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Efficacy of growth regulators in a lodging-sensitive wheat cultivar: grain yield, crop economic profitability and flour industrial quality

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Abstract

Growth regulators in annual crops such as wheat are being used for reducing plant lodging. Thus, this study aimed to assess the effects of applying different growth regulators on grain yield, industrial quality of flour, and the economic viability of a lodging-sensitive wheat cultivar, namely TBIO-Pioneiro. The RDB experimental design consisted of five treatments and nine replicates. The treatments used the following regulators: trinexapac-ethyl (T1), ethephon (T2), prohexadione calcium (T3), chlormequat chloride (T4) and a control (untreated) (T5). The rates were determined according to the manufacturer's recommendations for other crops. Plant height was reduced with application of regulators, for example, trinexapac (93.1 cm), and control (100.7 cm). This same growth regulator tested increased TGW (36.2 g) over the control (33.6 g) making plant lodging lowest (from 34%-control to about 10%-treated). Grain yields with application of growth regulators were higher than control (3.1 t ha^{-1}), ranging from 148.9 to 158.9% (means regulator-treated of 4.8 t ha^{-1}). Regarding grain alveograph indices, there was an increase in gluten strength (W) with the use of ethephon (309 10^{-4}J), prohexadione (309.3 10^{-4}J), and chlormequat (309 10^{-4}J), compared with control (240.3 10^{-4}J). The economic return on investment was higher than the control, of up to 35.7%. It is concluded that application of prohexadione, ethephon and chlormequat changes the gluten strength of wheat grains and that the growth regulators tested are efficient in controlling lodging, reducing plant height and increasing grain yields, thus providing productive stability and higher financial returns in wheat cropping.

Keywords: Chlormequat chloride. Ethephon. Prohexadione-calcium. Trinexapac-ethyl. *Triticum aestivum* L. Economic performance.
Abbreviations: CAV_Centro de Ciências Agroveterinárias; CEPA_Centro de Socioeconomia e Planejamento Agrícola – Epagri/Cepa; DAA_Days after application; EPAGRI_Empresa de Pesquisa Agropecuária e Extensão Rural de Santa Catarina; FMI_Foreign matter and impurities; GA_Gibberellin; GI_Gross income; GV_Grain volume; GY_grain yields; HW_Hectoliter weight; IA_Lodging index; L_Extensibility; M%_Grain moisture content; NDVI_Normalized difference vegetation index; P/L_Tenacity/extensibility ratio; P_Tenacity; RDB_Randomized block design; SPAD_Soil plant analysis development; TGW_Thousand grain weight; UDESC_Universidade do Estado de Santa Catarina/Santa Catarina State University; V%_base saturation; W_Gluten Strength

Introduction

Current increasing yields achieved by wheat (*Triticum aestivum* L.) producers are associated with the higher productive potential of modern cultivars and use of a greater number of crop inputs, such as nitrogen fertilization (Zagonel and Fernandes, 2007). This is due to increasing intensification of winter cereal production systems for the purpose of achieving higher yields (Subedi et al., 2021).
The use of high nitrogen doses and greater sowing density rates enhance plant growth of this cereal, which leads to lodging (Rodrigues et al., 2013; Fioreze and Rodrigues, 2014). The stem of lodged plants bends toward the ground as a result of lower resistance, occurrence of winds, and the weight of water accumulated in mature spikes (Espindula et al., 2010; Peake et al., 2020). Lodging is associated with wheat grain yields, quality of grains during the grain filling stage, reduced photosynthesis efficiency and translocation of assimilates to the spikes and, after maturation, it favoring deterioration, preharvest grain germination and, consequently, harvest losses (Zagonel and Fernandes, 2007).
One of the alternatives to reduce wheat plant lodging without the need to reduce nitrogen fertilization or sowing densities is the application of growth regulators. Regulators are synthetic substances not produced by plants and which affect their growth (Taiz et al., 2017). Plant growth regulators reduce plant height by reducing cell elongation or the cell division rate, and they are antagonistic to gibberellins and auxins (Rademacher, 2000).
Growth regulators can be classified into two groups: ethylene-releasing compounds (ethephon) and gibberellin (GA) biosynthesis inhibitors. Among GA biosynthesis inhibitors, there are compounds from the quaternary ammonium group (chlormequat chloride, mepiquat chloride and AMO-1618) and the phosphono group (chlorphenium chloride), which block GA synthesis before *ent*-kaurene, i.e., phase 1 of GA biosynthesis; the group of nitrogen-containing

heterocyclics, such as ancymidol (pyrimidines), cyclases (norbornane diazetines) and triazole (paclobutrazol and uniconazole), which inhibit the *ent*-kaurene oxidation into *ent*-kaurenoic acid, in phase 2 of GA biosynthesis; and derivatives of acylcyclohexadiones, such as trinexapac-ethyl and prohexadione calcium, which inhibit 2-oxoglutarate-dependent dioxygenases in phase 3 of gibberellin biosynthesis (Rademacher, 2000).

Concerning the use of growth regulators, previous reports have argued that they reduce plant height (Zagonel and Fernandes, 2007; Penckowski et al., 2010; Marco-Júnior et al., 2013; Chavarria et al., 2015; Hawerroth et al., 2015, Subedi et al, 2021), reduce the length of the second and third internodes (Schwerz et al., 2015) and culm length (Espindula et al., 2010), and reduce plant lodging (Penckowski et al., 2010; Zhang et al., 2014; Hawerroth et al., 2015; Corbin et al., 2016; Marolli et al., 2017; Ahmad et al., 2020). In addition, they can increase grain yield (Penckowski et al., 2010; Zhang et al., 2014; Chavarria et al., 2015).

Studies on growth regulators to obtain responses about their effects on cereal yields are essential in view of the good effects found for plant morphology and reduced lodging (Mykhalska et al., 2020). There is also little information about the relationship between productive traits, industrial flour potential, and the technical-economic viability of using these products. Thus, the aim of this study was to assess the effect of applying different growth regulators on a lodging-sensitive wheat cultivar on grain yield, industrial quality of grains and flour, and the economic viability of using these products.

Results

Chlorophyll content, plant height and lodging

The analysis of variance showed that there was no significant effect for chlorophyll B, NDVI and plant height at 14 DAA of different growth regulators applied to the wheat crop (Table 2).

It can be seen that chlorophyll A and total chlorophyll achieved lower values, 34.2% and 40.6% respectively, after application of ethephon, compared with control (without growth regulator). The application of prohexadione-calcium, with 35.5% of chlorophyll A and 42% of total chlorophyll, did not differ from the other treatments. Likewise, trinexapac-ethyl did not differ from the other growth regulators with respect to total chlorophyll, with 42.5% over the mean (Table 2).

Wheat plant heights at 14 days after application of growth regulators did not exhibit differences, with 52.0 cm on average. However, at 21 DAA, the untreated wheat plants and the ones sprayed with chlormequat chloride were taller, with 86.8 and 86.2 cm in height, respectively. This result did not differ from that of application with ethephon: 85.3 cm. The shortest plant height was achieved with application of trinexapac-ethyl, which accounts for a 4% reduction when compared with control (Table 2). Such result remained until harvest, i.e., plant height with application of trinexapac-ethyl at harvest was lower (93.1 cm), with a reduction of 7.5% in comparison to the control plants, which were 100.7 cm tall (Table 2).

With respect to the percentage of plant lodging, the lowest values were found with applications of trinexapac-ethyl and prohexadione-calcium: 8.6 and 12.5%, respectively. However, the highest lodging rate was found (34.2%) without application of growth regulators (control), a result that did not differ from the one after application with chlormequat chloride, with 25.2% (Table 2).

Moisture content in wheat grains, after application of growth regulators, was higher when applying chlormequat chloride, i.e., there was an increase of 1.5% in comparison to the seeds of the control treatment, i.e., 14.0% (Table 2).

Grain yield components

For the hectoliter weight (HW) of wheat grains, the highest values were found for application of trinexapac-ethyl and prohexadione-calcium, 77.9 and 77.5 kg 100 l^{-1} of grains, respectively, which did not differ from the grains of wheat plants that received ethephon application, which showed HW of 76.7 kg 100 l^{-1}. The increased HW values achieved with trinexapac-ethyl and prohexadione-calcium regulators compared with control were 3.7 to 3.1% higher, respectively (Table 2).

TGW after application of trinexapac-ethyl on wheat plants was 36.2 g, i.e., 7.0% higher than control, but it did not differ from the TGW of wheat grains treated with other plant growth regulators (Table 2). The application of growth regulators increased wheat grain yield from 3.1 t ha^{-1} (control) to 4.8 t ha^{-1} (mean of all regulators), which accounts for an approximate increase of 50% in GY (Table 2).

Farinography and economic yield

Concerning the alveograph variables of wheat flour obtained from the grains of plants treated with growth regulators, there was no significant effect for tenacity (P), extensibility (L) and for the tenacity/extensibility ratio (P/L) (Table 3). There was a significant effect only for gluten strength (W, 10^{-4}J), i.e., the application of prohexadione-calcium (309.3 10^{-4}J), ethephon (309.0 10^{-4}J) and chlormequat chloride (309.0 10^{-4}J) provided higher gluten strength compared to control (240.3 10^{-4}J) and the treatment with trinexapac-ethyl (240.3 10^{-4}J) (Table 3).

The process of analysis of the economic viability of use of each growth regulator is described in Table 2. The treatment with chlormequat chloride indicated higher net income, with 601.19 US$.$ha^{-1}$, and return of investment of 35.9%, followed by prohexadione-calcium with 35.7%, trinexapac-ethyl with 34.2% and ethephon with 32.2%, when compared with producer standard treatment. It can be seen that regardless of the growth regulator used, net income and return on investment are higher than the ones achieved with the standard treatment (Table 4).

Discussion

The occurrence of lodging in cereal crops such as wheat interferes with crop yield and, consequently, with grain quality (Mykhalska et al., 2020). Therefore, application of growth regulators is an alternative way to prevent plant lodging.

According to the results found for chlorophyll content in wheat plants after application of ethephon, which is a product characterized by ethylene release (Rademacher, 2000), it can be argued that it may influence the leaf senescence process. Ethylene is a plant hormone considered to be a positive regulator of leaf senescence (Jibran et al., 2013), and it is also important in the senescence of bracts and floral glumes and in the maturation of wheat grains (Beltrano et al., 1994).

Chlorophyll is associated with plant photosynthesis efficiency owing to the pigments that act in the photochemical phase of photosynthesis, which are specialized in capturing light (Taiz et al., 2017). Leaf chlorophyll contents decrease as the senescence process advances, when degradation of these pigments is accelerated (Jespersen et al., 2016). According to Schippers et al. (2015), senescence is an important process in agricultural crops because it affects grain yield and quality. According to these authors, delayed senescence allows greater assimilation of carbohydrates and, consequently, higher crop yields.

However, the use of other growth regulators did not have a harmful effect on the chlorophyll contents of plants. This can occur since these products favor the interception of sunlight by the leaves, because of the plants' upright structure, as reported by Fioreze and Rodrigues (2012). These authors studied plant density changes associated with application of trinexapac-ethyl in wheat crops (in the culm elongation phase) and found that the plants exhibited a more intense green color in leaves, with SPAD index ranging between 48.4 and 50.4. Chavarria et al. (2015) found increases of chlorophyl A, B and total chlorophyl contents, of 4.4, 5.4 and 4.5%, respectively, in wheat cv. Mirante plants sprayed with trinexapac-ethyl.

For plant height, the growth regulators applied in the wheat crop were especially effective in inhibiting gibberellins synthesis. Thus, with reduced levels of gibberellins, plants do not reach a stature considered as normal, i.e., they develop shorter and thicker stalks, which ensure more resistance to adverse conditions (Khodanitska et al., 2021). In addition, a shorter plant height allows reduction of losses caused by plant lodging and favors the interception of sun radiation (Zagonel and Fernandes, 2007; Peake et al., 2020).

Thus, these results corroborate the ones found by Espíndula et al. (2010), who studied the effect of application of chlormequat chloride and trinexapac-ethyl on wheat crops. The authors found that increased doses of both plant growth regulators provided a reduction of plant stalk length, with mean values ranging from 62.0 to 76.8 cm, compared with control, as well as a shorter peduncle length. Likewise, Chavarria et al. (2015) found that the application of trinexapac-ethyl in wheat cultivars Quartzo and Mirante reduced plant height by 16.9 and 15.8%, respectively.

Lower plant height is related to a lower percentage of plant lodging (Zagonel and Fernandes, 2007), which explains the findings. Ahmad et al. (2020) reported that the application of ethephon in wheat crops resulted in reduced plant height, less lodging, larger internode diameter and higher lignin content in such crops. In addition, there was a negative correlation between lignin content and lodging, that is, high lignin levels contribute to increased plant resistance to lodging.

The percentage of grain moisture that resulted from the application of prohexadione-calcium can be associated with the regulation of cytokinin contents in the plants, delayed leaf senescence and, consequently, delayed moisture loss in grains. The advance and rate of plant senescence may vary, but plant hormones are key factors that can delay or accelerate this process (Taiz et al., 2017). According to Peleg et al. (2011), leaf senescence is retarded when cytokinin contents increase. As reported by Grossmann et al. (1994) and Bekheta et al. (2009), prohexadione-calcium application increases the concentration of cytokinin and abscisic acid in plant tissues. This is due to reduction of ethylene hormone production (Grossmann et al., 1993).

Hectoliter weight (HW) of wheat grains is used in several countries as a traditional measure to determine grain quality (Costa et al., 2008). According to Normative Instruction no. 7 of August 15, 2001 (Brasil, 2001) wheat grains are classified into three types, based on the minimum HW value, moisture, extraneous matters and impurities. HW values ranging from 70 to 74.9 kg 100 l^{-1} classify wheat grains as type 3, ranging 75 to 77.9 kg 100 l^{-1} as type 2, and over 78 kg 100 l^{-1} as type 1. Thus, all grain volumes obtained with and without application of growth regulators meet the minimum quality value for HW. Stefen et al. (2014) found HW values for wheat grains of cv. Mirante between 72.0 and 77.9 kg 100 l^{-1} when they examined the effects of two different dosages and timing of application of foliar nitrogen and different growth regulators. However, the regulators did not influence differences in HW in the grains produced.

The results found for HW, TGW and yield indicate that the application of growth regulators in wheat has a favorable effect on these attributes. This may be due to lower plant height and, consequently, lower lodging rate, as well as better interception of solar radiation (Zagonel and Fernandes; 2007) owing to the angle of the flag leaf, i.e., arranged more uprightly, and changes in the plant foliar architecture (Peneckowski and Fernandes, 2010).

The results of this study agree with the results found by Penckowski et al. (2010), who reported increased grain yields of wheat cv. Avante, with mean values ranging from 5725 to 6234 kg ha^{-1} when they evaluated the time of application of trinexapac-ethyl and nitrogen doses. Stefen et al. (2014), however, assessed the effect of two different dosages and timing of application of foliar nitrogen and different regulators and found that growth regulators did not affect the TGW and grain yield of cv. Mirante. Similarly, Buzetti et al. (2006) did not find interference in rice yield with application of chlormequat chloride, and Hawerroth et al. (2015) in white oats with application of trinexapac-ethyl. It should be noted that the results of research with growth regulators and their effects on grain yield and quality has a strong component, which is the crop year-genotype interaction. In crop years more favorable to the occurrence of lodging, that is, when in fact there is greater plant lodging, grain yield and quality in the control treatment are more negatively impacted, and where growth regulators are applied, the difference in grain yield increases positively. This was found to occur in this study (Table 2, data on lodging and grain yield).

The use of growth regulators can influence plant growth and the industrial quality of wheat, and it may change the alveograph properties of wheat (Penckowski et al., 2010). In the present study, there was alteration only in gluten strength (W) (Table 3), unlike the finding reported by Penckowski et al. (2010) after application of trinexapac-ethyl, which promoted increased extensibility (L), reduced tenacity/extensibility ratio and increased gluten strength for cv. BRS 177, while cv. Avante did not exhibit alveograph changes. Similarly, Stefen et al. (2014) found that the application of trinexapac-ethyl in cv. Mirante did not provide changes in the flour's W index. Such results suggest that the response of W depends on the cultivar planted (Penckowski et al., 2010; Stefen et al., 2015). Thus, cv. TBIO-Pioneiro did not alter the flour's W index after application of trinexapac-ethyl, but the application of prohexadione-calcium, ethephon and chlormequat chloride increased W by nearly 28% (Table 3).

Application of growth regulators reduces the occurrence of lodging in wheat crops and enables adjustments in nitrogen

Table 1. Chemical analysis of the soil in the experimental area using growth regulators in wheat cultivation.

pH-water	pH-SMP	P	K	H + Al	CEC pH 7.0	V%	O.M.
		(mg dm-^{3})	(mg dm-^{3})	(cmol dm-^{3})	(cmol dm-^{3})	%	%
5.6	5.4	19.4	99	8.3	22	62	3.4

pH SMP = SMP-buffer index (Shoemaker-McLean-Pratt); CEC = cation exchange capacity; V% = base saturation; O.M. = organic matter.

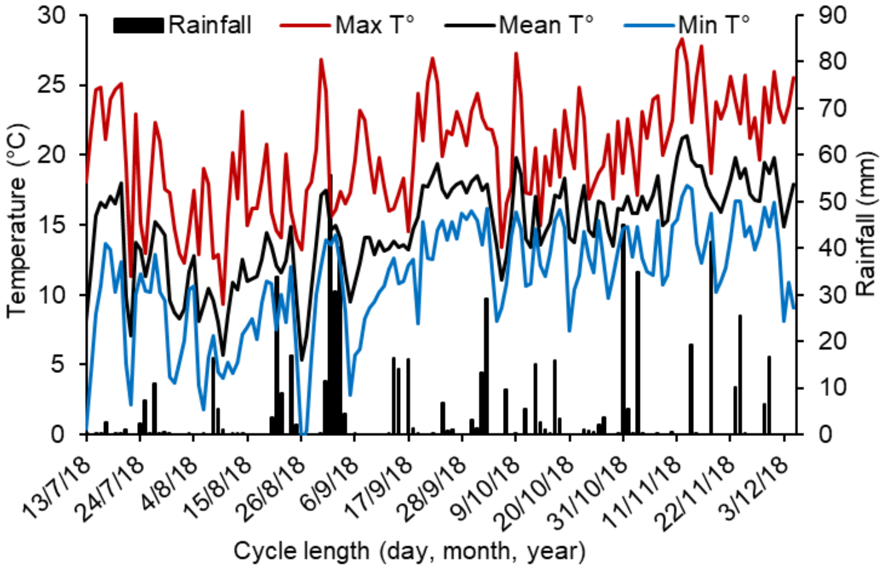

Fig 1. Rainfall, minimum (min T°), mean (mean T°) and maximum (max T°) temperatures recorded during the wheat growing period (2018 growing season). Source: INMET, 2019.

Table 2. Chlorophyll A and B, total chlorophyll, NDVI, plant height at 14, 21 DAA and at harvest, lodging, foreign matters and impurities (FMI), moisture (%), hectoliter weight (HW), thousand-grain weight (TGW) and grain yields (GY) of wheat produced with application of different growth regulators.

Variables	Control		Trinexapac		Prohexadione		Ethephon		Chlormequat		Mean	CV (%)*	P>f
Chlorophyll A	36.32	a	35.85	a	35.55	ab	34.18	b	36.58	a	35.70	3.17	<0.01
Chlorophyll B	7.30	ns	6.63	-	6.45	-	6.40		6.83		6.72	10.31	0.583
Total Chlorophyll	43.63	a	42.48	ab	42.00	ab	40.58	b	43.40	a	42.42	4.00	0.003
NDVI	7.27	ns	7.17		7.08		7.02		7.17		7.14	3.23	0.198
Height (14DAA) (cm)	54.44	ns	50.78		51.78		50.44		52.78		52.04	8.75	0.350
Height (21DAA) (cm)	86.78	a	83.33	c	84.00	bc	85.33	ab	86.22	a	85.13	1.59	<0.01
Height (harvest) (cm)	100.67	a	93.11	c	94.11	bc	95.56	bc	96.44	b	95.98	2.33	<0.01
Lodging (%)¥	34.17	a	8.61	c	12.50	c	16.11	bc	25.22	ab	19.32	6.44	<0.01
FMI (%)	10.59	a	3.74	b	2.05	b	1.67	b	2.62	b	4.14	6.17	<0.01
Moisture (%)	14.03	b	14.60	b	14.22	b	13.91	b	15.51	a	14.45	2.43	<0.01
PH (kg 100 l^{-1})	75.13	bc	77.89	a	77.46	a	76.73	ab	74.68	c	76.38	1.84	<0.01
TGW (g)	33.64	b	36.19	a	35.46	ab	34.93	ab	35.62	ab	35.17	4.33	0.013
GY (t ha^{-1})	3.09	b	4.83	a	4.88	a	4.60	a	4.91	a	4.46	14.77	<0.01

*Means followed by different letters in the rows differ from each other by Tukey's test ($p<0.05$); ¥: arcsine transformed data [$(x/100)^{0.5}$].

Table 3. Wheat flour alveograph indices resulting from application of plant growth regulators.

Variables	Control	Trinexapac	Prohexadione	Ethephon	Chlormequat	Mean	CV (%)	P>f
Tenacity (P)	165.7^{ns}	165.7	155.3	155.3	155.3	159.5	19.9	0.982
Extensibility (L)	53.0^{ns}	53.0	57.0	57.0	57.0	55.4	6.4	0.391
Gluten strength (W, 10^{-4}J)	240.3b	240.3b	309.3a	309.0a	309.0a	281.7	4.3	<0.01
P/L ratio	3.13^{ns}	3.13	2.73	2.73	2.73	2.89	20.6	0.791

*Means followed by different letters in the rows differ from each other by Tukey's test ($p<0.05$). CV: coefficient of variation.

Table 4. Economic viability (US$) of applying growth regulators in wheat crops.

Treatment	Expenses	Gross income	Net income	Return on
	------------------(US$ ha^{-1}) ------------------			Investment (%)
Producers' standard treatment	733.18	842.08	108.90	-
Trinexapac-ethyl	747.74	1317.46	569.72	34.23
Prohexadione-calcium	1062.77	1332.52	269.75	35.72
Ethephon	883.00	1257.11	374.12	32.25
Chlormequat chloride	738.23	1339.42	601.19	35.93

fertilization and sowing density for higher production potential, and reduces quantitative and qualitative losses of wheat grains caused by lodging. The reason is that lodging can reduce photosynthesis efficiency (Ingver et al., 2010; Packa et al., 2015) and translocation of photoassimilates, and increases the deterioration and germination of seeds and grains in the preharvest phase (Zagonel and Fernandes, 2007). As a result of the benefits achieved with application of growth regulators, there is a positive economic return, irrespective of the product chosen, as can be seen in the present study, which shows economic returns of 32.3 to 35.9 % for wheat cultivar TBIO-Pioneiro, when compared with control (Table 4).

Materials and Methods

Field trial and growth conditions

The experiment was conducted in the experimental site of the *Centro de Ciências Agroveterinárias- CAV* [Center of Agricultural and Veterinary Sciences] in the Santa Catarina State University - UDESC, in Lages -SC, at coordinates 27° 52' South latitude, 50° 18' West longitude and mean altitude of 930 m during 2018. The soil is characterized as an Aluminum Humic Cambisol with clayey texture (Embrapa, 2013). Temperature and rainfall data during the experiment, as shown in Figure 1, were recorded by the National Institute of Meteorology (Inmet). The lodging-sensitive wheat cultivar was TBIO-Pioneiro, one of the most cultivated wheat species in Brazil, used as flour in baking processes, but considered as sensitive to moderately sensitive to plant lodging (Kuhnem et al., 2020). A growth regulator is used with a view to achieving grain yield greater than 3 t ha^{-1}. Only TBIO-Pioneiro was used, because in lodging-tolerant cultivars, it is not technically-economically sensible to apply growth regulator to mitigate plant lodging.

Conduction of study and experimental design

Prior to sowing, which was conducted on July 13, 2018, the seeds were treated with a commercial product based on pyraclostrobin + thyofanate methyl + fipronil (Standak Top®, 5-45-50 g ai. 100 kg^{-1} of seeds, respectively). Base fertilization consisted of an application of 400 kg ha^{-1} of NPK 5-20-10 fertilizer. For foliar fertilization, 60 kg ha^{-1} of nitrogen was used, divided between the plant tillering and elongation phases, according to recommendations of the *Comissão de Química e Fertilidade do Solo* (CQFS, 2016) [Soil Chemical and Fertility Commission] and technical information for wheat cultivation (Kuhnem et al., 2020), targeting a grain yield of 5 t ha^{-1}.

A phytosanitary treatment was carried out according to technical recommendations for wheat crops (Kuhnem et al., 2020). The treatments with application of growth regulators were performed between stages GS31/32, according to Zadoks, Chang and Konzak scale (1974), corresponding to the period in which plants have the first visible node and the second perceptible node in the main plant stem.

The experiment used a randomized block design with five treatments and nine replications. The treatments consisted in applying the following growth regulators: trinexapac-ethyl (Moddus®, 125 g a.i. ha^{-1}), ethephon (Ethrel®, 480 g a.i. ha^{-1}), prohexadione-calcium (Viviful®, 130 g a.i. ha^{-1}), chlormequat chloride (Tuval®, 25 g a.i. ha^{-1}) and control (without application). The experimental plots consisted of five 10-m long sowing rows spaced 0.20 m.

Traits measured

The analyses performed after application of the growth regulators were NDVI (Normalized Difference Vegetation Index), chlorophyll A and B and total chlorophyll at 14 and 21 days after application (DAA); plant height (measured from the plant base, close to the ground, to the spike extremity at 14 and 21 DAA, and at the physiological harvest maturity); lodging index through visual evaluation, using the equation IA (%) = I x A x 2, where "I" is the vertical angle formed by the plant stalk in relation to the ground, with scores ranging from 0 to 5 (0 for absent inclination and 5 when all plants were lodged); "A" is the plot area with lodged plants, with scores ranging from 0 to 10 (0 for no lodging and 10 when all plot area contained lodged plants; and "2" is the correction coefficient to percentage, according to the methodology adapted from Moes and Stobbe (1991).

After harvesting, the percentage of moisture was determined by oven drying at 105 °C for 24 h, and using the equation M% = (iW – fW)/iW*100, where iW is the initial weight of the sample and fW, weight after drying; hectoliter weight, using a 0.25 L hectoliter scale and the equation HW = (GHW x 100)/ HW, where GHW refers to the weight of grains measured by the hectoliter scale, and GV is grain volume expressed in kg 100 l^{-1}; grain yield (weight of harvested grains >1.75 mm); percentage of foreign matters and impurities (FMI); thousand-grain weight (TGW) with percentage of grain moisture corrected to 13%.

Flour quality was analyzed by alveograph indices using the method 54-30 of AACC (1995; Stefen et al., 2015), for determination of gluten Strength (W, 10^{-4}J), Tenacity (P), Extensibility (L) and Tenacity/Extensibility Ratio (P/L).

The economic viability of using different growth regulators in wheat crops was also assessed for each hectare of production. Gross income (US$) was determined on the basis of the grain yield obtained for each treatment; net income, by the difference between gross income (US$) and expenses (US$); and return on investment through the following formula: (gross income with investment less gross income without investment) / (100 * gross income with investment). Data were collected from Epagri/ Cepa for fixed costs (based on April 2021) of a medium-technology farm, and price of a 60-kg bag of wheat marketed in the period, corresponding to 16.32 US$ (83,49 R$) (Cepa, 2021). The costs of growth regulators used per hectare were calculated on the basis of 2021 selling prices: trinexapac-ethyl (Moddus®) = 14.57 US$ ha^{-1}, prohexadione-calcium (Viviful®) = 329.95 US$ ha^{-1}, ethephon (Ethrel®) = 149.82 US$ ha^{-1} and chlormequat chloride (Tuval®) = 5.06 US$ ha^{-1}.

Statistical analysis

The results were subjected to analysis of variance (Anova) by the F-test, and when significant differences were found, Tukey's test was used ($p<0.05$).

Conclusion

Application of growth regulators in lodging-sentitive wheat cv TBIO-Pioneiro is effective for controlling lodging (trinexapac-ethyl, prohexadione-calcium and ethephon), reducing plant height (trinexapac-ethyl, prohexadione-calcium, ethephon and chlormequat chloride) and increasing grain yield (trinexapac, prohexadione, ethephon and chlormequat). Application of prohexadione-calcium, ethephon and chlormequat chloride as growth regulators positively change the gluten strength of wheat flour. Application of growth regulators in wheat plants provides higher financial return in grain production.

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