

## Barley Production Performance under NPK Fertilization, Growth Regulators and Artificial Lodging

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### ABSTRACT

Balanced fertilization is an alternative to increase yield, although high doses can make plants more susceptible to lodging, reducing both yield and grain quality. This study aimed to: (i) evaluate the effects of different levels of NPK fertilization and the application of growth regulators on barley grain yield (Imperatriz variety); and (ii) analyze the impacts of artificial lodging on yield and grain quality. The experiment was conducted in a completely randomized design, in two consecutive growing seasons (2022 and 2023), in a 4×3×2 factorial scheme, involving yield potential of 4-7 t/ha, growth regulators (trinexapac-ethyl, prohexadione-calcium and control) and presence/absence of artificial lodging. The variables analyzed included plant height, natural lodging, number of grains per spike, yield, sieve index, thousand-grain weight and hectoliter weight. The results indicated yields of 4.4–5.3 t/ha in the 2022 season and 1.5-2.1 t/ha in the 2023 season, not reaching the expected yield of 7 t/ha, even in highly fertile soil, due to adverse environmental factors. There was no significant difference in plant height, nor did natural lodging occur, even under high fertilization doses, showing that growth regulators were not necessary. However, artificial lodging caused significant losses of 9 to 35% in grain yield, confirming its negative effect on the yield and quality of grains destined for malting.

**Keywords:** *Hordeum vulgare*, grain yield, agromorphological performance.

### INTRODUCTION

Barley (*Hordeum vulgare*), a member of the Poaceae family, is cultivated almost exclusively for use in the production of malt, an essential raw material for the brewing industry. In addition, it has other uses, such as in the production of medicines, the composition of flour, and the formulation of dietary products and coffee substitutes, as well as being a viable alternative for animal feed (De Mori and Minella, 2012). Due to its economic importance, the crop justifies research aimed at increasing grain yield and expanding the viability of its cultivation (Barzotto et al., 2018).

During the 1970s and 1980s, the greatest growth in world barley production was observed. In Brazil, the expansion of cultivation began in the 1970s, driven by demand from the brewing industry (De Mori and Minella, 2012; Embrapa, 2023). Since then, the cultivated area has remained

relatively stable, while grain yield has shown significant growth, reaching approximately 4,000 kg/ha in 2022, with a production of 490,000 tons (Conab, 2023).

In Romania, historical studies by Vasilescu et al. (2022) documented barley grain morphometry and the evolution of winter barley cultivars over decades, providing critical insight into genetic progress, yield stability, and the impact of breeding on grain quality traits under varying pedoclimatic conditions. These findings underscore the value of long-term varietal studies for improving both agronomic performance and end-use quality in barley.

Despite the progress made, Brazil is still heavily dependent on imports of barley and malt, since domestic production cannot meet national demand. Currently, only 25-30% of the annual malt requirement is met domestically, which compromises the self-sufficiency of the brewing industry (Embrapa, 2023). This limitation stems, in

large part, from the rigorous quality requirements imposed by the sector, which relegate non-standard grains to the animal feed market, sold at lower prices, discouraging the production chain (Embrapa, 2023). In addition to quality criteria, edaphoclimatic factors, the regional concentration of cultivation in the South of the country and the low economic liquidity of production contribute to the stagnation of national supply. This structural dependence on imports not only impacts the trade balance but also reduces the competitiveness and technological sovereignty of the Brazilian brewing industry, highlighting the need for investments in genetic improvement programs, more efficient management practices, and public policies aimed at the sustainable expansion of cultivation.

The quality of grains intended for malting is strongly influenced by three main factors: edaphoclimatic conditions, varietal genetics, and agronomic management practices. These elements determine attributes such as germination, size, protein content, and health, as established by official standards. Decree No. 691/1996 of the Ministry of Agriculture, Livestock and Supply (MAPA) define rigorous parameters, including germination greater than 95%, a maximum moisture content of 13% at harvest, a protein content of less than 12%, less than 3% of foreign matter and impurities, and up to 5% of damaged grains (Minella et al., 2019). In Brazil, the difficulty in reconciling high grain yield levels with adequate quality standards is widely recognized, which explains the persistent need for imports. This limitation, however, also represents a strategic opportunity to expand cultivation and develop more efficient management technologies. Among the alternatives, balanced NPK fertilization stands out, although excess nutrients, especially nitrogen, can cause lodging and compromise grain yield. In this context, the associated use of growth regulators emerges as a complementary practice, capable of

mitigating the negative effects of lodging and ensuring greater productive stability, reconciling agronomic efficiency and grain quality destined for malting. Thus, the present study aimed to: (i) evaluate different levels of NPK fertilization associated with the use of growth regulators on barley grain yield; and (ii) investigate the impacts of lodging on agronomic efficiency, considering both the reduction in yield and the changes in the quality attributes of grains destined for malting.

## MATERIAL AND METHODS

The experiments were conducted in Lages, Santa Catarina, southern Brazil, in 2022 and 2023 growing seasons, using the Imperatriz barley variety. The soil in the experimental area was classified as a humic aluminic Cambisol (Embrapa, 2017). The results of the chemical analysis of the soil, performed in the arable layer (0-20 cm) in the 2022 and 2023 growing seasons, were respectively 4 mg/dm<sup>3</sup> and 18.3 mg/dm<sup>3</sup> for P, 168 mg/dm<sup>3</sup> and 175.6 mg/dm<sup>3</sup> for K, 2.33 cmolc/dm<sup>3</sup> and 6.4 cmolc/dm<sup>3</sup> for Ca, 2.7 cmolc/dm<sup>3</sup> and 2.6 cmolc/dm<sup>3</sup> for Mg, and 12.30 cmolc/dm<sup>3</sup> and 7.6 cmolc/dm<sup>3</sup> for H+Al. The organic matter content was 2.1% in 2022 and 3.4% in 2023, and clay content was 44% in 2022 and 42% in 2023 season. This soil is considered highly fertile due to successive years of cultivation and the application of soil amendments and fertilizers.

The region's climate, according to the Köppen classification, is type (Cfb), with average annual precipitation of 1441 mm and temperature of 16.6°C (Wrege et al., 2012). These characteristics provide a cold winter climate, with frequent sub-zero temperatures, frost occurrences, and well-distributed rainfall (Epagri, 2006), which ultimately favors the development of winter cereals. The rainfall and temperature values for the two growing seasons (2022 and 2023) are shown in Figure 1.

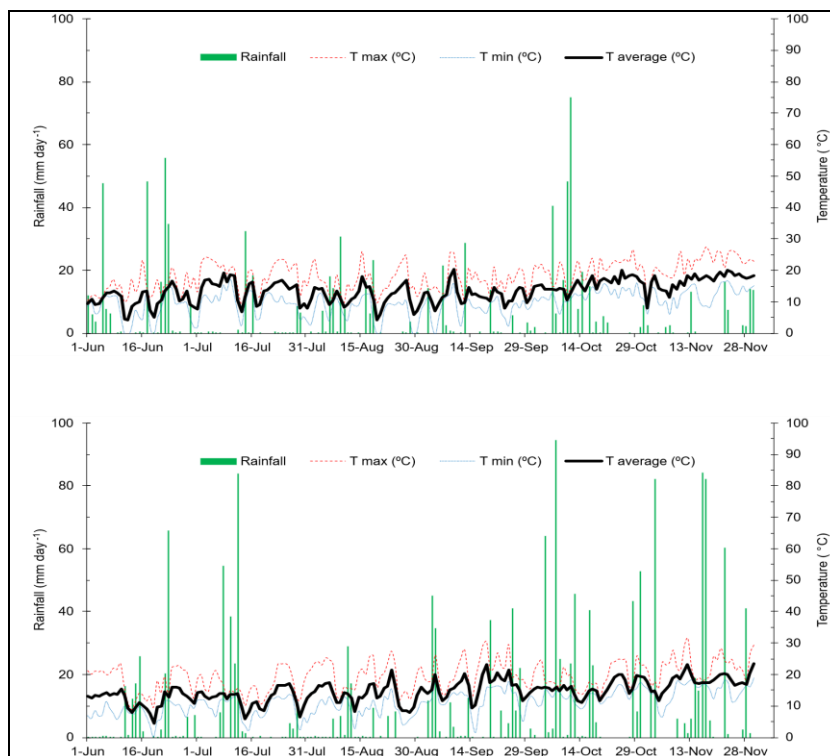


Figure 1. Rainfall (daily) and temperatures (daily) during the experiments

The experiment was sown using a no-till system on July 12, 2022, and July 24, 2023. The experimental design was completely randomized in a 4x3x2 factorial scheme, with 4 replications totaling 96 plots. The spring barley variety used was Imperatriz, subjected to factor A: four different doses of NPK fertilization, aiming to meet the expected grain yield of 4, 5, 6, and 7 t/ha, following the recommendation of the Liming and Fertilization Manual for the states of Rio Grande do Sul and Santa Catarina (CQFS - RS/SC, 2016); in factor B: use of growth regulators: prohexadione-calcium (Viviful®), trinexapac-ethyl (Moddus®), and the control (without regulator); and factor C: with and without the application of “artificial” lodging.

At sowing time, 400 kg of NPK, formulation 5-20-10 (N-P<sub>2</sub>O<sub>5</sub>-K<sub>2</sub>O), were added to the soil in the sowing row below the seeds. Additionally, topdressing nitrogen and potassium fertilization had to be split to a level of each grain yield potential from 4 to 7 t/ha in two stages: the beginning of tillering and stem elongation, using urea (45% N) and potassium chloride (KCl) (60% K<sub>2</sub>O) as sources.

The application of the regulators was carried out with the plants between the stage

of the first visible node and the second perceptible node, using a CO<sub>2</sub>-pressurized plot sprayer.

Artificial lodging was imposed on the plants when they were at stage 75 of the Zadoks scale (Zadoks et al., 1974). For this purpose, a cylindrical drum (1 m long and 70 cm in diameter) was rolled over the plants, and to complement the artificial lodging and keep the plants prostrate, it was covered with a polypropylene screen measuring 5.5 m long by 1.5 m wide with a 7 cm x 7 cm mesh. The plants were kept lodged in these conditions until harvest time.

The following parameters were evaluated: plant height measured close to harvest, natural lodging of plants using the Belgian index (I x A x 2: “I” corresponds to the inclination of the plants; “A” the area of the plot with lodged plants and “2” the conversion coefficient to percentage) according to the methodology proposed by Moes and Stobe (1991) adapted to our conditions; number of grains per spike from the sample of 5 plants per plot at physiological maturity, and from the grains obtained at harvest, the variables were determined: estimated grain yield (kg/ha) based on the production of the total

area of the plot, correcting the value at the standard water content of 13%, sieve index, taking into account grains with a transverse diameter greater than 2.5 mm -  $G > 2.5$ , hectoliter weight, with a standard cylinder (DalleMolle, model 45), and weight of one thousand grains measured with the aid of an electronic grain counter (Sanick, model ESC 2011), and subsequent weighing on a semi-analytical balance, with a precision of 0.01 g (Shimadzu, Brazil, model BL3200H).

The results were subjected to analysis of variance using the F-test ( $p < 0.05$ ), and when significant, were further analyzed using Tukey's test for qualitative treatments. For quantitative treatments, regression analysis was performed at a 5% probability of error, using the SISVAR program.

## RESULTS AND DISCUSSION

Plant height did not show significant variation as a function of treatments ( $p > 0.05$ ), with averages of 60.2 cm in the 2022 season and 57.2 cm in the 2023 season. This parameter is strongly influenced by the genotype, but also by the genotype  $\times$

environment interaction. In the present study, the average values were below the expected height for the Imperatriz cultivar ( $\approx 70$  cm), which can be attributed to the local edaphoclimatic conditions, characterized by a subtropical temperate climate, harsh winters and the occurrence of frosts, differing from the humid temperate environment for which the cultivar was originally developed (Brasil, 2025).

In the 2022 season, the increase in NPK fertilization, aiming to obtain a productive potential of 6 and 7 t/ha, resulted in an increase in the number of grains per spike (16.43 and 17.07, respectively), compared to the lower doses, which produced an average of only 14 grains (Figure 2). This result indicates a positive slope of approximately 1.07 grains per ear for each ton increase in yield potential, suggesting that adequate nutrient availability favored vegetative growth and, consequently, ear filling. Thus, although plant height did not vary, nutritional management demonstrated a direct impact on yield components, reinforcing the importance of balanced fertilization to maximize barley grain yield.

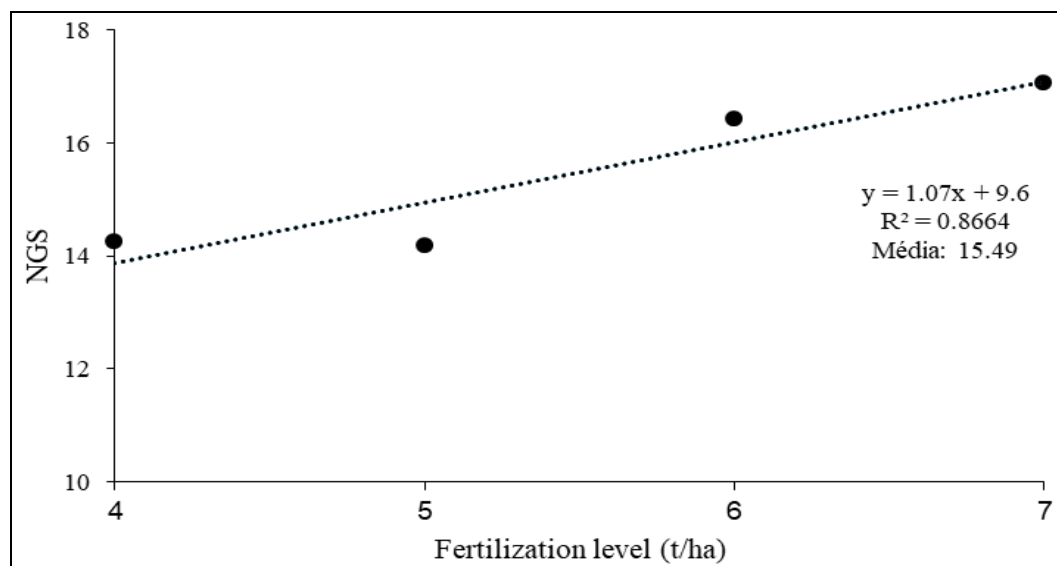


Figure 2. Number of grains per spike of barley as a function of NPK fertilization levels in the 2022 growing season, in Lages - SC

Balanced fertilization, with doses appropriate to the crop's needs, is essential for good plant development and increased grain yield, especially in the number of grains per spike. Nitrogen, for example, is directly

related to increased yield in barley (Tuppada et al., 2023), contributing to greater reproductive demand and number of grains (Rodrigues and Teixeira, 2003). Similar results were obtained in wheat by Cazetta et

al. (2007) and Shi et al. (2010), when using higher doses of nitrogen fertilization. Phosphorus, in turn, stimulates root growth, flowering, and grain formation (Malavolta, 1989; Malavolta et al., 1997), in addition to participating in essential energy processes via ATP, being crucial for the initial development of grains (Engels and Marschner, 1995; Fernandes, 2009). Studies such as that of Soares et al. (2020) also demonstrated a linear increase in the number of grains per plant with increasing phosphate fertilization. Potassium plays important physiological roles, acting as an enzymatic cofactor and contributing to carbohydrate translocation, promoting grain filling and development (Floss, 2011).

Ullah et al. (2024), working with NPK levels to increase wheat grain yield, found similar results, since using the highest NPK level also resulted in a greater number of

grains. This integrated action of NPK nutrients directly influences the increase in the number of grains per spike, as observed in this study, also corroborating results obtained by Vishwakarma et al. (2020) in wheat. Thus, NPK fertilization proves essential to meet the nutritional requirements of the crop, promoting more vigorous and productive crops, and these nutrients are widely used in agriculture (Croce, 2004; Neupane et al., 2025).

This variable also showed a significant difference in isolation for the regulatory effect; however, in both growing seasons in which the experiment was conducted (2022 and 2023), a small decrease was observed as a function of the application of growth regulators, mainly when the regulator trinexapac-ethyl (Moddus) was used, when compared to the control (Table 1).

Table 1. Number of grains per spike of barley with and without the use of growth regulators. Lages - SC, 2022 and 2023 growing seasons

Regulators	2022 season	2023 season
	NGS (n°)	
Control	16.5 a	13.3 a
Trinexapac-ethyl	14.1 b	12.4 b
Prohexadione-calcium	15.9 ab	12.6 b

Means followed by the same letter in the column do not differ from each other by Tukey's test at a 5% probability of error.

The application of growth regulators can negatively affect morphological and physiological characteristics of plants, such as reducing peduncle length and leaf area, which can compromise photosynthesis and, consequently, reduce the number of grains per plant (Espindula et al., 2010). In the present study, a lower number of grains was observed in the plots treated with trinexapac-ethyl (Moddus®) and prohexadione-calcium (Viviful®), with approximately 14.1 and 15.9 grains per spike, respectively, compared to the control, which had 16.5 grains per spike.

These results agree with those found by Guerreiro and Oliveira (2012), who reported a reduction in the number of grains per panicle in white oats with the use of trinexapac-ethyl, attributed to the reduction of the peduncle. Similarly, studies with rice

have also identified negative effects of the regulator on the number of grains (Nascimento et al., 2009). However, the literature also presents divergent results; Barausse et al. (2024) found no significant differences in wheat, while Kaspary et al. (2015) observed an increase in the number of grains per plant in white oats with the use of the regulator, indicating that the response may vary between species, variety, and experimental conditions.

The variable barley grain yield (kg/ha) showed a significant result for the artificial lodging treatment, in isolation, in both years of the experiment, where lodging reduced yield by 35% (3718 x 5726 kg/ha) in the 2022 crop season and, again, a 9% reduction in yield (1656 x 1809 kg/ha) was observed in the 2023 crop season (Table 2).

Table 2. Grain yield (kg/ha) of barley as a function of the simple effects of artificial lodging, use of growth regulators, and NPK fertilization levels. Lages - SC, 2022 and 2023 growing seasons

Factor	2022 season	2023 season
Induced lodging	GY (kg/ha)	
Without lodging	5726 a	1809 a
Lodged plants	3718 b	1656 b
Regulator		
Control	5067 ns	1976 ns
Trinexapac-ethyl	4212	1513
Proexadiona-calcium	4885	1707
NPK levels		
4	4237 ns	1526 ns
5	4464	1643
6	4929	1729
7	5257	2021

Means followed by a different letter in the column differ from each other according to Tukey's test, at a 5% probability of error ( $p < 0.05$ ). ns, not significantly different ( $p > 0.05$ ).

Although there were two harvests with quite contrasting environmental conditions, with excess rainfall in 2023 to provide a difference in grain yield, even so, lodging was confirmed as a factor in reducing the productive potential of the barley.

Lodging is defined as a state of stem modification, from vertical to prostrate (lodged), and is detrimental to agricultural production, as it can reduce the efficiency of mechanized harvesting and cause significant declines in productive potential and grain quality (Berry and Berry, 2015; Chavarria et al., 2015; Zhang et al., 2016). In the present work, it was confirmed that plant lodging is detrimental to grain yield and its impact is greater the higher the productive potential of the crop (Table 2). According to Peterson et al. (2005), Rajkumara (2008), Schepak et al. (2025) lodging is a serious problem in cereals, representing one of the most important agronomic problems for farmers to use and market grains, since it impacts the quality of grains that reach the industry or the final consumer.

The results of the present work corroborate with Arenhardt et al. (2017) and Liu et al. (2024), who found for the oat crop that the presence of lodging significantly reduced the yield and quality of the grains. As well as for Marchezan et al. (2004) who found that plant lodging limited the productive potential for irrigated rice, and

Buzzello et al. (2013) and Matos et al. (2021), who stated in their work with the soybean crop that plant lodging caused significant losses in grain yield.

The negative effects of lodging are attributed to the reduction in photosynthesis, assimilation, and translocation of carbohydrates and minerals essential to the grains (Pinthus, 1973; Engels and Marschner, 1995). This reduction in productive performance is aggravated when lodging occurs at critical stages of the plant cycle, especially during grain filling, as it is a developmental plant phase highly sensitive to the limitation of photoassimilates (Jandrey et al., 2024). In the present study, artificial lodging was imposed precisely at this stage, which may have intensified the losses observed in the barley crop.

With the imposition of artificial lodging on barley plants in the 2022 season, the index of grains larger than 2.5 mm (grain sieve) was 91.0%, while without artificial lodging it was 93.7%. According to Rodrigues and Teixeira (2003), lodging reduces solar radiation on the lower part of the plants during the grain-filling phase, negatively affecting the final grain size. This occurred with barley, mainly in the 2022 season, but did not repeat the trend in the 2023 season. However, the results followed the same general pattern of most grains being large, i.e., retained on the sieve ( $G > 2.5$ ) (Table 3).

Table 3. Grain sieve/Sieve index (>2.5; >2.2; >2.0 mm; %) of barley grains with and without artificial lodging for two seasons (2022 and 2023) in Lages - SC

Induced Lodging	2022 season	2023 season	2022 season	2023 season	2022 season	2023 season
	>2.5mm (%)		>2.2mm (%)		>2.0mm (%)	
Without lodging	93.7 a	91.9 ns	5.6 ns	7.2 ns	0.7 ns	1.2 ns
Lodged plants	91.0 b	91.6	5.8	7.0	0.6	1.0

Means followed by a different letter in the column differ from each other according to Tukey's test, at a 5% probability of error ( $p < 0.05$ ). ns, not significantly different ( $p > 0.05$ ).

This behavior also occurred for grain yield (Table 2), and as previously highlighted, it can be justified by the fact that lodging of plants ends up limiting photosynthesis and reducing the translocation of photoassimilates, and this limitation ends up preventing sufficient transport of photoassimilates present in the leaves and stem to the spike and grains in formation, negatively affecting these variables, an effect that was more pronounced in the 2022 season, in which the highest yield was obtained.

The use of growth regulators did not have an effect on the productive performance of barley ( $p > 0.05$ ). Increasing NPK fertilization levels also did not result in an effect on the productive performance of barley ( $p > 0.05$ ) (Table 2).

Kharub et al. (2022) in barley, wheat and white oats applied growth regulators to mitigate the effects of plant lodging and also did not obtain responses on the grain yield of these crops. However, Rodolfo et al. (2019) showed a small increase in yield, an increase attributed to improved leaf architecture and an increase in the photosynthetic rate. On the other hand, it is also suggested that the root system grows deeper into the soil, increasing the capacity to absorb more water and nutrients from deeper layers within the soil profile.

Marolli et al. (2017) observed in their work that the application of the recommended dose of growth regulator in oat cultivation did not influence grain yield. Similarly, Fioreze and Rodrigues (2014) found no difference in wheat yield with the use of growth regulator.

In this sense, Zagonel and Fernandes (2007) reported that the use of growth regulator can be efficient in reducing plant height, but also in improving the leaf architecture of wheat and optimizing the use of solar radiation. Chavarria et al. (2015) found that another effect of using growth regulator is the increase in chlorophyll content and the root-to-shoot ratio of wheat.

Works such as that of Liu et al. (2024), were corroborated by the results shown, which suggest that the use of regulators in higher doses of nitrogen enhances the effects of this nutrient, resulting in superior grain yield due to better use of photosynthesis and reduced environmental stress in plants.

The thousand-grain weight and hectoliter weight of barley grains, in both the 2022 and 2023 growing seasons, were affected only by the isolated growth regulator factor, where the values were higher when the growth regulators prohexadione-calcium (Viviful®) and trinexapac-ethyl (Moddus®) were used (Table 4).

Table 4. Thousand-grain weight and hectoliter weight of barley as function of growth regulators sprayed on plants for two seasons (2022 and 2023) in Lages - SC

Regulators	2022 season	2023 season	2022 season	2023 season
	TGW (g)		HW (kg/100 l)	
Control	44.2 b	35.5 b	62.9 b	63.2 b
Trinexapac-ethyl	45.5 a	36.6 a	63.6 a	64.6 a
Prohexadione-calcium	45.8 a	36.7 a	63.9 a	64.9 a

Means followed by a different letter in the column differ from each other according to Tukey's test, at a 5% probability of error ( $p < 0.05$ ).

This result was probably due to the photoassimilates being more geared towards improving grain filling, and consequently, increasing the values of these variables, which corroborates with Nascimento et al. (2009), who found a similar situation for rice cultivation, as well as with Guerreiro and Oliveira (2012), who worked with white oats, and Fernandes (2009) in wheat cultivation also verified an increase in the thousand-grain weight as a function of the application of growth regulators. However, Baruassee et al. (2024) and Da Costa et al. (2018) did not find significant differences in their experiments with wheat.

Another fact that may explain the greater thousand-grain weight (Table 4) is when compared to the number of grains per spike (Table 1), which decreased as the application of regulators occurred, and this may be due to a compensatory effect of the plant, where it presents a smaller number of grains, but heavier, resulting in greater weight, and which occurs due to the phenotypic plasticity of the plants. This compensatory effect on grain yield components was also observed by Milner et al. (2021), Slafer et al. (2021) and Vicentin et al. (2024), who found a reduction in the number of grains per wheat plant, accompanied by an increase in the thousand-grain weight.

## CONCLUSIONS

Barley grain yield was not significantly affected by different NPK fertilization levels; however, an increase in NPK application enhanced the number of grains per spike.

The increase in NPK fertilization did not increase the occurrence of natural lodging of plants of the Imperatriz cultivar.

The use of regulators did not affect plant height, grain yield or number of grains per spike. However, treatment with the growth regulators prohexadione-calcium (Viviful®) and trinexapac-ethyl (Moddus®) positively influenced grain quality traits, resulting in increased thousand-grain weight and hectoliter weight.

The imposition of artificial lodging on barley plants, when they are in grain-filling

stages (between milky grain and doughy grain), consequently causes a reduction in grain yield and in the grain sieve (diameter greater than 2.5 mm).

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