number of pods per plant (NP_{plant}), number of seeds per plant (NS_{plant}), number of seeds per pod (NS_{pod}), thousand seed weight (TSW), seed yield (SY), and seed germination (G%). Defoliation D50% always reduced PH and TSW; the other yield components and SY recovered both in cv. M_5917_IPRO in 2022/23 at the R1 and R3 stages and in 2023/24 only at the R3 stage. The products had an effect on the evaluated characteristics depending on the cultivar, especially an increase of SY in cv. NS_5000_IPRO for the plants treated with mepiquat in comparison with the other plant growth regulators (considering all defoliation levels). It was concluded that defoliation D100% at the reproductive stages reduces SY, and defoliation D50% can be feasible depending on defoliation level and cultivar. Exogenous applications of plant growth regulators in defoliated plants has little or no effect on mitigation seed yield.

Keywords: *Glycine max*, artificial defoliation, growth regulators, reproductive stages.

INTRODUCTION

Stress is defined as any external factor that may harm plants, which respond differently to overcome deleterious effects. Under natural or agricultural conditions, plants are exposed to biotic and abiotic stresses, the latter of which (temperature, precipitation, relative air humidity) are determinant for the adaptation and distribution of species (Taiz et al., 2017; Gull et al., 2019; Umar et al., 2022).

Defoliation may be caused by insect attacks, diseases, water deficit, or hailstorms, whose mechanical impacts - often associated with strong winds - result in torn or shredded leaves, stem breakage, and damage to reproductive structures (Cunha et al., 2001; Ha et al., 2022; Holman et al., 2022).

The response of plants to defoliation depends on their physiological stage and levels of tolerance (Taiz et al., 2017). Soybean plants tolerate injuries when their remaining leaf area maintains a sufficient rate of photosynthesis to sustain productivity (Bueno et al., 2010; Poudel et al., 2025). Long-cycle cultivars have higher recovery capacity (Glier et al., 2015), while defoliation between stages R3 and R5 cause higher reductions in yield (Diogo et al., 1997; Peluzio et al., 2004; Glier et al., 2015; Casteel, 2024; Parvej et al., 2025; Poudel et al., 2025).

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Plant hormones, which are active organic substances present in small quantities, regulate physiological processes such as germination, cell elongation, flowering, and senescence, and they act either alone or in an integrated manner according to age, organ, and environment (Taiz et al., 2017; Kerbauy, 2019). Several studies (Travaglia et al., 2009; Passos et al., 2011; Albrecht et al., 2012; Gouveia et al., 2012; Martin-Mex et al., 2012; Brito et al., 2013; Fioreze et al., 2013; Nonokawa et al., 2015; He et al., 2019; Wang et al., 2025; Yao et al., 2025) showed positive effects of exogenous application of plant hormones on morphological and productive characteristics, stimulating further research with different species and environmental conditions.

Thus, the present study evaluated the impact of three levels of artificial defoliation, whether or not associated with the application of plant regulators, as a strategy to mitigate the effects of defoliation in soybeans during the reproductive phase, and the consequences for yield components, yield and seed germination.

MATERIAL AND METHODS

Three experiments were conducted in commercial soybean crops in the city of Brunópolis (state of Santa Catarina, Brazil): Experiment 1 with the cultivar Syngenta Seeds NS_5000_IPRO in the 2022/23 growing season, and Experiments 2 and 3 with Monsoy M_5917_IPRO in the 2022/23 and 2023/24 seasons, respectively.

Brunópolis is located on the southern plateau of Santa Catarina, with a Cfa climate. Rainfall between sowing and harvest was 775.6 mm, 783.4 mm, and 656.4 mm in the respective growing seasons (Epagri/Ciram). These volumes are suitable for soybean development, within the ideal range of 650 to 800 mm (Farias et al., 2007; Pilau et al., 2022). Soil pH was amended to 6.0 and fertilized for potential productivity of 4,000 kg/ha, according to the Fertilization and Liming Handbook for RS and SC (SBCS-CQFS-RS/SC, 2016).

The experiments were conducted with 17 treatments (Table 1) and with four replications (total of 68 experimental units). Each experimental unit contained four rows spaced at 0.5 m and 8 m long, with a final usable area of 7.0 m² after disregarding the edges. The T1 - control (without defoliation), T2 - defoliation of 50% at R1 stage; T3 - defoliation of 100% at R1; T4 - defoliation of 50% at R3; T5 - defoliation of 100% at R3; from T6 to T17 were defoliation of 50% plus plant growth regulator spaying as described (Table 1).

Table 1. Description of the treatments, defoliations levels, products applied codes and plant stages of soybean

Treatments	Description	Stage
T1	Control (0%)	-
T2	50%	R1
T3	100%	R1
T4	50%	R3
T5	100%	R3
	Defoliation of 50% plus plant growth regulator spray	
T6	Acetyl salicylic acid (ASA)	R1
T7	Indole-butyric acid (IBA)	R1
T8	Ethylene precursor (ETEPHON)	R1
T9	Mepiquat Chloride (MEPIQ)	R1
T10	Aviglycine (AVG)	R1
T11	Mixture of gibberellic acid + 4-indole-3-butyric acid + kinetin (GIK)	R1
T12	Acetyl salicylic acid (ASA)	R3
T13	Indole-butyric acid (IBA)	R3
T14	Ethylene precursor (ETEPHON)	R3
T15	Mepiquat Chloride (MEPIQ)	R3
T16	Aviglycine (AVG)	R3
T17	Mixture of gibberellic acid + 4-indole-3-butyric acid + kinetin (GIK)	R3

The levels of artificial defoliation: 0% (no defoliation), 50% (removal of about half the leaf area with a defoliant, prioritizing the upper portion), and 100% (total removal of leaves). The products details simulating plant hormones (Table 2). Products were applied with adjuvant non-ionic silicon sticker-spreaders were used (Brak True®, 0.1% of the spray volume).

Table 2. Description of the products [trade name, active ingredient (a.i.) and use rate (c.p./ha or a.i./ha)] used for mitigating the effects of defoliation on soybean

	Hormone (analog)	Brand name	Active ingredient	Use rate
1	Auxin	Vetec/laboratorial	Indole-butyric acid (IBA)	80.0 g/80.0 g
2	Cytokinin	Pix HC	Mepiquat chloride (MEPIQ)	1.0 L/0.25 L
3	Ethylene-releasing agent	Ethrel	ETEPHON	0.45 L/324 g
4	Ethylene inhibitor	Retain	Aviglycine hydrochloride (AVG)	170 g/25.5 g
5	Acetyl salicylic acid	Aspirin	Acetyl salicylic acid (ASA)	60.0 g/300 mg
6	Gibberellin, auxin, and cytokinin mixture	Stimulate	GIK - equivalents Gibberellic acid 4-indole-3-butyric acid Kinetin	0.5 L c.p./ 0.025 g 0.025 g 0.045 g

Use rate was based on the recommendations made by the manufacturers of the products (Pix HC, Ethrel, and Stimulate) and on previous studies (AVG, ASA, IBA). The products were applied on the experimental plots, spaced at 0.5 m each, using a “Herbicat H” CO_2-pressurized backpack sprayer with four fan spray nozzles (TeeJet XR 110 02 VP), and a spray volume of 200 L/ha. Application was performed 24 hours after defoliation (Table 3), at 5 p.m., with wind speed below 10 km/h and air temperature below 30°C.

Table 3. Summary of the dates of sowing, application of treatments, and harvest for three soybean field experiments conducted to evaluate the effects of defoliation and its mitigation, in the municipality of Brunópolis, SC, in the 2022/23 and 2023/24 growing seasons

Management	Dates		
	Experiment 1	Experiment 2	Experiment 3
Sowing	Nov. 21, 2022	Dec. 3, 2022	Oct. 30, 2023
Defoliation (R1)	Jan. 4, 2023	Jan. 25, 2023	Jan. 10, 2024
Product application - Plant hormones	Jan. 5, 2023	Jan. 26, 2023	Jan. 11, 2024
Defoliation (R3)	Jan. 18, 2023	Feb. 9, 2023	Jan. 21, 2024
Product application - Plant hormones	Jan. 19, 2023	Feb. 10, 2023	Jan. 22, 2024
Harvest	Mar. 28, 2023	Apr. 20, 2023	Apr. 8, 2024

Crop treatments were carried out while following technical recommendations for soybean crops in Rio Grande do Sul and Santa Catarina, in the 2018/19 and 2019/20 growing seasons (Setrem, Embrapa, and Emater, 2019). At the end of the cycle, 10 plants were sampled per experimental unit (central row) to determine: plant height (PH), measured from the cotyledonary node to the last apical node; number of pods per plant (NP_{plant}), mean count in 10 plants; number of seeds per pod (NS_{pod}), average of 50 pods; and number of seeds per plant (NS_{plant}), obtained by $NS_{pod} \times NP_{plant}$.

The plots were harvested with the aid of a plot combine (Wintersteiger), and the samples were analyzed in the Laboratory of Crop Plants, CAV/UDESC. Next, the following parameters were determined: thousand-seed weight (TSW); estimated seed yield of the plot (SY) (kg/ha); and seed germination (G%).

Owing to the environmental differences between the three experiments (altitude, soil, temperature, rainfall, sowing, and cultivar), the analyses were made individually for each experiment, considering only the following factors: phenological stage, defoliation levels, and plant growth regulators.

The data underwent analysis of variance one-way ANOVA of various treatments versus control. When significant, the means of treatments were compared with control by Dunnett ($p<0.05$) tests. The germination data were arcsine transformed $[(x/100+0.5)^{0.5}]$ to meet the assumptions of the analysis of variance. Statistical analysis was carried out using the SISVAR software.

RESULTS AND DISCUSSION

The first experiment assessed the cultivar NS_5000_IPRO in the 2022/23 growing season, and analysis of variance showed a simple effect of stage (S) for the variables PH, NP_{plant}, NS_{plant}, TSW, and SY (Table 4); of defoliation (D) for all variables; and of products (P) for the variables PH, NS_{plant}, NS_{pod}, and SY (Table 4), and a double effect of the SxD interaction for all variables, and of the SxP interaction for the variables TSW and G% (Table 5).

Table 4. Effects of three levels of defoliation performed at two phenological stages of soybean plants, and effects of the application of plant growth regulators at two phenological stages of soybean plants on the following traits: plant height (PH), number of pods per plant (NP_{plant}), number of seeds per plant (NS_{plant}), number of seeds per pod (NS_{pod}), thousand seed weight (TSW), and seed yield (SY) for seeds obtained from three different experiments. Brunópolis, SC

		Exp 1	Exp 2	Exp 3		Exp 1	Exp 2	Exp 3
Defoliation	Stage	PH (cm)				NP_{plant} (n°)		
Control (0%)	-	68	76	103		43	44	70
50%	R1	55 **	72 **	96 **		47 **	44	73
100%	R1	47 **	65 **	82 **		40 **	31 **	60 **
50%	R3	63 **	75 **	96 **		37 **	41	63 **
100%	R3	52 **	63 **	85 **		22 **	22 **	42 **
Defoliation of 50% plus plant growth regulator spray								
ASA	R1	58 **	70 **	92 **		40 **	30 **	60 **
IBA	R1	59 **	70 **	95 **		44	36 **	61 **
ETEPHON	R1	57 **	69 **	94 **		46	37 **	66
MEPIQ	R1	62 **	69 **	94 **		42 **	32 **	62 **
AVG	R1	59 **	76	93 **		45	35 **	58 **
GIK	R1	59 **	70 **	96 **		42 **	34 **	69
ASA	R3	58 **	72 **	95 **		32 **	30 **	60 **
IBA	R3	59 **	76	97		38 **	35 **	62 **
ETEPHON	R3	57 **	69 **	98		33 **	37 **	66
MEPIQ	R3	62 **	69 **	94 **		30 **	33 **	61 **
AVG	R3	59 **	72 **	97		35 **	35 **	59 **
GIK	R3	59 **	74 **	96 **		36 **	34 **	70
Defoliation	Stage	NS_{plant} (n°)				NS_{pod} (n°)		
Control (0%)	-	77	63	112		1.8	2.0	1.7
50%	R1	68 **	61	100 **		1.5 **	1.4 **	1.4 **
100%	R1	45 **	48 **	58 **		1.2 **	1.6 **	1.0 **
50%	R3	65 **	63	94 **		1.8	1.6 **	1.5 **
100%	R3	25 **	26 **	70 **		1.2 **	1.3 **	1.6
Defoliation of 50% plus plant growth regulator spray								
ASA	R1	59 **	58	96 **		1.6	1.7 **	1.4 **
IBA	R1	57 **	61	91 **		1.4 **	1.8	1.4 **
ETEPHON	R1	57 **	58	95 **		1.6	1.5 **	1.4 **
MEPIQ	R1	62 **	58	87 **		1.7	1.9	1.3 **
AVG	R1	59 **	55 **	86 **		1.4 **	1.6 **	1.5 **
GIK	R1	56 **	55 **	88 **		1.5 **	1.6 **	1.3 **

Defoliation	Stage	NS$_{plant}$ (n°)				NS$_{pod}$ (n°)		
Control (0%)	-	77	63	112		1.8	2.0	1.7
ASA	R3	59 **	53 **	84 **		1.7	2.2	1.6
IBA	R3	57 **	51 **	88 **		1.8	1.6 **	1.6
ETEPHON	R3	56 **	54 **	81 **		1.5 **	1.6 **	1.3 **
MEPIQ	R3	62 **	52 **	89 **		1.9	1.7	1.8
AVG	R3	58 **	46 **	83 **		1.6	1.5 **	1.5 **
GIK	R3	57 **	50 **	85 **		1.6	1.7	1.4 **
Defoliation	Stage	TSW (g)				SY (kg/ha)		
Control (0%)	-	182	165	180		3.363	2.973	4.304
50%	R1	178	161 **	164 **		2.937 **	2.819	3.706 **
100%	R1	175 **	151 **	163 **		1.882 **	2.120 **	2.062 **
50%	R3	174 **	160 **	175		2.671 **	3.051	3.556 **
100%	R3	145 **	156 **	157 **		882 **	1.076 **	2.396 **
Defoliation of 50% plus plant growth regulator spray								
ASA	R1	175 **	160 **	170 **		2.432 **	2.706	3.565 **
IBA	R1	178	157 **	168 **		2.446 **	2.801	3.394 **
ETEPHON	R1	181	155 **	165 **		2.397 **	2.627	3.430 **
MEPIQ	R1	178	160 **	166 **		2.691 **	2.719	3.331 **
AVG	R1	177 **	157 **	170 **		2.371 **	2.576	3.225 **
GIK	R1	182	160 **	170 **		2.455 **	2.646	3.032 **
ASA	R3	166 **	163	171 **		2.432 **	2.561	3.176 **
IBA	R3	168 **	158 **	170 **		2.446 **	2.472 **	3.413 **
ETEPHON	R3	161 **	159 **	168 **		2.397 **	2.469 **	3.086 **
MEPIQ	R3	169 **	157 **	172 **		2.691 **	2.405 **	3.320 **
AVG	R3	170 **	165	172 **		2.371 **	2.268 **	3.124 **
GIK	R3	169 **	158 **	170 **		2.455 **	2.384 **	2.955 **

Means followed by the asterisk in the column differ from control by the Dunnett test, at 5% probability of error.

Table 5. Effects of three levels of defoliation performed at two phenological stages of soybean plants, and effects of the application of plant growth regulators at two phenological stages of soybean plants on the germination percentage (G%) of seeds obtained from three different experiments. Brunópolis, SC

Defoliation	Stage	Exp 1	Exp 2	Exp 3
		G (%)		
Control (0%)	-	88	90	89
50%	R1	85 **	91	92
100%	R1	89	88	80 **
50%	R3	78 **	91	90
100%	R3	76 **	84 **	82 **
Defoliation of 50% plus plant growth regulator spray				
ASA	R1	83 **	88	89
IBA	R1	88	87	89
ETEPHON	R1	93	92	93
MEPIQ	R1	87	89	92
AVG	R1	86	86	83 **
GIK	R1	85 **	90	90
ASA	R3	81 **	88	90
IBA	R3	80 **	87	86 **
ETEPHON	R3	73 **	82 **	84 **
MEPIQ	R3	82 **	89	89
AVG	R3	81 **	91	85 **
GIK	R3	83 **	84 **	92

Means followed by asterisk in the column differ from control by the Dunnett test, at 5% probability of error.

There was a reduction in height of plants in all experiments as a result of defoliation, with variations depending on intensity of defoliation and growth stage. In the NS_5000_IPRO variety, complete defoliation (100%) at the R1 growth stage reduced the height by 30.9% while in the M_5917_IPRO variety the reduction was 14.5% (first season) and 20.4% (2nd season) (Table 4). At R3 stage the heights reductions were 23.5, 17.1, and 17.5%, respectively.

For number of pods per plant, there was a reduction in all experiments due to the defoliation, with variations depending on intensity of defoliation and growth stage. In the NS_5000_IPRO variety, complete defoliation (100%) at the R1 growth stage reduced the NP_{plant} by 6.9% while in the M_5917_IPRO variety the reduction was 29.5% (first season) and 14.3% (2nd season) (Table 4). At R3 stage the NP_{plant} reductions were 40.8, 50.0, and 40.0%, respectively. Confirming that complete defoliations always reduced NP_{plant} (Table 4).

There was a reduction in number of seeds per plant in all experiments as a result of defoliation, with variations depending on intensity of defoliation and growth stage. In the NS_5000_IPRO variety, complete defoliation (100%) at the R1 growth stage reduced the NS_{plant} by 41.5% while in the M_5917_IPRO variety the reduction was 23.8% (first season) and 48.2% (2nd season) (Table 4). At R3 stage the NS_{plant} reductions were 67.5, 58.7, and 37.5%, respectively (Table 4).

The number of seeds per pod decreased in all experiments because of defoliation, with variations depending on intensity of defoliation and growth stage. In the NS_5000_IPRO variety, complete defoliation (100%) at the R1 growth stage reduced the NS_{pod} by 33.3% while in the M_5917_IPRO variety the reduction was 20.0% (first season) and 41.1% (2nd season) (Table 4). At R3 stage the NS_{pod} reductions were 33.3, 35.0, and 5.9%, respectively (Table 4).

The thousand seeds weight decreased in all experiments due to the defoliation, with variations depending on intensity of defoliation and growth stage. In the NS_5000_IPRO variety, complete defoliation (100%) at the R1 growth stage reduced the TSW by 3.8% while in the M_5917_IPRO variety the reduction was 8.5% (first season) and 9.4% (2nd season) (Table 4). At R3 stage the TSW reductions were 20.3, 5.4, and 12.8%, respectively (Table 4).

There was a reduction in seed yield in all experiments as a result of defoliation, with variations depending on intensity of defoliation and growth stage. In the NS_5000_IPRO variety, complete defoliation (100%) at the R1 growth stage reduced the SY by 44% while in the M_5917_IPRO variety the reduction was 28.7% (first season) and 52% (2nd season) (Table 4). At R3 stage the heights reductions were 73.7, 63.8, and 44.3%, respectively (Table 4).

Germination (G%) was not affected by defoliation at R1, but it was reduced at R3 stage. In the NS_5000_IPRO variety, complete defoliation (100%) at the R3 growth stage reduced the G% by 13.6% while in the M_5917_IPRO variety the reduction was 6.7% (first season) and 7.9% (2nd season) (Table 5).

Regarding the effect of plant growth regulators, it was found in Experiment 1 (NS_5000_IPRO variety) that the applications of ASA, IBA, ETHEPHON, MEPIQ, AVG, and GIK at R1 and R3 decreased plant height ranging from 8.8 to 14.7% (Table 4). In Experiment 2 (M_5917_IPRO variety; first season), only AVG at R1, and IBA at R3 do not decreased height of plants (Table 4). In experiment 3, all products at R1 resulted in the reduction of heights, but at R3 only ASA, MEPIQ, and GIK lead to shortest height of plants ($p<0.05$; Table 4).

There was a mitigation in NP_{plant} in first and third experiments as a result of regulators spraying on plants. In the NS_5000_IPRO variety, 50% defoliation in the R1 growth stage plus regulators IBA, ETEPHON, and AVG mitigate the NP_{plant} (Table 4). In the M_5917_IPRO (2nd season), 50% defoliation in the R1 and R3 growth stage plus regulators only ETEPHON and GIK mitigate the NP_{plant} (Table 4).

There was a mitigation in NS_{plant} in 2nd experiment as a result of regulators spraying on plants. In the M_5917_IPRO variety (2nd season), 50% defoliation in the R1 growth stage plus regulators ASA, IBA, ETEPHON, and MEPIQ mitigate the NS_{plant} (Table 4).

There was a mitigation in NS_{pod} as a result of regulators spraying on plants. In the NS_5000_IPRO and M_5917_IPRO variety, 50% defoliation in the R1 growth stage plus regulator MEPIQ mitigate the NS_{pod} (Table 4). In the NS_5000_IPRO and M_5917_IPRO varieties, 50% defoliation at the R3 growth stage plus regulators ASA and MEPIQ mitigate the NS_{pod} (Table 4).

In the NS_5000_IPRO variety, 50% defoliation in the R1 growth stage plus regulators IBA, ETEPHON, MEPIQ, and GIK mitigate the TSW (Table 4). In the M_5917_IPRO variety, 50% defoliation at the R1 or R3 growth stage plus regulators spraying do not mitigate the TSW (Table 4; $p>0.05$).

There was a mitigation in yield as a result of regulators spraying on plants. In the M_5917_IPRO variety (first season), 50% defoliation in the R1 growth stage plus regulators ASA, IBA, ETEPHON, MEPIQ, AVG, and GIK mitigate the SY (Table 4). But, in the NS_5000_IPRO and M_5917_IPRO variety (2nd season), 50% defoliation at the R1 or R3 growth stage plus regulators spraying do not mitigate the SY (Table 4; $p>0.05$).

In the NS_5000_IPRO variety, 50% defoliation in the R1 growth stage plus regulators IBA, ETEPHON, MEPIQ, and AVG mitigate the G%; while ASA and GIK do not mitigate the G% (Table 5). In the M_5917_IPRO variety (first and 2nd season), 50% defoliation at the R1 growth stage plus regulators spraying mitigate the G% (Table 5; $p<0.05$). In the NS_5000_IPRO variety, 50% defoliation in the R3 growth stage plus regulators do not mitigate the G% (Table 5). In the M_5917_IPRO variety (first and 2nd season), 50% defoliation at the R3 growth stage plus regulators ASA and MEPIQ spraying consistently mitigate the G% (Table 4; $p<0.05$).

The first objective of this study was to evaluate the impacts of defoliation on seed yield, yield components, plant height, and soybean seed germination. In both defoliation intensities, SY was reduced in the cultivar NS_5000_IPRO, which matures earlier than M_5917_IPRO. In turn, the latter cultivar was more resistant to defoliation, keeping SY stable with D50% at R1 (Experiment 2) and R3 (Experiments 2 and 3). These findings corroborated the results found by Glier et al. (2015), but they disagree with those reported by Durli et al. (2020). It should be noted that leaf area removal, D50%, was concentrated in the upper portion of the plants, simulating a hailstorm. This defoliation favored the entry of light, increasing the photosynthetic production of leaves of the lower 1/3 of the plant (previously shaded) and kept SY of the plants with intermediate defoliation.

The reduction of excessive leaf area indices (LAI) up to levels of 4.0-4.5 does not necessarily result in decreased SY, as it allows plants to redirect photoassimilates that were previously destined to leaf expansion for grain filling. Thus, it can be inferred that when D50% did not reduce SY of the cultivar M_5917_IPRO, the plots maintained optimum LAI for SY (Srinivasan et al., 2017; Yamamoto et al., 2023; Chiozza et al., 2024).

Studies conducted by Peluzio et al. (2004) and Diogo (1997) reported a reduction of SY only in the most severe defoliation (D100%) performed at stage R2, while at R4, the intensities of D66% and D100% were sufficient to negatively affect production, clearly showing the higher sensitivity of the plants at this stage. More recent studies confirmed this trend: moderate defoliation (up to 40-50%) at the early stages (R1-R3) can be compensated by physiological reconfiguration and increased photosynthetic efficiency in the remaining leaves, while severe defoliation at R4 and R5 cause significant reductions in seed yield (Moscardi et al., 2012; Glier et al., 2015; Raza et al., 2021; Vilas Boas et al., 2022; Casteel, 2024; Parvej et al., 2025; Poudel et al., 2025, Schardong et al., 2025a, 2025b).

The yield components were influenced by defoliation intensities. Whenever there was D100% defoliation, NP_{plant}, NS_{plant}, and TSW were reduced. The yield components led the plants to maintain stable SY levels with D50%, but there was an increase in NP_{plant} in the cultivar M_5917_IPRO in the 2022/23 growing season. This way, despite the reduction of the other yield components (NS_{pod} and TSW), SY was not reduced.

The beginning and full bloom (R1 and R2) and beginning and full pod (R3 and R4) stages are periods of great increase in the number of sinks in soybean plants. In addition to an increase in height and number of nodes and branches, reproductive structures are developed. Thus, there are peaks of photosynthetic activity in these periods, supplying the demands for photoassimilates. Therefore, when the source producing photoassimilates is drastically reduced at these stages, there will be a reduction in NP_{plant}. However, if there is enough remaining leaf area after defoliation, and preferably, if the plant is at the beginning of the reproductive stage (R1), where there are not so many drains, the plant will have reproductive plasticity, and will achieve a peak of photosynthetic activity, without a consequence for NP_{plant} (Peluzio et al., 2004).

There was an increase in NS_{pod} for the cultivar M_5917_IPRO in the 2023/24 growing season, and NS_{pod} is one of the most important yield components to maintain SY with D50% defoliation in comparison to the plants with D0%. In the other experiments, defoliation reduced NS_{pod}, a result that is in line with the findings of Peluzio et al. (2004), Raza et al. (2021), and Poudel et al. (2025), who pointed out that increases in the level of defoliation, regardless of the stage of occurrence, may reduce NS_{pod}.

TSW was reduced in defoliated plants, but the greatest reductions occurred when the plants were at stage R3, with losses of up to 20.5%. Glier et al. (2015) found that there is a mean reduction in TSW by 6.2% in the reproductive phase, and it is more severe at stages R3 and R5. Soybean defoliations reduce TSW, and defoliations at stages R3 have the most impact on TSW because plants lose their capacity to produce photoassimilates that would supply the demand of developing seeds. Similar results were recently reported by Raza et al. (2021), Parvej et al. (2025), Poudel et al. (2025), and Schardong et al. (2025a, 2025b).

There was a reduction in PH in all experiments and times of occurrence of defoliation. The lowest PH was found to occur with complete defoliation at stages R1 and R3, when the plants were further from reaching their final height. The results are in line with those found by Peluzio et al. (2004), and Diogo et al. (1997), namely that defoliation occurring as at early as stage V2 may reduce plant height. However, Glier et al. (2015) and Raza et al. (2021) did not find any effect of defoliation on plant height, although there was a difference between the height values of the cultivars in their study. In addition, Bueno et al. (2010) showed that defoliation of up to 33.3%, regardless of the stage of occurrence, did not change the height of soybean plants, if defoliation only occurs at such stage.

Seed germination was influenced by defoliation. At stage R1, soybean plants are blooming; even after losing all leaf area, there was enough time for them to produce photosynthetic seeds and generate seeds suitable for germination, that is, germination was not changed in any experiment. When defoliation occurred at stage R3 (beginning pod) in the cultivar NS_5000_IPRO, defoliation of D50% and D100% reduced seed germination to values below 80%, which is the minimum germination allowed for marketing of soybean seeds in Brazil. For the cultivar M_5917_IPRO (stage R3), seed germination showed an opposite behavior, and the higher levels of defoliation resulted in the highest germination rates (>80%).

This opposite behavior can be explained by the fact that the two cultivars have different development cycles. The cultivar NS_5000_IPRO has an early cycle, with a total period of 128 days, with a time span of 70 days between defoliation at stage R3 and harvest. The cultivar M_5917_IPRO has a longer cycle: 160 days between sowing and harvesting, and 77 days between defoliation at R3 and harvest. Despite the reduced production of photoassimilates, the cultivar has more reserves and developed structures (leaves, branches, pods), and it had a longer recovery time, directing the photoassimilates to ensure seed germination (to a lesser extent), even though SY was not recovered.

The second objective of this study was to evaluate the efficiency of plant hormones as a measure to mitigate the effects of source restriction on soybean grain productivity and other agronomic characteristics.

It was found that the application of plant hormones during the reproductive stage did not result in a significant increase in SY in comparison to the control ($p>0.05$). This finding corroborates those of several studies, namely that the efficiency of plant hormones depends strongly on phenological stage, cultivar, and the environmental conditions at the time of application (Souza et al., 2013; Amoanimaa-Dede et al., 2022). Although plant hormones play a relevant role in plant growth modulation, tolerance to stresses, and physiological quality of seeds, consistent yield gains do not always occur, especially when applications are made at advanced reproductive stages.

Similarly, Cheng et al. (2025) found that the application of plant hormones such as NAA, prohexadione-calcium, and ICE6 to soybean at stages V4 and R4, reduced floral shedding and optimized pod distribution, but the effect on yield was variable according to environment and application stage. Cannon et al. (2025), evaluating different plant hormones in several regions of the United States, also reported inconsistent responses on yield, reinforcing that the effects depend on the interaction between genotype and environment. These findings update and complement previous results, such as those of Klahold et al. (2006), and Albrecht et al. (2012), who had found increases in yield under specific conditions, especially when regulators were applied at initial vegetative stages or through seed treatment.

In classical studies by Albrecht et al. (2012), the application of GIK at V5 promoted greater vegetative growth, an increase in the number of nodes and, consequently, a higher number of reproductive structures, reflecting higher SY. Similar results were reported by Souza et al. (2013), who pointed out that the stimulation of early vegetative growth favors the development of the canopy and increases photosynthetic capacity, promoting greater accumulation of photoassimilates. However, applications starting at R1, as in the present study, tend to have a limited effect, since the number of vegetative and reproductive structures is already defined, restricting the action of regulators only to the transport and redistribution of assimilates (Amoanimaa-Dede et al., 2022; Cheng et al., 2025).

The application of MEPIQ in present work decreased plant height in the NS_5000_IPRO and M_5917_IPRO varieties in distincts magnitudes. This result was also found by Souza et al. (2013). This variation between cultivars may be associated with the difference in hormonal sensitivity and in the endogenous relationship between gibberellins and cytokinins. Recent studies have reinforced that mepiquat reduces cell elongation and may improve photosynthetic efficiency and drought resistance, depending on use rate and genotype (Wang et al., 2022; Dong et al., 2023). In soybean, this regulator acts on the endogenous hormonal balance and the redistribution of photoassimilates between vegetative and reproductive tissues, which explains the difference in response between the cultivars analyzed in this study.

For ethylene-releasing agents and inhibitors, it was found that the application of AVG and ASA (ethylene synthesis inhibitors) did not result in increased SY or higher NP_{plant}. This result shows that AVG can mitigate oxidative stress, but without consistent effects on final yield. On the other hand, ETEPHON (ethylene - releasing agent) applied at R1 increased seed germination percentage (G%), suggesting that the transitory increase of ethylene may have signaled the end of the cycle, directing photoassimilates to the development of more vigorous seeds. However, late applications (R3) reduced G%, possibly owing to ethylene accumulation during embryogenesis, thus damaging the physiological maturation of seeds. A similar behavior was reported by Campos et al. (2010).

Thus, the present study reinforces that the use of plant regulators at advanced soybean reproductive stages has limited effects on SY, but it can positively affect yield components and the physiological quality of seeds, depending on type and time of application. Applications at vegetative stages (V4-V6) tend to be more effective for the development of productive structures, while those performed at as early as R1 predominantly act in the redistribution of assimilates and in the biochemical composition of seeds (Amoanimaa-Dede et al., 2022; Gu et al., 2024).

CONCLUSIONS

Severe defoliation (100%) reduced plant height, number of pods per plant, number of seeds per plant, number of seeds per pod, thousand seed weight, seed yield, and seed germination percentage. Intermediate defoliation (50%) affected plant height and thousand seed weight, while its effects on other yield components and overall seed yield varied according to cultivar, stage of the defoliation, and growing season. For the cultivar M_5917_IPRO, seed yield was negatively affected by severe defoliation at reproductive stages R1 and R3, and yield reductions were also observed when defoliation occurred at these stages under both intermediate and severe defoliation levels. The exogenous applications of plant regulators to defoliated plants, occasionally showed a small mitigating effect, promoting partial recovery of defoliation and contributing positively to some yield components, seed yield and its germination.

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