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EFFECT OF RETARDANTS ON THE BIOMETRIC CHARACTERISTICS OF WINTER WHEAT (*TRITICUM AESTIVUM* L.) STEMS

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ABSTRACT

This paper presents the results of a study on the effect of three retardants on the length of the stem, ear internode and successive internodes, as well as on the mechanical properties and geometric features of the stem of winter wheat, i.e. inner and outer stem diameter, as well as stem wall thickness. The following retardants: Antywylegacz Płynny 675 SL, Moddus 250 EC and Cecefon 465 SL, were applied at the recommended rates and at rates reduced by 50 and 67% at the beginning of stem elongation (BBCH 31) or at the 2nd node stage (BBCH 32) of winter wheat. The study showed that the lengths of individual internodes, their outer diameters as well as the diameter and thickness of the 4th internode were most influenced by the growth regulators used at the highest rate. The diameter of the stem gradually decreased from the lower internodes towards the ear.

Key words: inner and outer stem diameter, internode length, lodging, retardants, stem wall thickness, winter wheat.

INTRODUCTION

Cereals belong to strategic crop plants in most countries of the world. More than 75% of human demand for energy is met by products of plant origin, mainly by cereals (Boros, 2005).

Cereals, when well supplied with nutrients used in an appropriate proportion and at a proper growth stage, as well as under appropriate weather conditions during the growing period, grow intensely producing large vegetative biomass and high grain yields (Brzozowska et al., 2008). However, factors that promote the luxuriant growth of plants can contribute to their lodging, which involves the falling of stems, their bending over in the lower internodes or breaking off in the middle part or in the area of the ear internode (Berry et al., 2000; Verma et al., 2005). As a result of a reduced rate of photosynthesis in the crop canopy and impaired nutrient and water uptake from the soil, lodged plants mature more slowly and their ears show poorer grain filling. As a consequence, lodging leads to reduced yields and causes deterioration in the quality of harvested grain. The greatest losses in grain yield occur when cereals lodge during the period from the beginning of flowering to the milk stage. In such case, the productivity of ears is reduced, 1000 grain weight decreases, and the proportion of offal in total grain yield increases (Tripathi et al., 2004; Kowalczyk and Jakubczak, 2008; Zhang et al., 2010; Acreche and Slafer, 2011). Moreover, lodging impedes mechanical harvesting of cereals and increases harvest costs (Leszczyńska and Nieróbca, 2004; Kong, 2013). Therefore, the prevention, delay and reduction of lodging of cereals increase the quantity and quality of yields and promote the achievement of a good economic effect (Rajala and Peltonen-Sainio, 2000; Berry et al., 2004).

The more the elongation growth of an internode weakens its resistance, the greater is the risk of lodging. In this case, light is an important factor. Under its influence, the action of auxins, responsible for elongation growth, weakens and in effect plants become shorter and produce more rigid cells. On the other hand, light deficiency (as a result of too

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high plant density, a too high rate of nitrogen, or inappropriate crop location) leads to etiolating of plants. From the point of view of the bending mechanics of the stem, the most important geometric feature is its length. The magnitude of stresses resulting from ear weight and wind action, which are transmitted by tissues of the lower internodes to the root system, depends on stem length (Niu et al., 2012).

One of the methods to prevent lodging is the use of exogenous growth substances, commonly called plant growth and development regulators or retardants. The action of these compounds involves reducing the height of plants and beneficially modifying their habit (Rajala and Peltonen-Sainio, 2001; Kierzek and Głowacki, 2004; Espindula et al., 2009).

The aim of the study was to evaluate the impact of various active ingredients of retardants used in three doses (recommended and reduced) on the mechanical and geometrical characteristics of winter wheat stalks. Retardant action was compared on two levels of nitrogen fertilization. Additionally inhibitory effect on the growth of wheat plants was evaluated in combination with an adjuvant or without it.

MATERIAL AND METHODS

Experimental design

A field study was carried out in the period 2004-2007 at the Czesławice Experimental Farm (51030’N; 22026’E), belonging to the University of Life Sciences in Lublin. It was located on grey-brown podzolic soil (sandy), designated as PWsp, slightly acidic (pH in 1M KCl – 6.3-6.6), with high or very high availability of phosphorus, potassium and magnesium. The experiment was set up as a split-split-plot design in three replicates, in 10 m2 plots. Its design included treatments without retardant (control treatment) and treatments with the following retardants: Antywylegacz Płynny 675 SL (chlormequat chloride, CC – (675 g L^{-1}), Moddus 250 EC (trinexapac-ethyl, TE – 250 g L^{-1}), and Cecefon 465 SL (chlormequat chloride, CC – 310 g L^{-1} + ethephon, E – 155 g L^{-1}), applied at the recommended rates and at rates reduced by 50 and 67%. The retardants were used in the following way: CC at the 1st node stage (BBCH 31); TE and CC + E at the 2nd node stage (BBCH 32) of wheat – in combination with the adjuvant Atpolan 80 EC (76% of SN 200 mineral oil) or without adjuvant. They were applied with a P161 field sprayer (Tee-Jet Turbo 02) at a pressure of 0.25 MPa, using 250 L of liquid per hectare. Winter wheat, cv. ‘Muza’, was sown after vetch grown for seed. Tillage of soil for wheat was done following good agricultural practices. Before sowing of the test plant, phosphorus and potassium fertilization in an amount of 40 kg P ha^{-1} and 110 kg K ha^{-1} was applied. Nitrogen fertilization in the form of ammonium nitrate and urea was used in doses of 100 and 150 kg of pure component per 1 ha in two periods: first part (60 and 95 kg) after the start of vegetation – BBCH 29 and the second part (40 and 55 kg) in phase 3 internode - BBCH 33. The whole experiment was sprayed with the herbicides Apyros 75 WG (sulphonylurea, at a rate of 20 g ha^{-1}) and Starane 250 EC (fluroxypyr 250 g L^{-1}, at a rate of 0.6 L ha^{-1}) at the full tillering stage (BBCH 29-30). The following fungicides were used against fungal diseases: Alert 375 SC (a.i. flusilazole 125 g L ha^{-1} + carbendazim 250 g ha^{-1}) at a rate of 1 L ha^{-1} and Tilt Plus 400 EC (a.i. propiconazole 125 g L^{-1} + fenpropidin 275 g L^{-1}) at a rate of 1 L ha^{-1}. The winter wheat was sown in the third 10-day period of September at a seeding density of 500 germinating seeds per 1 m^2. Before sowing, seeds were treated with Dividend 030 FS (a.i. difenoconazole 30 g L^{-1}) at a rate of 300 ml of the seed dressing per 100 kg of seed.

Measurements

The canopy height of winter wheat plants was determined before harvest (measuring it from the soil surface to the ear tip, excluding awns). The biometric characteristics of winter wheat stems were determined based on 30 stems sampled at the fully ripe stage (BBCH 89) in each plot. The length of successive internodes was measured from the stem base.

The inner and outer stem diameter was determined using a special gauge designed by the Institute of Agrophysics of Polish Academy of Sciences in Lublin. The degree of wheat lodging was determined several days before harvest using a 9-point scale (where 1° means a crop completely lodged, whereas 9° – no lodging). The mechanical lodging susceptibility index was determined based on the stem length/diameter ratio (Baier, 1965).

Statistical analysis

The study results were statistically analyzed by analysis of variance, while the differences between means were evaluated by Tukey's test at a significance level of α=0.05. The statistical analysis was presented using Statgraphics 5.0 software.

Weather conditions at the study site

The growing seasons in the period 2004-2007 varied in rainfall intensity and

Table 1. Weather conditions at the Experimental Station

Years	Months												Total/ Mean
	IX	X	XI	XII	I	II	III	IV	V	VI	VII	VIII	
Precipitation (mm)													
2004/2005	21.1	26.1	65.5	15.8	34.8	35.4	42.2	21.2	146.9	48.0	55.8	46.2	559.0
2005/2006	23.1	4.2	24.6	55.7	16.1	24.4	47.4	26.1	68.1	23.2	26.6	202.5	542.0
2006/2007	10.1	31.0	43.7	22.7	83.7	23.8	32.6	16.4	46.4	85.1	70.0	31.4	496.9
1951-2005	51.6	40.1	38.1	31.5	22.7	25.6	26.3	40.2	57.7	65.7	83.5	68.6	551.7
Air temperature (°C)													
2004/2005	12.5	9.8	2.8	1.1	-0.7	-4.0	-1.1	8.4	13.0	15.6	19.8	17.0	7.8
2005/2006	14.7	8.7	2.7	-1.3	-8.2	-4.6	-2.0	8.5	13.3	16.9	21.1	17.4	5.8
2006/2007	15.1	9.8	4.7	2.5	2.0	-2.0	5.7	8.2	14.9	18.2	18.8	18.8	9.7
1951-2005	12.6	7.8	2.5	-1.4	-3.5	-2.7	1.1	7.4	13.0	16.2	17.8	17.1	7.3

RESULTS

Plant height

Winter wheat plant height was significantly differentiated by all experimental factors and some interactions between them, but the growth regulators and their rates modified this trait to the greatest extent (Table 2). The plant height in the control treatment (without retardant) was highest, on average 93.0 cm for the three-year study period. Stem length was most shortened by the recommended rates of the retardants. Compared to the control treatment, the shortest winter wheat plants were found in the treatment with CC+E applied at a rate of 2.0 L ha^{-1}. In this case, the difference was as much as 21.2%, i.e. 19.7 cm. The lowest, though also significant, retardation effect was found in the plots sprayed with TE at a rate of 0.2 L ha^{-1}. In comparison with the control treatment, wheat plants were shorter there by 7.1 cm (7.6%).

The varying weather conditions during the experiment differentiated winter wheat plant height at a level of 9.5%. Significantly lower plants developed in each successive year of the study, reaching a stem length of 86.4, 83.9 and 78.2 cm, respectively. The means of years were found to show a positive and statistically confirmed effect of the adjuvant on the reduction in wheat stem length (by 4%).

Nitrogen rate per 1 ha was also a factor on which winter wheat length of stems was dependent. Fertilization with this nutrient at the reduced rate (100 kg ha^{-1}) significantly shortened the average wheat stem length by 3%. Its effect on reducing wheat plant height was observed in each year of the experiment, though it was not statistically proven.

Table 2. The height of the winter wheat plants (cm)

Retardant	Dose (L ha^{-1})	Mean for N dose		Mean for adjuvant		Mean for years			Mean
		100	150	a*	b	2005	2006	2007	
WR		92.3	93.7	94.5	91.6	100.5	94.6	84.0	93.0
CC	2.00	76.8	80.6	80.4	76.9	82.0	82.2	71.9	78.7
	1.00	80.9	83.1	83.0	81.0	82.8	83.0	80.2	82.0
	0.67	82.4	85.0	84.9	82.5	84.2	84.6	82.3	83.7
TE	0.40	76.2	80.3	81.1	75.4	81.0	83.5	70.1	78.2
	0.20	84.0	87.9	87.4	84.4	89.2	88.9	79.6	85.9
	0.13	87.4	89.8	89.6	87.7	95.9	88.2	81.7	88.6
CC+E	2.00	73.2	73.5	76.0	70.7	78.5	69.2	72.3	73.3
	1.00	80.3	82.4	82.6	80.1	82.6	82.0	79.4	81.4
	0.67	82.7	84.4	85.2	81.9	87.1	83.1	80.5	83.5
Mean		81.6	84.1	84.5	81.2	86.4	83.9	78.2	82.8
$LSD_{\alpha = 0.05}$ years = 0.96; N doses = 0.66; adjuvants = 0.66; retardants = 2.38; years × adjuvant = 1.66; years × retardant = 4.62									

WR – without retardant; CC – chlormequat chloride; TE – trinexapac-ethyl;
CC+E – chlormequat chloride + ethephon; *a – without adjuvant; b – Atpolan 80 EC adjuvant.

Internode length

The trait in question, important from the point of view of resistance of cereals to lodging, was dependent on all factors of experiment (Figures 1 and 2). First internode length was significantly modified by year and nitrogen fertilization level as well as by the interactions of these two factors. Significantly the longest first internode length was found in 2005-2.83 cm. In the next years, which did not differ significantly from each other, the length of this internode was lower by at least 31.8%. On average during the study period, shorter internodes (by 8.3%) were found under the conditions of the lower nitrogen rate (100 kg ha^{-1}). In the first year of the experiment, the difference in first internode length induced by nitrogen fertilization rate was statistically proven (Figure 1). The second and third internodes were modified to the greatest extent by varying weather conditions in individual research seasons. In the last year of the study, the second internode shortened by 3.01 cm, that is, by as much as 32.5%, compared to the second year of the experiment, whereas the third internode was shorter by 23.2% in the last year of the study in comparison with earlier years.

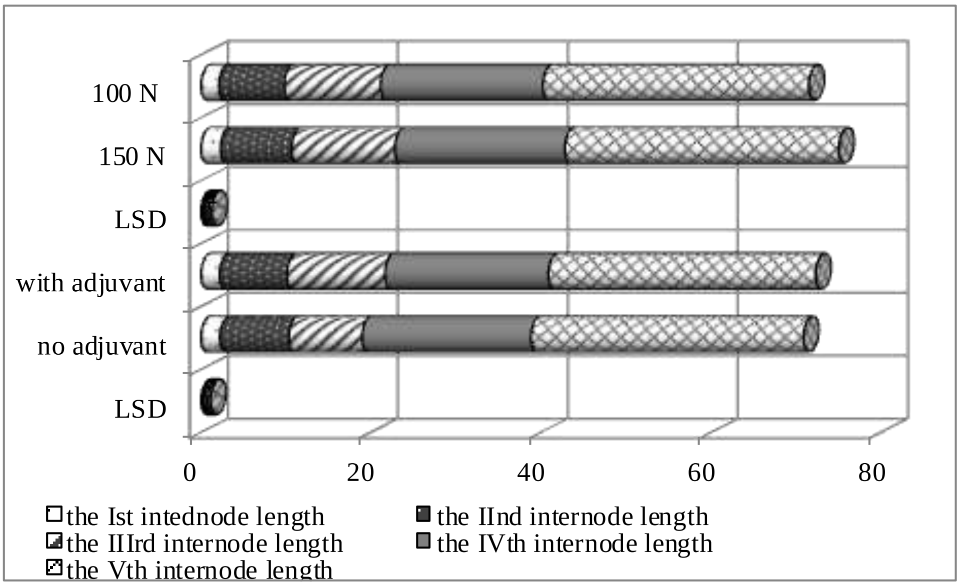
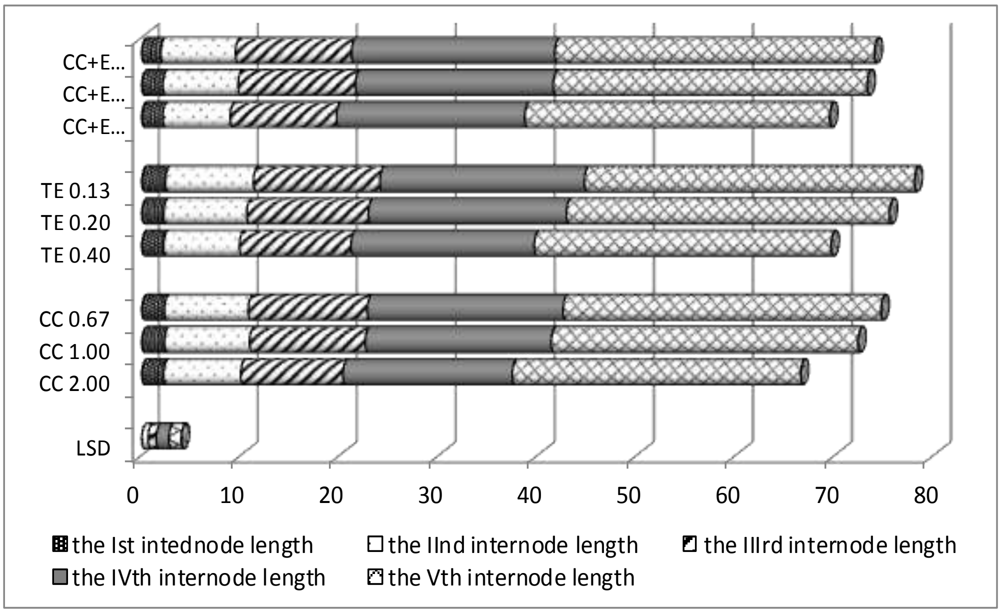


Figure 1. Internodes length depending on the N doses (kg ha^{-1}) and adjuvant

The growth regulators used, in particular their highest doses, significantly shortened the internodes (Figure 2). The shortest second internode (6.82 cm) was found in the treatment with CC applied at the recommended rate. Compared to the control treatment (8.49 cm), the difference was 19.7%. The third internode was most shortened (by 2.48 cm) in the treatment with the highest dose of the CC+E. Analyzing the data shown in Figure 2, we found that the second internode was not shortened only by the retardants with TE at the lowest rate and CC+E at the rate of 1 L $^{ha-1}$.



CC – chlormequat chloride; TE – trinexapac-ethyl; CC+E – chlormequat chloride + ethephon

Figure 2. The internodes length depending on the type and doses of the retardant (L ha^{-1})

Taking into account only nitrogen rates, the 2nd and 3rd internodes were proved to be significantly shorter when the lower level of fertilization was used (100 kg ha^{-1}). In the case of the second internode, the difference between rates was 8.4%, while the third internode was shortened by 6.7% under the conditions of the lower nitrogen rate compared to the higher rate (150 kg ha^{-1}) (Figure 1). The adjuvant used in the experiment significantly shortened the second internode (by 2.5%) and the third internode (by 3.3%). The retardants with the addition of adjuvant were found to shorten the length of these internodes in each year of the study, though this was not statistically proven (Figure 1).

The fourth and fifth internodes were most affected by all rates of the growth regulators used. Compared to the control treatment, significantly the shortest both mentioned internodes were observed in the plots with the recommended dose of the CC+E. In this treatment, the fourth internode was shortened by 18.7% (from 21.04 cm to 17.11 cm), whereas the fifth one by 15.6% (from 34.52 cm to 29.12 cm) (Figure 2). The varying growth conditions during the experiment differentiated the fourth internode length at a level of 6.3%, while that of the fifth internode by 4.8%. Both internodes were shorter in each year of the experiment. As a result of that, the fourth internode length was 20.27 cm in the first year, whereas in the last year it was only 18.99 cm. In turn, the fifth internode shortened from 32.38 cm to 30.81 cm during the same study period. The fourth internode, similarly to the second and third ones, was shorter in the treatment with the lower rate of nitrogen (100 kg ha^{-1}) by 4.4%. In the case of the fifth internode, an opposite situation was found, since it was shorter (by 2.9%) when the rate of 150 kg N ha^{-1} was used. The adjuvant used increased the retardation effect of the growth regulators investigated. Under its influence, the fourth internode was found to be significantly shorter by 3.4%, while the fifth internode by 1.8% (Figure 1).

Outer internode diameter

The outer diameters of all the five internodes significantly varied between years and nitrogen fertilization levels (Figure 3). The highest values of the diameters of the first three internodes were observed in the first research season. In the next two years, these diameters were significantly lower by 8-13%. Weather conditions in the second year of the study had the most beneficial effect on increasing the thickness of the fourth and fifth internodes. The above-mentioned internodes were found to be significantly thinnest in the last year of the experiment.

Taking into account only nitrogen rates, the higher level of fertilization with this nutrient was proved to have a beneficial effect on increasing the outer diameters of all the five internodes (150 kg N ha^{-1}). The retardants and adjuvant used in the experiment did not affect significantly the trait in question.

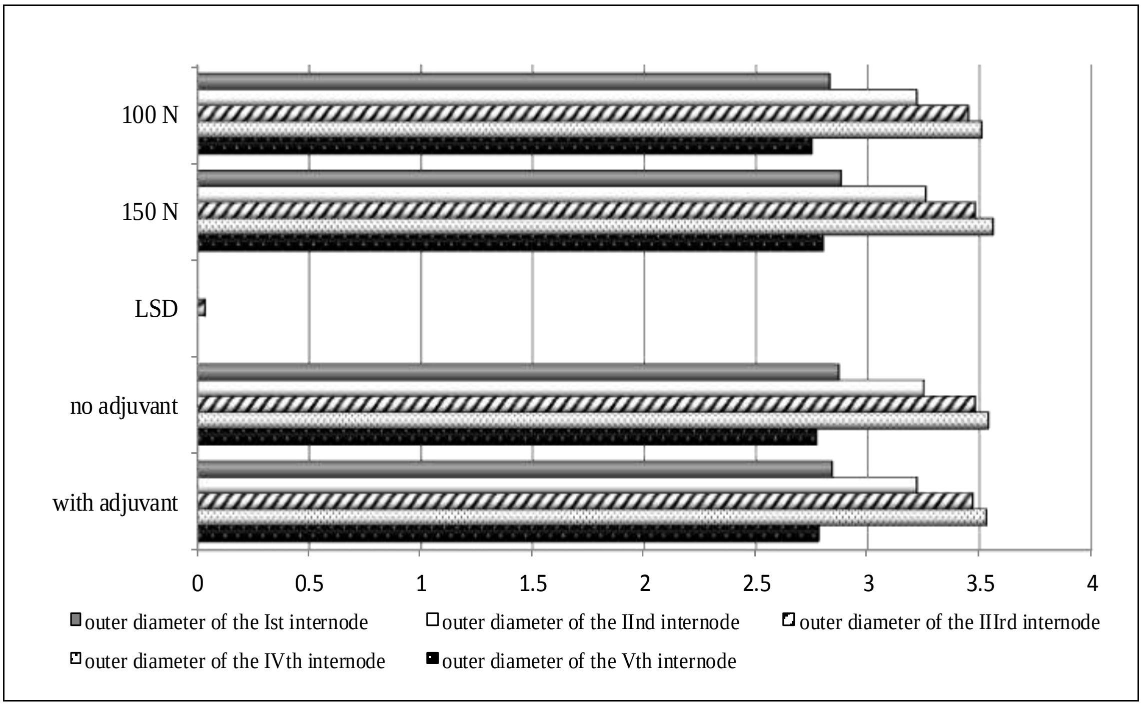


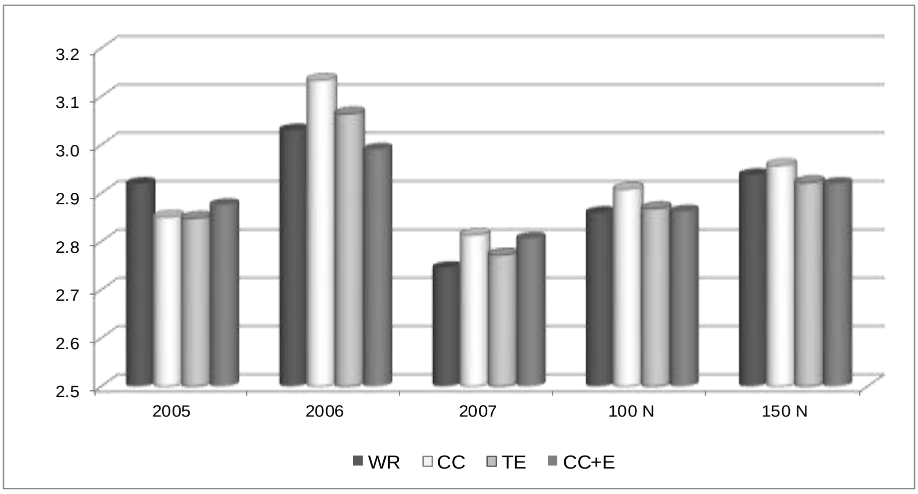
Figure 3. The outer diameter of the internodes depending on the N doses (kg ha^{-1}) and adjuvant

Inner diameter of the fourth internode

The inner diameter of the fourth internode, similarly as its thickness, was most modified by weather conditions during the study period and nitrogen rate per 1 ha (Figure 4). The highest diameter was found in 2006 – 3.06 mm, a slightly lower one in 2005 – 2.86 mm, whereas it was significantly lowest – 2.79 mm – in the last year of the study (2007).

The higher rate of nitrogen (150 kg ha^{-1}) increased the inner internode diameter of winter wheat by 1.7% compared to the lower rate (100 kg ha$^{-1).}$ The beneficial effect of increased fertilization on the trait in question was proven in each year of the experiment.

Among the retardants used, Antywylegacz Płynny 675 SL (CC) showed the most beneficial effect, compared to the control treatment, on increasing the inner diameter of the fourth internode at all the rates applied. The growth regulators with TE and CC+E, applied at the medium rates, caused a tendency towards thickening of the inner diameter of the fourth internode.

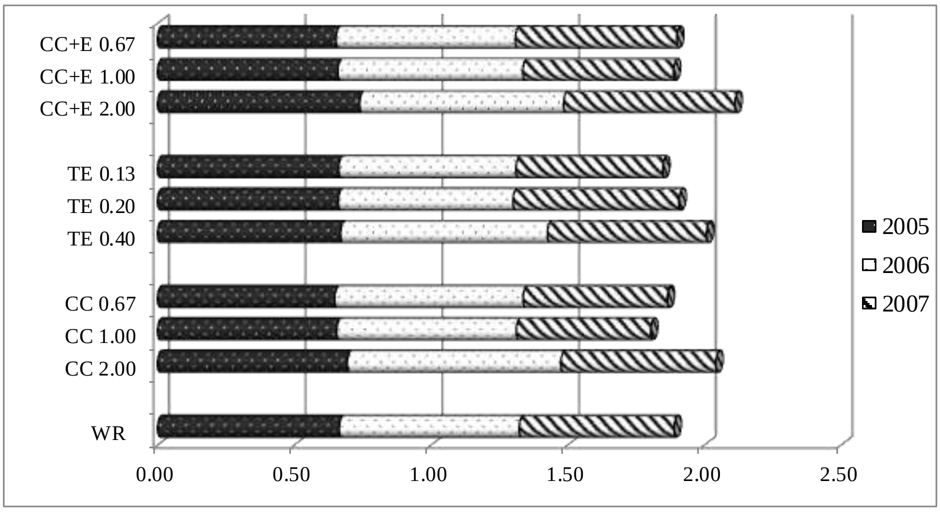


WR – without retardant; CC – chlormequat chloride; TE – trinexapac-ethyl;
CC+E – chlormequat chloride + ethephon.

Figure 4. The inner diameter of the IVth internode depending on years of research and N doses (kg ha^{-1})

Wall thickness of the fourth internode

This trait varied between years and under the influence of the growth regulators used in the experiment (Figure 5). The thickest wall was found in the second year of the study – 0.69 mm, while it was slightly thinner in the first year (0.67 mm) and significantly thinnest in the last research season (0.56 mm). The difference between years was as much as 18.8%. The wall thickness of the 4th internode was found to increase in all the treatments with the recommended rates of the retardants, compared to the control treatment. The medium and lowest rates did not change the value of the studied trait. The nitrogen fertilization level and the adjuvant used did not differentiate significantly the wall thickness of the fourth internode, either.



WR – without retardant; CC – chlormequat chloride; TE – trinexapac-ethyl;
CC+E – chlormequat chloride + ethephon.

Figure 5. Wall thickness of the fourth internode depending on the doses of retardant (L ha^{-1}) and years of research

Mechanical lodging susceptibility index

Lodging susceptibility of cereal plants most frequently relates to their stem and lodging occurs in the two lowest internodes. The length of the lower internodes indicates plant growth conditions at the initial period of stem elongation. This trait, in combination with internode diameter, determines the so-called mechanical lodging susceptibility index. The lower the value of this index, the higher is the resistance of plants to lodging. In the present experiment, the highest values of the lodging rate in the case of the three lowest internodes were found in the control treatment (Table 3).

The value of the lodging index for the first internode decreased with increasing rates of the TE and CC+E, which most shortened the internode length. In the case of the CC, an opposite situation was observed. As the rate of this regulator increased, the lodging index increased. Analyzing the effect of the retardants on the second and third internodes, the investigated index was found to have increasingly lower values with reducing rates of all the retardants preventing lodging.

The adjuvant Atpolan 80 EC used in the experiment decreased the lodging index of the second internode by 2%, while in the case of the third internode by 3% compared to the treatments without adjuvant. As far as the first internode is concerned, the adjuvant slightly increased the value of this measure in the treatments where it was used.

The value of the index in question increased in the treatments with the higher level of nitrogen fertilization (150 kg ha^{-1}) in all the three internodes in each year of the experiment. In the case of the first internode, the study found an average increase in this index by 6.3%, for the second internode by 6.6%, while for the 3rd internode by 5.2% in comparison to the lower rate of nitrogen (100 kg ha^{-1}).

Table 3. Mechanical lodging susceptibility index

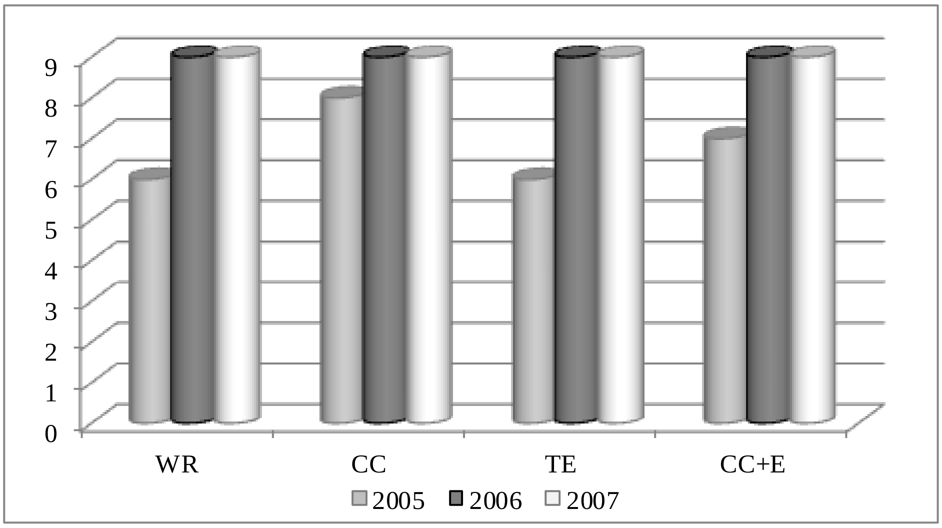
Retardant dose (L ha^{-1})		I internode					II internode					III internode				
		N		Ad		R	N		Ad		R	N		Ad		R
		100	150	a*	b		100	150	a	b		100	150	a	b	
WR		0.83	0.76	0.87	0.76	0,81	2,55	2,78	2,79	2,53	2,66	3,64	3,83	3,91	3,56	3,74
CC	2.00	0.65	0.86	0.78	0.70	0.74	2.00	2.21	2.17	2.05	2.11	2.90	3.19	3.07	3.02	3.04
	1.00	0.77	0.70	0.75	0.73	0.73	2.34	2.32	2.26	2.42	2.33	3.36	3.44	3.46	3.34	3.40
	0.67	0.62	0.73	0.69	0.64	0.67	2.20	2.44	2.31	2.34	2.32	3.22	3.52	3.35	3.37	3.36
TE	0.40	0.74	0.82	0.73	0.80	0.77	2.28	2.48	2.40	2.35	2.38	3.20	3.30	3.30	3.20	3.25
	0.20	0.72	0.76	0.74	0.77	0.75	2.45	2.67	2.59	2.54	2.56	3.37	3.69	3.59	3.48	3.54
	0.13	0.80	0.88	0.80	0.85	0.82	2.66	2.82	2.77	2.70	2.73	3.59	3.84	3.77	3.65	3.72
CC+E	2.00	0.70	0.84	0.78	0.77	0.77	2.29	2.51	2.34	2.54	2.40	2.80	3.08	2.91	2.97	2.94
	1.00	0.74	0.81	0.83	0.74	0.78	2.50	2.76	2.73	2.52	2.62	3.31	3.37	3.48	3.20	3.37
	0.67	0.83	0.74	0.74	0.83	0.79	2.59	2.62	2.62	2.60	2.61	3.46	3.48	3.46	3.49	3.47
Mean		0.74	0.79	0.77	0.76	0.76	2.39	2.59	2.50	2.45	2.47	3.29	3.47	3.43	3.33	3.38

N – mean for N dose (kg ha^{-1}); Ad – mean for adjuvant; R – mean for retardant; WR – without retardant; CC – chlormequat chloride; TE – trinexapac-ethyl; CC+E – chlormequat chloride + ethephon; *a – without adjuvant; b – Atpolan 80 EC adjuvant.

Lodging

Lodging of winter wheat was evaluated based on the degree of stem inclination using a 9-point scale. This measure takes into account not only the angle of deviation of plants from the vertical position, but also the percentage area of the crop lodged. The lower the value of this degree, the more severe was lodging. In the present experiment, the susceptibility of plants to lodging was mostly dependent on meteorological conditions in individual growing seasons as well as on retardant rate and nitrogen fertilization level. The growth regulators used in the experiment effectively protected winter wheat against lodging in the last two years of the experiment. Only in the first year (2005) of the experiment, which exceeded the long-term mean in terms of rainfall, a slight degree of crop inclination (6-70) was observed in the plots with the lowest rate of the CC + E and TE with increased level of nitrogen fertilization (150 kg N ha^{-1}) as well as in the control. Due to record high rainfall in May

2005 which was recorded at the stem elongation stage, thus in the period that affects the length of internodes and their thickness as well as the structure of the stem walls, winter wheat proved to be more sensitive to lodging (Figure 6).



WR – without retardant; CC – chlormequat chloride; TE – trinexapac-ethyl; CC+E – chlormequat chloride + ethephon

Figure 6. Lodging (9° scale)

DISCUSSION

The research of many authors (Li et al., 2000; Jagodziński, 2005; Berry and Spink, 2012) showed that stems with very weak internodes affect the development of the structure of the aerial part of the whole plant. Resistance to breaking of the lowest internodes is the most appropriate indicator for lodging which leads, among others, to reduced yields. The most important action of growth regulators on winter wheat plants is the reduction of the total length of the stem by shortening the length of its individual internodes. Retardants not only shorten the stems of cereal plants, but they also effectively modify their habit by increasing the outer and inner diameter of the stems as well as the thickness of their walls. Due to this, plant resistance to lodging increases. In the present study, all the rates of the retardants reduced the height of winter wheat plants compared to control plants. Stems were most shortened in the plots treated with the full dose of the growth regulators. The retardant with CC shortened stem length by 15.4%, TE by 15.9%, whereas CC+E by as much as 21.2% relative to the control treatment. Over the three-year study period, the highest efficacy of the action of the growth regulators on winter wheat plant height (78.2 cm) was obtained in the last year of the study, which was most favourable in terms of temperature (2007), whereas this efficacy was lower in the second year (83.9 cm) and lowest in 2005 (86.4 cm). Similar results were obtained by Pietryga and Drzewiecki (2003) as well as Espindula et al. (2009). The above cited authors obtained a significant (12-18.5%) reduction in the height of cereal plants as influenced by the TE and CC, only under favourable weather conditions.

As regards the resistance of cereals to lodging, in addition to stem length, the greatest influence is attributed to the length of the lower internodes (in particular the three lowest ones). This characteristic often indicates plant growth conditions at the initial period of stem elongation. The significant correlation between stem length and stiffness with lodging is confirmed, among others, by the research of Zubera et al. (1999) and Verma et al. (2005). The present study proved the influence of atmospheric conditions in the successive growing seasons on the length of individual internodes of winter wheat plants.

In the case of the first internode, a significant reduction in its length was obtained in 2006, whereas the other internodes (2nd, 3rd, 4th, and 5th) significantly shortened in the last research season. The growth regulators used in the experiment also significantly strongly shortened the internodes, especially at their highest doses.

The literature on the subject shows that the rate of changes in the diameter along the stem is important. It is best when the diameter decreases gradually in the direction from the lower internodes to the ear, since the stems of such plants bend over under the influence of wind and rain in their upper part or along their entire length, not transferring loads to the roots. The present experiment found a positive tendency towards thickening of the outer diameters of individual internodes after the application of most retardant rates. The higher rate of nitrogen also affected beneficially the investigated trait (150 kg ha^{-1}).

The wall thickness of the stem, which is usually associated with the thickness of the sclerenchyma layer and with a larger number of vascular bundles, similarly to the outer and inner diameter, affects the geometric component of its stiffness and is of significant importance for stem resistance to bending. Higher values of the above-mentioned traits indicate higher resistance to lodging. This correlation is confirmed by the studies of Konga et al., (2013) and Kaccka et al., (2003). The above quoted authors found a higher content of lignins and cellulose in the supporting tissue layer where the cells around the vascular bundles are rich in these compounds. In the present study, an increase in wall thickness of the fourth internode was obtained in all treatments with the full dose of the growth regulators. Compared to the control treatment, the thickest wall was found in plants treated with the CC+E (by 11%) and CC (by 7.9%). Weather conditions in the first two research seasons also had a beneficial effect on increasing the wall thickness of the investigated internode, thickening the stem by 0.11-0.13 mm relative to the third year of the study. In the case of the inner diameter of the fourth internode, all the rates of the CC and the highest doses of the CC+E had a clear effect on its increase. As regards the TE, there was an opposite situation, since the largest inner diameter of the fourth internode was found in plants growing in the plots with the lowest retardant rate.

An indirect method for measuring the susceptibility of cereals to lodging is to estimate the lodging index. In the study of Milczarski (2008) this index was significantly correlated with plant height (-0.93) and second internode length (-0.5). In the present study, this index reached positive values for the second and third internodes under the influence of all the growth regulators used and the addition of adjuvant.

The regulators used in this experiment to prevent lodging effectively reduced winter wheat plant height, thereby protecting the crop against lodging and yield losses.

CONCLUSION

Depending on the dose used, the growth regulators studied shortened winter wheat stems by respectively 4.7-21.2% relative to the control treatment. The recommended rates of retardant, in combination with the adjuvant Atpolan 80 EC, most shortened wheat stem length at the lower rate of nitrogen fertilizer (100 kg ha^{-1}).

The biometric characteristics of winter wheat stems were significantly dependent on the experimental factors as modified by varying weather conditions throughout the study period.

The length of individual internodes was most shortened by the growth regulators used at the highest rate. In most cases this factor thickened their outer diameter. The tested retardants beneficially influenced the inner diameter and wall thickness of the fourth internode.

The first four internodes were found to be significantly shorter at the lower rate of nitrogen (100 kg ha^{-1}). Increasing fertilization to 150 kg ha^{-1} had an effect on shortening the length of the fifth internode and on thickening the outer diameters of all internodes. The higher rate of nitrogen also significantly increased the inner diameter of the fourth internode.

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