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Soybean performance in response to growth regulators, herbicides, and biofertilizers

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ABSTRACT

There is only a small number of products that can be applied to soybeans at post-emergence to mitigate plant lodging and increase grain yield. In this way, the objective of this experiment was to mitigate lodging of soybean plants through the application of growth regulators, herbicides, and a biofertilizer, and to evaluate the effect of the herbicide lactofen on the growth of soybean plants. The experiment was carried out on the CAV-UDESC experimental farm, with soybean cultivar BS 2606, in two seasons (2020/21 and 2021/22). The experiment used a randomized block design (RBD), with five replications. The eight treatments consisted of growth regulators (prohexadione calcium, mepiquat chloride, and benzyladenine), herbicides (lactofen 1x and 2x and bentazon+imazamox), a biofertilizer (amino acids), and the control. The treatments were applied to soybean plants cv. BS 2606 is in the vegetative stage of eight nodes on the main stem of the plant (V8). Assessments of SPAD, NDVI, and plant height (7, 14, 21, 28 DAA) were more influenced by the seasons than by the products. Lactofen caused injury to the plants, but these injuries eased over the course of the assessments, and no negative difference was found in the yield components of the soybean plants. Lactofen 2x can be used as a growth regulator in soybeans to increase the number of lateral branches of plants. In both seasons, lodging was less than 8%, thus not affecting grain yield. The use of prohexadione on BS 2606 soybean resulted in grain yield gains ranging from 17 to 19%.

Keywords: *Glycine max*, foliar injury, photosystem II, protoporphyrinogen oxidase, acetolactate synthase

INTRODUCTION

Soybean (*Glycine max* (L.) Merrill) is a major summer crop in Brazil. In the 2022/23 growing season, a total of 154.62 million tons were harvested in an area of 44.06 million hectares, which outperforms by 10.9% the record production in the 2020/21 season, with a productivity of 3,508 kg/ha (Conab, 2025). Currently, there is a range of technological solutions on the market to help boost crop productivity, as a result of the interaction between the genetic potential of each cultivar and the fine-tuning of management practices based on environmental conditions (Cabral, 2019).

Some plant regulators and some specific herbicides can slow down the plant's growth rate, affecting plant height and inducing lateral branches. That is, the plant produces fewer nodes on the main stem, but more productive nodes on lateral branches, thus enabling a greater number of flowers and pods per plant (Matos et al., 2021).

Lodging causes self-shading, which reduces photosynthesis, thus decreasing the number of photoassimilates available for grain filling. In addition, it increases humidity in the microclimate, leading to depreciation of soybean grains and increased incidence of diseases (Basilio et al., 2022). Loss of grain yield is caused by plant lodging, and it is directly linked to the development stage at which it occurs and its intensity, especially when it occurs during grain filling (Souza et al., 2013). According to the literature, grain yield of lodging plants shows a productive decrease between 20-30% in their (Balbinot-Junior, 2012; Kohler et al., 2025). Despite the benefits that plant growth regulators and herbicides may offer to agriculture, they must be used with caution. If handled incorrectly, they may cause production losses (Pacentchuk et al., 2018). They may also cause injury or phytotoxicity to plants in varying levels, according to the concentration (rate) used or the cultivar's level of tolerance to a given product (Buzzello et al., 2017). Herbicides also act as growth regulators, inflicting severe injury on plants; for example, Protox inhibitors are contact agents that cause damage at the site of application by producing ROS, which results in lipid peroxidation of the plasma membrane of cells (Cabral, 2019).

Some of the major mechanisms of action with greater selectivity in soybean crops include the inhibitors of the enzymes protoporphyrinogen oxidase (Protox) and acetolactate synthase (ALS), represented by the herbicides lactofen and cloransulam (Zhang et al., 2021). In addition, few studies to date have focused on the effects of the association between bentazon and imazamox on soybean plants.

This scenario also includes biofertilizers, which have the ability to enhance metabolic and physiological processes in plants (Szparaga et al., 2021). Additionally, the use of such substances tends to provide greater productive stability; as a result, plants can express their maximum genetic productive potential, and are prone to obtaining higher yields. By enhancing nutrient uptake efficiency, hormonal balance, and stress tolerance, biofertilizers contribute to greater productive stability. This stability enables plants to more fully express their genetic yield potential, often resulting in higher grain yield.

Therefore, this work aimed to mitigate plant lodging and enhance the productive potential of soybeans through the application of growth regulators (prohexadione calcium, mepiquat chloride, and benzyladenine), herbicides (lactofen 1x, lactofen 2x and bentazon+imazamox) and a biofertilizer (sugarcane molasses), and to evaluate the growth performance of soybean plants in field conditions.

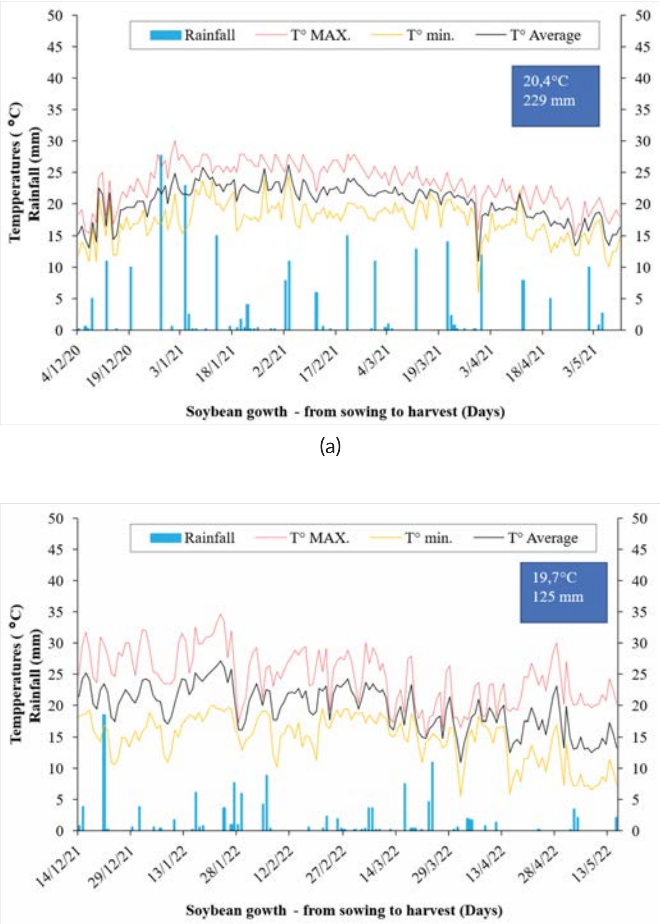
MATERIAL AND METHODS

Study site and experimental design

The field experiment in the 2020/21 and 2021/22 growing seasons was carried out on the experimental farm of the Santa Catarina State University (UDESC), in the municipality of Lages/SC. This location has an altitude greater than 900 m, and its environment is conducive to the occurrence of plant lodging. The geographical coordinates are: 27° 52' South latitude and 50° 18' West Longitude. The climate of the region, according to the Köppen classification, is Cfb (temperate climate with mild summers). Figure 1 shows the meteorological data (maximum, average, and minimum temperature and cumulative rainfall) of Lages during the experimental periods. Both experiments were implemented in an aluminum humic Cambisol (Embrapa, 2017), with the following characteristics: pH in water: 6.3; Ca: 9.1 cmolc/dm3; Mg: 3.9 cmolc/dm3; Al+H: 3.2 cmolc/dm3; K: 143 mg/dm3; P: 35.2 mg/dm3; cation exchange capacity: 21.7 cmolc/dm3; organic matter: 2.8%, and clay: 50%.

The seeds were mechanically sown under a no-tillage system on December 4, 2020, and December 14, 2021. Soybean was sown immediately after the harvest of winter cereals (white oats and wheat) in the two seasons, respectively. Before sowing, the seeds were treated with insecticide (imidacloprid + thiodicarb + fipronil), fungicide (pyraclostrobin + thiophanate-methyl), and inoculant (*Bradyrhizobium elkanii* strain - SEMIA 5019 + *Bradyrhizobium japonicum* strain - SEMIA 5080).

The experiments used a randomized block design (RBD) with five replications. The eight treatments consisted of growth regulators (prohexadione calcium, mepiquat chloride, and benzyladenine), herbicides [lactofen 1x: 144 g/ha of active ingredient (a.i.) (positive check), lactofen 2x: 288 g/ha a.i., and bentazon+imazamox: 600+28 g/ha a.i.] and biofertilizer, as well as the control (no application; negative check). The biofertilizer was Vorax®, which contains amino acids and is obtained through biological fermentation of sugarcane molasses. Each plot consisted of 5 rows of 5 m in length, with intra-row spacing of 0.4 m, spaced 0.5 m apart, totalling 10 square meters. The population was 30 plants per square meter.



Note: T° max; Maximum temperature; T° min: minimum temperature; T° average: average temperature.

Figure 1. Rainfall, maximum, minimum, and average air temperatures from sowing to harvesting of soybean in the experiments during the 2020/21 (a) and 2021/22 (b) growing seasons

Cultivation technology

The cultivar BS IRGA 2606 IPRO (BS 2606 IPRO) used in this experiment has the following characteristics: maturity group 6.0, early cycle, and indeterminate habit. It currently accounts for 5-15% of all soybeans cultivated in the southern region of Brazil. This cultivar has a broad root system that makes it tolerant to water stress and to the root rot complex. Also, it is flexible about variation in plant population because it has good branching capacity and is less susceptible to plant lodging (Soytech, 2025).

The products were applied on February 2, 2021 and February 1, 2022, when the plants reached the V8 stage according to Fehr and Caviness scale (1977), characterized by the eighth visible node (seventh fully developed trifoliate leaf and eighth trifoliate leaf with leaflet expansion), with the aid of a CO_2-pressurized backpack sprayer at a constant pressure of 200 KPa. To obtain a productive potential of 5 t/ha, specific management practices were adopted for the experiments, based on the South-Brazilian Soybean Production Guidelines (Indicações, 2020),

Soil was fertilized with 400 kg/ha of N-P_2O_5-K_2O commercial formulation, totalling 8 kg/ha of N, 100 kg/ha of P_2O_5, and 100 kg of K_2O. Phytosanitary management was carried out to minimize occurrences of pests, diseases, and weeds. A remotely piloted aircraft (agricultural drone) was used to spray the products. Six applications were carried out at the following phenological stages of the plants, using the respective products: the first application was carried out at the V3 stage with the insecticide thiodicarb (Larvin WG, 0.1 kg p.c./ha), the herbicide glyphosate (Round UP, 1 L p.c./ha); the 2nd application was performed at the V6 stage with the herbicide fluazifop-butyl (Fusilade, 1.0 L p.c./ha), the insecticides thiamethoxam + lambda cyhalothrin (Engeo Pleno S, 0.1 L p.c./ha), and the fungicide metconazole (Caramba 90, 1.0 L p.c./ha); the 3rd application was carried out at the V9 stage with the insecticides thiamethoxam + lambda-cyhalothrin (Engeo Pleno S, 0.1 L p.c./ha), the fungicides trifloxystrobin + tebuconazole (Nativo, 0.7 L p.c./ha), the herbicide clethodim (Select 240, 0.35 L p.c./ha), and methylated soybean oil (Mees, 0.5 L p.c./ha); the 4th application was performed at the R2 stage with the fungicides trifloxystrobin + tebuconazole (Nativo, 0.75 L p.c./ha), the insecticides thiamethoxam + lambda-cyhalothrin (Engeo Pleno S, 0.1 L p.c./ha) and methylated soybean oil (Mees, 0.5 L p.c./ha); the 5th application was carried out at the R5 stage with the fungicides trifloxystrobin + prothioconazole + bixafen (Fox Xpro, 0.5 L p.c./ha), the insecticide lambda-cyhalothrin (Karate Zeon 250 CS, 0.1 L p.c./ha), and methylated soybean oil (Mees, 0.6 L p.c./ha); the 6th application was performed at the R5.5 stage with the fungicides epoxiconazole + fluxapyraxad + pyraclostrobin (Ativum, 0.8 L p.c./ha), the insecticide teflubenzuron (Nomolt 150, 0.2 L p.c./ha), and methylated soybean oil (Mees, 0.5 L p.c./ha).

The mechanical harvest was carried out on May 10, 2021, and May 11, 2022, respectively, via self-propelled harvesting of experimental plots. Evaluations were carried out during the crop cycle, namely phytointoxication, SPAD index, normalized difference vegetation index (NDVI), and plant height. At pre-harvest: plant height, number of pods per plant (NPP), number of branches per plant (NBP), number of grains per plant (NGP), and plant lodging index (LI). At post-harvest: thousand-grain weight (TGW) and grain yield (GY).

Assessment of traits

The injury in soybeans caused by the herbicide lactofen was assessed subjectively by two evaluators at 7, 14, 21 and 28 days after application of the product (DAA) based on visual symptoms. The percentage values range from 0 (no symptoms) to 100% (plant death), according to the guidelines proposed by the Brazilian Society of Weed Science (SBCPD, 1995). The average score of the two evaluators represents the observed injury. For phytotoxicity analysis, a 2 x 4 design was used, with 2 doses of the herbicide lactofen, and 4 sequential assessments (at 7, 14, 21 and 28 DAA).

After application of the products, NDVI, the SPAD index, and plant height were assessed in previously ticked plants (five plants per plot), using only the central leaflet of the trifoliate leaf of each plant that was positioned at the fourth node, identified from top to bottom of the main stem of the plant. The portable proximal devices Plant Pen 300U (PD Instruments) and SPAD 502 (Minolta) were used for this purpose. Plant height was measured using a ruler graduated in centimeters positioned from the base of the plant close to the soil to the last visible node of each sampled plant. These plants were measured for height, SPAD and NDVI at 7, 14, 21 and 28 DAA. An 8 × 4 design was considered for the analysis of SPAD, NDVI and height, with eight treatments and four sequential evaluation times.

At the plant maturity (stage R7/R8), plant height (PH, cm) was assessed again, measured from the soil surface to the last node on the main stem of each plant. Number of pods per plant (NPP, n°) was assessed by direct counting on the plant; Number of grains per plant (NGP, n°) was determined by manually counting the grains. These variables were also analyzed in five plants from each experimental plot.

In the pre-harvest phase, plant lodging was assessed using the Lodging Plant Index (IL%) according to a previous study (Basilio et al., 2022): it was estimated and expressed as a percentage, considering the angle formed by the vertical position of the plant stem in relation to the soil and the area of lodging plants. The Lodging Index was considered:

$$LI(\%) = I \times A \times 2,$$

where "I" is the degree of inclination of the lodging plants (ranging from 0 to 5; 0 plants vertical and 5 plants completely prostrate); "A" is the area in the plot with lodged plants (ranging from 0 to 10; 0 absence and 10 all plants are lodged) and "2" is the correction factor for percentage.

The grains were harvested using a self-propelled harvester of experimental plots. Grain water content (moisture content) was determined at the time of harvest using the grains sampled from the useful area of each plot. After that, the grains were dried in a forced air circulation oven, where 50 g of grains were kept for 24 h at 105±3 °C. Then, the grains were weighed again.

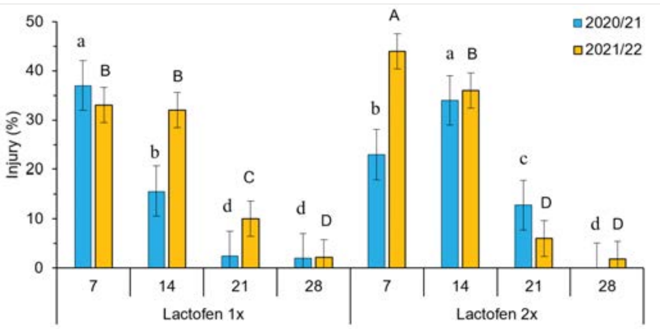
Thousand-grain weight (TGW) was measured by counting 1,000 grains from each repetition of each field plot using an electronic grain counter (Sanick, model ESC 2011) and subsequently weighing them on a semi-analytical scale with an accuracy of 0.001 g, correcting moisture content to 13% (standard grain moisture). Grain yield was estimated based on the production of the total area of the plot, also correcting the value to the standard moisture content of 13%, generating the correction factor, and converting its value to hectares, as kg/ha.

Statistical analysis

The data underwent the homogeneity and normality tests. After that, if the assumptions were satisfied, the data underwent analysis of variance (F test); when significant (*P*<0.05), the products were compared with each other using Fisher's protected LSD at *P*<0.05, and each product was compared with the control (negative check) using the Dunnett test at *P*<0.05. The analyses were performed using the SAS software (2023).

RESULTS

For plant injuries, only the lactofen 1× and 2× treatments were determined, as there were significant effects at 7, 14, 21 and 28 DAA (Figure 2). However, there was an isolated effect of growing season and product and their interaction (harvest × product). At 7 DAA, there was a significant interaction for the product × harvest factors: the application of lactofen 2× resulted in greater plant injury in the 2021/22 season than in the 2020/21 season, while for lactofen 1×, the greatest injury occurred only in the 2020/21 growing season.



Note: Different lowercase (first season) and uppercase (second season) letters, differ statistically by the LSD test (*P*<0.05). Vertical bars represent the standard error of the mean.

Figure 2. Injury at 7, 14, 21 and 28 DAA on plants of the soybean BS 2606 after the application of lactofen 1× or 2× at the recommended rate. Lages-SC, 2020/21 and 2021/22 seasons

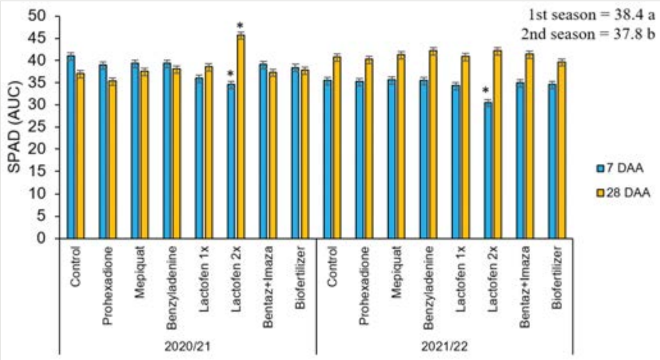
There was a significant isolated effect for product and harvest for the plant injury at 14 DAA; in the 2021/22 season, the greatest injury occurred in soybean leaves, and lactofen 2× caused greater injury than lactofen 1×. The product × harvest interaction for injury at 21 DAA demonstrates a similar behavior as for injury at 7 DAA. For the 2020/21 season, there was a greater injury rate for lactofen 1×, but there was no difference between lactofen 1× and lactofen 2× (Figure 2) in the 2021/22 season. At 28 DAA, no difference was found between the factors, which demonstrates a decrease in leaf injury in the plants. It is also noteworthy that no symptoms were observed in young leaves, which were emitted after the application of the products. Moreover, only some of the old leaves showed wilting/wrinkling.

The product lactofen 2× caused greater injury compared to lactofen 1×, as noted in the first evaluations (7 and 14 DAA) in the two growing seasons. However, there was no injury for the herbicide based on bentazon+imazamox.

Lactofen caused initial phytotoxicity (7 DAA) in most of the soybean leaves, with necrosis and wilting. At 14 DAA, the new leaves no longer showed symptoms of necrosis; however, there were still leaves that were beginning to be emitted and had deformations. In the later evaluations (21 and 28 DAA), the symptoms did not persist in the new leaves, only in the old leaves, which showed some injuries. The higher rate of lactofen caused greater damage, characterized by necrosis in most of the leaf blades, which were also deformed.

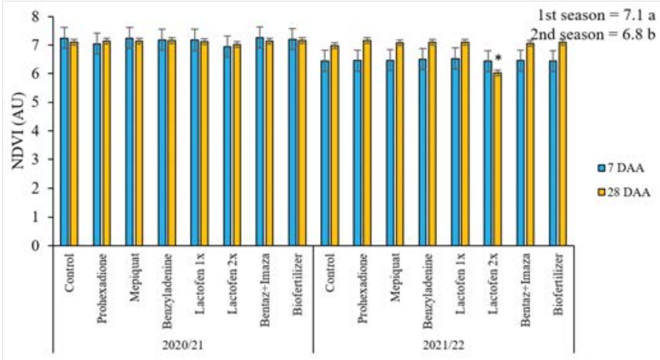
At 28 DAA, the soybean plants already showed good recovery from the injuries (without new necrosis and with increasingly less deformation of the produced leaflets). In the present study, such a fact can also be explained by regular rainfall in the months after application of the treatments in both growing seasons. This may have increased the recovery capacity of the plants after the foliar stresses caused by lactofen, thus preserving the yield components, without affecting grain yield.

There was a significant isolated effect of product and growing season on the chlorophyll index (SPAD) at 7 DAA in the 2020/21 season (Figure 3), namely the highest SPAD index values, while lactofen 1× and lactofen 2× had the lowest SPAD values, compared to the other products and with the control.



Note: The results at 14 DAA and 21 DAA were not shown because they did not show a significant difference in at least one treatment. Asterisk, within each time, per season, indicates statistical difference in relation to the control by the Dunnett test (*P*<0.05). Vertical bars denote the standard error of the mean.

Figure 3. SPAD index (arbitrary unit of chlorophyll) at 7 and 28 DAA according to the application of products on soybean BS 2606. Lages-SC, 2020/21 and 2021/22 growing seasons



Note: Figure 4 only shows the results at 7 DAA and 28 DAA because there is a significant difference in at least one treatment. The asterisk, within each time, per season, indicates statistical difference in comparison to the control by the Dunnett test (*P*<0.05). Vertical bars represent the standard error of the mean.

Figure 4. NDVI (arbitrary unit) at 7 and 28 DAA according to the application of products on cultivar BS 2606. Lages-SC, 2020/21 and 2021/22 seasons

The assessment of SPAD at 28 DAA showed an interaction between product × season: in the 2020/21 season, the highest SPAD value was found for lactofen 2×, but there was no difference between lactofen 1× and lactofen 2× in the 2021/22 season.

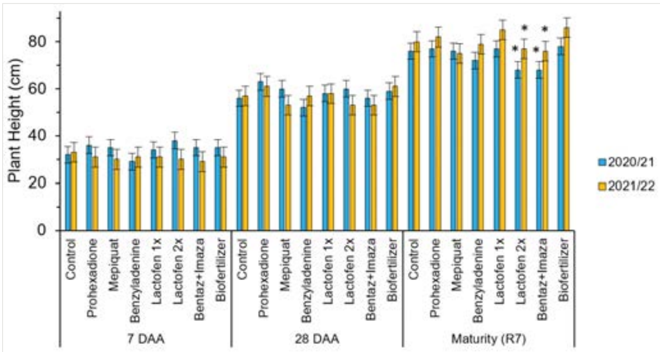
The SPAD was lower at 7 DAA, which may be due to the higher levels of injury. However, at 28 DAA, there was an increase in the chlorophyll content of the plants, possibly because the plants may already have recovered from the stress caused by the lactofen spray.

At 7 DAA, there was an effect of season on NDVI, whose values were lower in all the treatments in the second season in comparison to the first one (Figure 4). At 28 DAA, there was an interaction between product × season for NDVI; the treatment with lactofen 2× resulted in the lowest averages in 2021/22 when compared to the control group.

Plant height, as evaluated at 7 DAA, showed an isolated season effect for the 2020/21 season. There was no difference for the products over the DAA in the experiment carried out across the 2020/21 season. A similar behavior was observed in the 2021/22 season, with no differences (Figure 5). For plant height at 28 DAA, no difference was found between treatments, which showed plant recovery from injuries.

However, plant height at harvest time was consistently lower for two products - lactofen 2× and bentazon+imazamox - in both growing seasons (Figure 5).

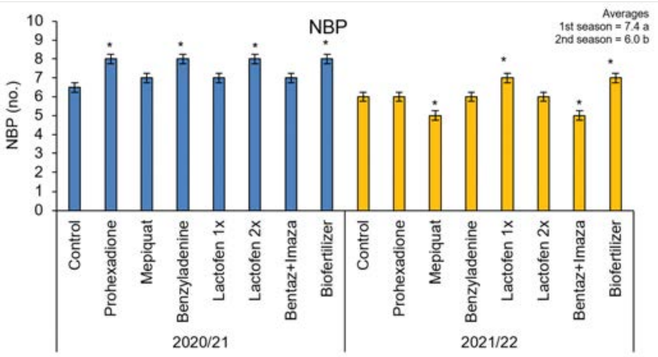
In this study, plant height was not affected by the products applied to the plants of the BS 2606 cultivar, and the number of branches per plant was high and ranged from 6 to 8 NBP, and it did not differ between treatments (*P*>0.05; Figure 6a).



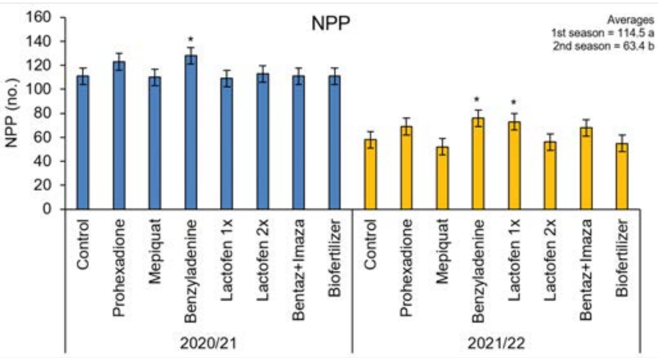
Note: Asterisk, within each time, per season, indicates statistical difference in relation to the control by the Dunnett test (*P*<0.05). Vertical bars denote the standard error of the mean.

Figure 5. Plant Height of soybean (PH, cm) at 7, 28 DAA and in R7 (Maturity), according to the application of products on cultivar BS 2606. Lages-SC, 2020/21 and 2021/22 seasons

For the variables assessed at pre-harvest and post-harvest, there was a significant isolated effect of season on plant height at stage R7 - maturity (Figure 5), number of branches per plant (NBP) and number of pods per plant (NPP) (Figure 6), number of grains per plant (NGP) and thousand-grain weight (TGW) (Figure 7), grain yield (GY) (Figure 8), and plant lodging index (LI) (Figure 9). In the treatments with lactofen 2× and bentazon + imazamox, plant height at the maturity stage (R7) was lower than that of the control: 10.5 and 10.4% in the first season and 3.5 and 5.0% in the second season, respectively (Figure 5). NBP for lactofen 2× (1st season), lactofen 1× (2nd season), and the biofertilizer (both seasons) were higher than that of the control (Figure 6a).



(a)

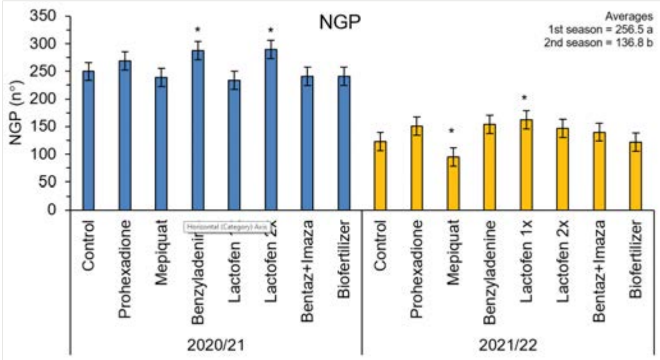


(b)

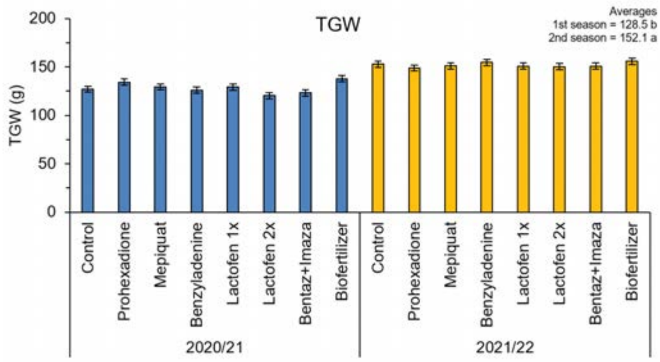
Note: Asterisk, within each time, per season, indicates statistical difference in relation to the control by the Dunnett test (P<0.05). Vertical bars denote the standard error of the mean.

Figure 6. (a) Number of branches (NBP) and **(b)** pods per plant (NPP) according to product application on soybean BS 2606. Lages-SC, 2020/21 and 2021/22 growing seasons

NPP for benzyladenine (both seasons) and lactofen 1× (2nd season) was higher than that of the control (Figure 6b). NGP for lactofen 2× (1st season) and lactofen 1× (2nd season) was higher than that of the control (Figure 7a). TGW in the 2nd season was 23.5 g heavier than in the 1st season.



(a)



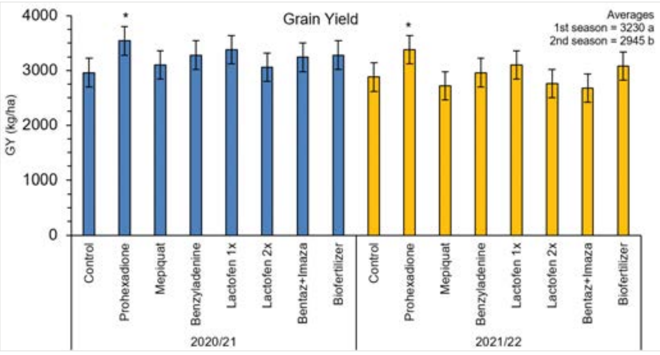
(b)

Note: The asterisk, within each time, per season, indicates statistical difference in comparison to the control by the Dunnett test (P<0.05). Vertical bars indicate the standard error of the mean.

Figure 7. (a) Number of grains per plant (NGP) and **(b)** thousand grain weight (TGW) according to product application on soybean BS 2606. Lages-SC, 2020/21 and 2021/22 growing seasons.

In the 2020/21 season, NPP, NGP, and GY had higher values than in the 2021/22 season; only plant height showed higher values in the second season. In the present work, there was no difference in TGW among the products applied (Figure 7), indicating that even though lactofen caused injuries, it did not result in losses in the yield components or in grain yield. For NPP, NGP, and TGW, there were no negative variations in BS 2606 soybean as a result of the post-emergence application of lactofen on plants at the V8 stage, and similar results were found for the regulators, the biofertilizer, and lactofen when applied also at V8.

The assessments of yield components (NPP, NGP, and TGW) and GY showed no significant differences between the products. In this respect, the occurrence of lactofen-induced leaf injuries was not enough to negatively affect the productive response of the BS 2606 soybean cultivar. Grain yield in the prohexadione treatment was higher than in the control: around 19% and 17% in the first and the second seasons, respectively (Figure 8).



Note: The asterisk, within each time, per season, indicates statistical difference in comparison to the control by the Dunnett test (*P*<0.05). Vertical bars indicate the standard error of the mean.

Figure 8. Grain Yield (GY) according to product application on soybean BS 2606. Lages-SC, 2020/21 and 2021/22 growing seasons

In general, in the second season, the number of pods per plant was lower (Figure 6b), which resulted in a lower number of grains per plant (Figure 7a); this was decisive for the occurrence of lower grain yield (Figure 8). Although thousand-grain weight was greater (in the 2nd season) (Figure 7b), this was not enough for grain yield to have the same value as in the first season.

Soybean BS 2606 did not respond in grain yield to the application of the biofertilizer (Figure 8), which contains amino acids derived from fermented sugarcane molasses. Taking together the results of two growing seasons, which were particularly contrasting in terms of rainfall regime and volume (Figure 1a and 1b), it can be argued that the treatments with different growth regulators, herbicides, and biofertilizer had little influence on the development and productive potential of BS 2606 soybean. Also, there were no effects of plant lodging (*P*>0.05; lower than 5% of lodging) in any of the treatments (including the control; Figure 9) in either season.

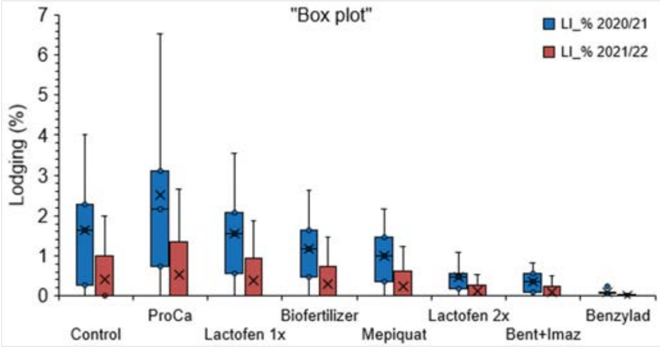


Figure 9. Plant lodging index (percent) according to product application on soybean BS 2606. Lages-SC, 2020/21 and 2021/22 seasons

This does not allow inferences about the efficiency of the products in mitigating plant lodging, but it can be inferred that the BS 2606 cultivar, in fact, is resistant to plant lodging even when cultivated at an altitude over 900 m. However, the BS 2606 cultivar can be safely produced after the application of these products, since GY and yield components remained constant in the treated plants compared to the control.

DISCUSSION

The higher rate of lactofen caused greater damage, characterized by necrosis in most of the leaf blades, which were also deformed. This characteristic is common in post-emergent Protox-inhibiting herbicides, which decrease the persistence of symptoms in plants owing to their rapid action after absorption (Oliveira-Júnior, 2011).

The initial foliar symptoms of injury observed after application of this herbicide were like those described by Alonso et al. (2013), including chlorosis with subsequent necrosis and wrinkling.

Lactofen can reduce plant height, as found in the study by Gallon et al. (2016) on soybeans. In this case, the cultivar BS 2606 was tolerant to the herbicide lactofen, especially in the assessments at 28 DAA. Soybeans could recover from injury, corroborating data from Krenchinski et al. (2017), who found that injuries were also significantly reduced after 28 DAA. The same authors mentioned that injuries are proportional to the increase in the rate of lactofen, but over time, the plants could detoxify from the effects of herbicide.

Lactofen inhibits protoporphyrinogen-IX oxidase (Protox), which is involved in chlorophyll biosynthesis. However, in the case of this soybean cultivar (BS 2606), there was an increase in SPAD, suggesting that the momentary cessation of leaf expansion led to the accumulation of chlorophyll in these leaves, reflecting the increase in SPAD, as reported by Wu et al. (2017).

NDVI values showed a greater increase in the first assessments (7 and 14 DAA), which indicates that NDVI variability decreased as crop development continued (Beneduzzi et al., 2017). Therefore, with the increase in NDVI values, the greater differences between infrared and red reflectance indicate a greater amount of chlorophyll and cumulative dry weight and, consequently, a greater potential for grain yield (Rissini et al., 2015).

The chlorophyll index (SPAD) was lower at 7 DAA, which may be due to the higher levels of injury. However, at 28 DAA, there was an increase in the chlorophyll content of the plants, possibly because they had already recovered from the stress induced by the lactofen spray, as reported by Zobiole et al. (2010). Basal and Szabó (2020), when working with inoculated soybean plants with *Bradyrhizobium japonicum*, also found high SPAD values in their assessments at all study stages. This result was due to increased pod fertility, that is, the effectiveness of flowers in pods and of grains in these pods, which was significantly higher in the late reproductive stages (R4 and R6). In this same study, the reproductive structures in inoculated plants showed a higher rate of effectiveness because the leaves showed increased NDVI values, as a result of a better supply of N to the soybean plants.

Gallon et al. (2016), who worked with soybeans that received the application of trinexapac-ethyl and herbicides applied to plants at the V5 phenological stage, did not find differences in plant height as a function of the different rates of trinexapac-ethyl. According to those authors, the application of some herbicides can stop the vegetative growth of plants, break the apical dominance in the main stem, and induce an increase in plant branching, consequently leading to an increase in the number of internodes in lateral branches. Although it can be inferred that some herbicides have a similar behavior to that of growth regulators in breaking the apical dominance of plants, this was not found to occur in the present study.

Some authors have found an effect between regulators and herbicides on soybean plant height; for example, Souza et al. (2013) reported a reduction in soybean plant height by applying chlormequat chloride under field conditions. The plants treated were more productive than those in control. In the work of Coradin et al. (2023), Protox-inhibiting herbicides (fomesafen and lactofen) associated with glyphosate caused significant reductions in plant height compared to the control without herbicides. According to Pereira et al. (2022), the application of sub-rates of herbicides (2,4-D, imazetapyr, and lactofen) also influenced plant height in different soybean cultivars. Such herbicides at sub-rates acted as growth inhibitors and caused significant reductions in plant height of 19%, 15.8%, and 24% for 2,4-D, imazetapyr, and lactofen, respectively, compared to the control treatment. This result differs from the one found in the present work.

Soybean plant height decreased after the application of chlormequat chloride in a study carried out by Ramesh and Ramprasad (2013). This indicates that these characteristics are affected by the application of regulators, but it depends on the product (type and dose) and genotype (cultivar).

In another study, the application of trinexapac-ethyl did not influence the agronomic characteristics of soybean plants; that is, using this herbicide did not cause changes in the architecture of the plants (Bossolani et al., 2019). This suggests that there was a specific response from each study cultivar.

According to Souza et al. (2013), the application of chlormequat chloride reduced the height of soybean plants when applied to plants at the R1 stage; however, when applied at V8, benzyladenine and lactofen decreased plant height. According to Prieto et al. (2017), the application of a biofertilizer to soybean plants at the R8 stage did not influence plant height when evaluated two times: at 28 DAA and at plant maturity. This finding suggests different responses in a manner dependent on plant stage and product being applied.

These results can be explained by the fact that most of the growth regulators are recommended for Poaceae (Correia and Leite, 2012), and to a lesser extent for soybean (Souza et al., 2013), and their action in other plant groups may not have the desired effect. In addition, there may be interactions between genotypes, environment, phenological stage of application and product rate (Gallon et al., 2016). Another aspect to consider about our results was that plant height (regardless of products and season) was around 80 cm because of insufficient rainfall, which may have masked the possible effect of the products.

At higher rates, lactofen can cause leaf necrosis and stress, which leads to increased lignin synthesis in stems, making them sturdier and reducing lodging. In trials, rates around 180 g/ha reduced plant height by up to 15.6% and lodging by over 30%, without significantly affecting yield (Martins et al., 2020). However, the lack of response may be due to cultivar resistance because some soybean cultivars, especially newer ones, are bred for greater tolerance to chemical stress, which includes not responding to lactofen or other growth regulators (Martins et al., 2020). Another study, with *Phaseolus vulgaris* in field trials, was conducted in Ontario over two years (2003 and 2006) to evaluate the effect of imazamox plus bentazon applied at post-emergence at 25 + 600 and 50 + 1200 g a.i. ha^{-1} on black, brown, cranberry, kidney, otebo, pinto, white, and yellow eye beans. The authors found that the herbicides did not affect plant height (Hekmat et al., 2008).

For Pereira et al. (2022), the application of lactofen was positive for NGP, which does not corroborate the results found in the experiment conducted in the present study. For NPP, NGP and TGW, there no negative variations in BS 2606 soybean owing to the post-emergence application of lactofen on plants at the V8 stage, as well as regulators, the biofertilizer and herbicide that were also applied at V8 This result differs from the findings of the study carried out by Alonso et al. (2013), who reported that the association of glyphosate and lactofen caused a significant reduction in TGW. However, our results are in line with those of Pereira et al. (2022) and Bossolani et al. (2019), who also did not find increases in TGW and GY.

In general, biofertilizers are based on microbiologically enriched ferments and have been used as a strategy to increase grain yield (Prieto et al., 2017), and their use tends to boost grain yield (Oliveira and Santos, 2011). The soybean plants showed a positive response to the application of biofertilizer in terms of grain yield compared to the control (Prieto et al., 2017). These results disagree with those found by Oliveira and Santos (2011), who did not find an increase in grain yield after the application of a biofertilizer.

In peanuts, in a study involving three rates of prohexadione-Ca and three harvest times, the treatments that received application of the product showed a greater number of pods and, consequently, greater grain yield (29.5%) compared to the control. This suggests a beneficial effect of Prohexadione-Ca, possibly because of the increase in leaf longevity and the allocation of its photosynthates to the grains (Finoto et al., 2011).

Soybean growth and yield are significantly influenced by temperature and rainfall patterns throughout the growing season. Optimal soybean development generally occurs with average temperatures between 20 and 30 °C, and total rainfall from 400 to 800 mm should be adequate to avoid water stress, particularly during critical phases such as legume formation and grain filling (Battisti and Sentelhas, 2014). Total rainfall was 229 mm and 125 mm in the first and the second seasons, respectively (Figure 1), which represented only 1/2 and 1/4 of the total amount required to achieve the desired water volume and the desired yield of 5 t/ha.

Because of the consistent absence of negative adverse effects of these products on GY, agronomists and farmers may choose to adopt this technology as an investment to reduce the risk of plant lodging in a particular season, place, or cultivar that presents a high risk of lodging.

CONCLUSIONS

Plant height at soybean maturity were shorter (small difference) after the application of lactofen 2× and when using bentazon + imazamox; therefore, it cannot be claimed that the growth regulators and the herbicides lactofen and bantazon plus imazamox mitigate plant lodging, but they increase the number of lateral branches in the plants in a manner that depends on the product and the agricultural season.

Lactofen causes injuries, but even a double-rate application allowed the plants to recover from these injuries in 28 DAA. This result was confirmed by the fact that grain yield was not negatively affected because of injury induced by this herbicide.

The application of bentazon plus imazamox, growth regulators, and the biofertilizer (containing amino acids) on soybeans is safe and does not affect the grain yield of the BS 2606 IPRO cultivar.

Spraying prohexadione on the soybean cv. BS 2606 plants at the V8 stage resulted in an increased number of productive branches per plant, and they increased grain yield consistently in both seasons.

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