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ORIGINAL ARTICLE

Studies on trinexapac-ethyl dose reduction by combined application with adjuvants in spring barley

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Abstract

Trinexapac-ethyl is a popular plant growth regulator used in various crops, mostly due to its unique anti-lodging properties. Recently it has been found that this substance is also active in stress protection, which may increase its importance in the coming years. This paper presents a new approach to its application. Trinexapac-ethyl belongs to the cyclohexanedione class of herbicide chemistry, thus it is structurally similar to common graminicides frequently used with adjuvants. This study examines the effects of the application of trinexapac-ethyl with adjuvants. Field trials were conducted in the Institute of Plant Protection in Poznań (Poland), in 2014 and 2015. Trinexapac-ethyl was applied at recommended ($0.4\,l \cdot ha^{-1}$) and reduced doses ($0.2\,l \cdot ha^{-1}$) with organosilicone surfactant, ammonium sulphate and citric acid on spring barley. Stem shortening, yield components and grain quality were examined. The results of the study confirmed the possibility of dose reduction of trinexapac-ethyl by way of combined application with citric acid that reduced the pH of spray liquid or with ammonium sulphate without affecting its effectiveness. The greatest stem height reduction was observed after the application of a full dose of trinaxapac ethyl and its reduced dose in the mixture with citric acid or ammonium sulphate. Depending on the year of study, the effectiveness of the substances on stem reduction ranged from 5.6 to 16.5%. The tested mixtures did not have any significant impact on the number of grains per ear or the yield of spring barley. Trinexapac-ethyl and its mixtures with adjuvants did not influence the crude protein and starch in spring barley grains.

Key words: ammonium sulphate, organosilicone surfactant, plant growth regulator, spray liquid pH, yield components

Introduction

In intensive cultivation of grains, obtaining stable yields depends on many factors including the level of plant protection which involves the use of substances limiting the risk of plant lodging during vegetation. Depending on the date of the occurrence of permanent crop lodging, crop losses may range from 0 to 60%. Decreased grain yield is most often due to a disturbance of plant growth and development, decreased photosynthetic capacity and absorption of nutrients from the soil. As a consequence of this adverse phenomenon, the expenditures connected with harvesting increase, since harvesting is more time consuming and the grain quality is decreased (Kelbert *etal.* 2004; Tripathi *et al.* 2004). During the vegetation of grains, the risk of lodging may be reduced by using exogenous growth retardants. However, some authors believe that growth retardants not only prevent permanent crop lodging but also increase the grain's resistance to stress factors, such as drought (McCann and Huang 2007; Ahmed *et al.* 2014). Plant growth regulators that are targeted to further shorten cereal straw may also enhance realization of yield potential by improving partitioning of dry matter into harvestable yield (Rajala and Peltonen-Sainio 2000). However, the effectiveness of plant growth regulators depends on several factors, including weather conditions (Rajala and Peltonen-Sainio 2002). The adverse effects of weather can be mitigated by a combined application of plant protection chemicals and adjuvants.

Most adjuvants significantly modify the physical and chemical properties of the spray liquid, resulting in enhanced retention of spray droplets on the surface of the leaves (retention) and increased infiltration of active substances (adsorption) (Fagerness and Penner 1998; Hazen 2000). However, the application of adjuvants does not usually prevent the adverse effects of mineral salts in the water on the effectiveness of plant protection chemicals. Adding mineral adjuvants to spray liquids directly and indirectly increases the effectiveness of leaf herbicides (e.g. ammonium sulphate, ammonium nitrate, urea). These adjuvants can overcome hard water salts antagonism and in consequence improve the distribution of active substances in the deposit, slow down the precipitation and crystallisation of sediments, increase the permeability of cell membranes, and increase the transportation of active substances (Nalewaja and Matysiak 1993; Idziak *et al.* 2013; Roskamp *et al.* 2013).

Trinexapac-ethyl is a popular foliar absorbed plant growth regulator with a well-known mode of action (Adams *et al.* 1992). It is in the cyclohexanedione class of herbicide chemistry, structurally similar to graminicide sethoxydim and clethodim, and therefore its spray application parameters may follow the same trends that exist for the mentioned herbicides. Many adjuvants have been tested with sethoxidim and clethodim with varying results. This means that the choice of adjuvant can be very important for final efficacy. Studies with several turf grass species have shown that the adjuvant combination of silicone surfactant and urea ammonium nitrate could significantly enhance the efficacy of trinexapac-ethyl (Fagerness and Penner 1998; Heckman *et al.* 2001). It has already been determined that the solubility of some of the plant protection chemicals, including sulfonylurea herbicides, depends on the pH of the spray liquid. According to Green and Cahill (2003) and Woźnica *et al.* (2003), the appropriate addition of an adjuvant reducing the pH of spray liquid results in increased effectiveness of some herbicides or recommended doses of trinexapac-ethyl (Miziniak 2013).

The aim of the present study was to test the effects of reduced doses of trinexapac ethyl by its combined application with adjuvants: organosilicone surfactant, ammonium sulphate and citric acid on the growth, yield components and grain quality of spring barley.

Materials and Methods

Experimental design and treatments

Field trials were conducted in the Experimental Station of the Institute of Plant Protection in Poznań, Poland (Toruń, 53°1’ N, 18°36’ E) during the 2014 and 2015 growing seasons (April – July). The trials were carried out on spring barley cv. KWS Olof as randomised complete block designs with four replicates. The plot size equalled 12 m^2. In both experimental years, the spring barley was planted after potatoes. The spring barley was sown at a density of 350 seeds · · m^{-2} with inter row spacing of 11 cm. The soil of the experimental site was loam with an organic matter content of 1.14%, and, depending on the experimental year, the pH varied from 6.4 to 6.6. Soil preparation consisted of ploughing followed by harrowing and mineral fertilisation (107 kg N, 40 kg P_2O_5, 80 kg K_2O · ha^{-1}) applied pre-sowing.

The experiment included up to 8 treatments. Trinexapac-ethyl was applied using Moddus 250 EC formulation at the recommended dose of 0.4 l · ha^{-1} alone and at a reduced dose of 0.2 l · ha^{-1} alone or with citric acid at 0.2 kg · ha^{-1}, ammonium sulphate at 5.0 kg · ha^{-1}, organosilicone surfactant Slippa at 0.1% or mixtures of this organosilicone surfactant at 0.1% plus citric acid at 0.2 kg · ha^{-1} or ammonium sulphate at 5.0 kg · ha^{-1}. The control treatment was water only.

The mixtures were applied at the BBCH 31 growth stage of the crop. The application was conducted using a bicycle-mounted Victoria sprayer equipped with TEEJET 110 02 VP nozzles using 200 l of spray liquid per ha, with an operating pressure of 0.25 MPa. The pH of liquids was measured at 20°C using an electronic pH-meter equipped with a glass electrode. The pH-meter accuracy was +/– 0.2.

Measurements

The plant height of 25 randomly selected plants from each plot was measured at the BBCH 83 growth stage of spring barley. The length of the stem was measured from the ground to the ear base. Before harvest, plant lodging was evaluated and the number of ears per 1 m^2 on each plot was counted. The lodging was assessed visually, using a percentage scale, where: 0% – no lodging, 100% – complete lodging. During the vegetation period, the plants were visually examined on a regular basis to determine the sensitivity of spring barley to the chemicals applied. The thousand grain weight was assessed on the basis of five replications of 100 grains. The number of grains per ear was determined from 25 ears randomly collected from each plot. Grain yield was adjusted to 14% grain moisture and calculated per 1 h surface area. The crude protein and starch content in grain were determined by near-infrared transmission with an InfratecTM 1241 Grain Analyser (FOSS).

Statistical analysis

Statistical analyses were carried out with the ARM software (Agricultural Research Manager). The results of the Fisher test were evaluated at 5% significance level. Upon discovering significant differences, a detailed comparison of means using the Student's t-distribution test was performed, determining the lowest significant difference at a 5% significance level.

The results are presented separately for each experimental year, because of different weather conditions during the years 2014 and 2015 (Tables 1–2).

Results and Discussion

Water used for the preparation of the applied solution had a neutral pH of 7.22. Dissolving in water just the trinexapac-ethyl or its mixture with an ammonium sulphate or an organosilicone surfactant did not affect the pH of the spray liquid. When citric acid was added to the spray liquid containing only the trinexapac-ethyl or to the mixture of a retardant with Slippa adjuvant, the pH of the spray liquid was strongly decreased (Table 3). The two-year field trials did not show any phytotoxic symptoms of the tank mixes on the KWS Olof spring barley.

The effectiveness of growth retardants depended significantly on weather conditions. In both experimental

Table 1. Temperature and precipitation during the growing of spring barley in the experimental years

Month	Experimental year			
	2014		2015	
	average temperature [°C]	precipitation [mm]	average temperature [°C]	precipitation [mm]
April	11.1	35.5	8.9	18.1
May	13.6	81.1	12.7	35.0
June	16.3	43.2	15.7	47.3
July	21.9	60.8	18.9	121.5

Table 2. Air temperature during the 14 days after the application of the growth regulator

Day	Experimental year					
	2014			2015		
	min daily temperature [°C]	max daily temperature [°C]	average	min daily temperature [°C]	max daily temperature [°C]	average
1	30.0	16.0	22.5	19.5	10.0	14.3
2	28.5	17.0	21.9	24.0	8.0	14.4
3	27.4	13.0	19.1	19.0	4.0	12.7
4	26.4	13.5	20.4	25.0	10.0	16.3
5	22.0	14.0	16.8	27.5	10.0	17.1
6	12.2	11.0	11.4	30.0	15.0	20.0
7	11.5	7.2	9.0	21.0	7.0	14.6
8	17.0	5.0	11.3	24.0	5.0	14.5
9	22.5	8.8	15.2	25.0	10.0	20.3
10	21.5	7.5	15.7	25.5	7.0	15.8
11	19.5	8.0	12.9	22.0	4.0	13.5
12	16.5	11.0	13.4	15.0	10.0	12.3
13	21.0	13.0	17.0	21.0	5.0	12.8
14	25.0	10.0	17.3	24.0	5.0	14.5

Table 3. The pH of spray liquids containing trinexapac-ethyl with additives

Treatment	Dose [l · ha^{-1}/kg · ha^{-1}]	Spray liquids pH
Water	–	7.22
TE	0.4	6.30
TE	0.2	6.60
TE + CA	0.2 + 0,2	3.33
TE + MA	0.2 + 5.0	6.50
TE + OSS	0.2 + 0.1%	6.72
TE + OSS + CA	0.2 + 0.1% + 0.2	3.36
TE + OSS + MA	0.2 + 0.1% + 5.0	6.79

TE = trinexapac-ethyl (Moddus 250 EC); OSS = organosilicone surfactant (Slippa), MA = mineral adjuvant ammonium sulfate; CA = citric acid

years, during the 14 days after the plant growth regulator application, an approximate average air temperature for 24 h was recorded (Fig. 1). However, despite the comparable average daily results, during the second year of study (2015), much lower minimum temperatures were recorded compared to the analogous 2014. Another important factor determining the effectiveness of plant growth regulators, apart from air temperature, is the volume and distribution of precipitation during the plant vegetation period. In 2015, central Poland suffered from drought. From April until the end of July, 221.9 mm of precipitation was recorded. Most of this precipitation occurred in July (121.5 mm), especially during the last 20 days (106.4 mm). For comparison, in 2014, the total precipitation volume was slightly lower (220.6 mm), however, it was equally distributed throughout the vegetation period of spring barley (Table 2). The above weather conditions significantly affected the effectiveness of the spray liquids during the two years of the study.

In both years of the field study, no lodging of spring barley plants was observed. The effectiveness of trinexapac-ethyl, expressed as the reduction of the stem length in the first year of study, ranged from 6.8 to 14.6% compared to the control treated only with water. During the second year of study, it fluctuated between 11.4 and 16.5% (Table 4). There is consistency between our results and those of others e.g. Tatnell (1995) and Supronienė *et al.* (2006) as well as Pricinotto (2015) who found that trinexapac-ethyl can reduce the stem length of crops.

Matysiak (2006) and Miziniak and Matysiak (2016) observed that the effectiveness of growth regulators is significantly affected by weather conditions. The main weather factor seems to be precipitation, especially during the months of intensive growth and development of the crop. Our own studies showed that a precipitation deficit accompanied by air temperatures oscillating between 5 and 10°C, did not decrease the retarding effectiveness of trinexapac ethyl applied at both the recommended and the reduced doses.

In this study, based on trinexapac-ethyl at reduced doses, the highest effectiveness was observed in the study variant where the plant growth regulator was applied in combination with ammonium sulphate (14.6% reduction of stem height in comparison with the control). A change of pH of the spray liquid (by adding citric acid) only insignificantly improved the effectiveness of trinexapac-ethyl applied at a reduced dose (Table 4). Adding the organosilicone surfactant neither affected the effectiveness of the growth regulator when applied individually, nor of the mixture based on trinexapac-ethyl and ammonium sulphate. In the second year of the study, no significant differences between the study variants were observed. However, despite the lack of

Table 4. The influence of the application of trinexapac-ethyl with additives on spring barley stem length

Treatment	Dose [l · ha^{-1}/kg · ha^{-1}]	2014		2015	
		stem length [cm]	reduction [%]	stem length [cm]	reduction [%]
Untreated	–	65.6 a	–	54.4 a	–
TE	0.4	57.2 cd	12.8	46.4 b	14.7
TE	0.2	61.1 bc	6.8	47.4 b	12.8
TE + CA	0.2 + 0.2	60.2 bcd	8.2	45.8 b	15.8
TE + MA	0.2 + 5.0	56.0 d	14.6	47.1 b	13.4
TE + OSS	0.2 + 0.1%	61.9 ab	5.6	47.5 b	12.7
TE + OSS + CA	0.2 + 0.1% + 0.2	60.4 bc	7.9	48.2 b	11.4
TE + OSS + MA	0.2 + 0.1% + 5.0	56.0 d	14.6	45.4 b	16.5

TE = trinexapac-ethyl (Moddus 250 EC); CA = citric acid; MA = mineral adjuvant (ammonium sulphate); OSS = organosilicone surfactant (Slippa) differences, there was a tendency for the effectiveness of the active substance to be improved when combined with citric acid and the mix of the plant growth regulator with ammonium sulphate and an organosilicone surfactant.

The study results confirmed the possibility of reducing the doses of trinexapac-ethyl by a combined application with citric acid that reduced the pH of spray liquid or with ammonium sulphate without affecting its effectiveness. Stachecki and Praczyk (2005) as well as Miziniak and Piszczek (2014) reached the same conclusions in their study on the reducibility of the CCC doses applied in combination with adjuvants in winter wheat cultivation.

Additionally, the experiment assessed the individual impact of the trinexapac-ethyl and the impact of its mixes with adjuvants on different elements of the spring barley crop structure (Table 5–6). Application of the plant growth regulator resulted in increased grain yields, including different elements of the crop structure: number of ears per 1 m^2, number of grains per ear and the weight of a thousand grains. With regard to the number of plants per 1 m^2 and the number of grains per ear, most researchers have seen a positive effect of these substances on the above elements of the crop structure. Discrepancies most often apply to the effect of growth regulators on the grains' weight (Giltrap and Garstang 1991; Woolley 1991; Rajala and Peltonen-Sainio 2002).

In general, the method of application of trinexapac-ethyl (individually or in a mix) did not have a significant impact on the number of plants per 1 m^2, the number of seeds per ear and the weight of a thousand grains (Table 6). Despite the lack of significant differences, in the first year of study there was a tendency for the weight of a thousand grains to slightly decrease

Table 5. The influence of the application of trinexapac-ethyl with additives on the number of plants per 1m^2 and the number of grains per ear of spring barley

Treatment	Dose [l · ha^{-1}/kg · ha^{-1}]	Number of ears per 1 m^2		Number of grains per ear	
		2014	2015	2014	2015
Untreated	–	854 a	781.3 b	18.0 a	15.8 a
TE	0.4	893 a	788.0 b	17.8 a	15.2 a
TE	0.2	930 a	798.0 b	18.4 a	16.0 a
TE + CA	0.2 + 0.2	879 a	776.7 b	18.9 a	16.2 a
TE + MA	0.2 + 5.0	852 a	815.3 ab	18.6 a	15.9 a
TE + OSS	0.2 + 0.1%	943 a	910.7 b	17.9 a	15.2 a
TE + OSS + CA	0.2 + 0.1% + 0.2	924 a	783.3 b	18.9 a	16.3 a
TE + OSS + MA	0.2 + 0.1% + 5.0	884 a	839.3 ab	18.0 a	16.4 a

TE = trinexapac-ethyl (Moddus 250 EC); CA = citric acid; MA = mineral adjuvant (ammonium sulphate); OSS = organosilicone surfactant (Slippa)

Table 6. The influence of the application of trinexapac-ethyl with additives on the weight of a thousand grains and the yield of spring barley

Treatment	Dose [l · ha^{-1}/kg · ha^{-1}]	Weight of a thousand grains [g]		Yield [t · ha^{-1}]	
		2014	2015	2014	2015
Untreated	–	46.03 a	47.75 a	7.04 a	5.88 ab
TE	0.4	44.62 a	47.07 a	7.09 a	5.63 b
TE	0.2	45.17 a	47.56 a	7.73 a	6.05 ab
TE + CA	0.2 + 0.2	45.14 a	47.98 a	7.51 a	6.03 ab
TE + MA	0.2 + 5.0	44.27 a	47.49 a	7.00 a	6.15 ab
TE + OSS	0.2 + 0.1%	45.66 a	47.14 a	7.70 a	6.51 a
TE + OSS + CA	0.2 + 0.1% + 0.2	44.77 a	48.13 a	7.81 a	6.12 ab
TE + OSS + MA	0.2 + 0.1% + 5.0	45.39 a	47.28 a	7.20 a	6.51 a

TE = trinexapac-ethyl (Moddus 250 EC); CA = citric acid; MA = mineral adjuvant (ammonium sulphate); OSS = organosilicone surfactant (Slippa)

Table 7. The influence of the application of trinexapac-ethyl with additives on the protein and starch content in spring barley grains

Treatment	Dose	Protein content [%]		Starch content [%]	
		2014	2015	2014	2015
Untreated	–	10.00 a	12.73 a	64.80 a	62.20 a
TE	0.4	10.83 a	13.35 a	64.88 a	62.00 a
TE	0.2	10.45 a	13.15 a	64.78 a	62.38 a
TE + CA	0.2 + 0.2	11.08 a	13.40 a	63.93 a	61.83 a
TE + MA	0.2 + 5.0	10.38 a	12.93 a	64.43 a	61.90 a
TE + OSS	0.2 + 0.1%	9.60 a	13.13 a	64.80 a	62.13 a
TE + OSS + CA	0.2 + 0.1% + 0.2	11.00 a	12.98 a	64.05 a	62.23 a
TE + OSS + MA	0.2 + 0.1% + 5.0	9.90 a	13.13 a	64.53 a	61.78 a

TE = trinexapac-ethyl (Moddus 250 EC); CA = citric acid; MA = mineral adjuvant (ammonium sulphate); OSS = organosilicone surfactant (Slippa)

in all of the study variants in which trinexapac-ethyl was applied. This trend was visible only in the first year of study. The method of application of the chemical did not affect the weight of a thousand grains in the second year of study (2015). This is similar to the results obtained by Matysiak (2006). However decreased thousand grain weight following trinexapac-ethyl application was observed by Grijalva-Contreras *et al.* (2012).

There are different opinions as to the influence of plant growth regulators on grain yield. According to Tatnell (1995) in the absence of lodging, the application of trinexapac-ethyl did not affect yield or grain of barley. Henderson *et al.* (1991) presented a different view on the matter, showing that the positive effect of trinexapac-ethyl on the yield could be observed only in the case of early lodging of plants. Our own studies showed that the plant growth regulator application method did not have any significant impact on the grain yield (2014). In the second year of study, with precipitation deficit, the application of a reduced dose of the plant growth regulator combined with an adjuvant or a mix of trinexapac-ethyl with adjuvants resulted in improved grain yield compared to the study variant in which the full dose of the plant growth regulator was applied. Other study variants did not show any significant impact of the plant growth regulator application method on the obtained grain weight. Rademacher (2000) and Rajala and Peltonen-Sanio (2001) obtained different correlations, showing a decrease in grain yield as a result of metabolic stress after the application of growth regulators in times of drought. However according to Rajala and Peltonen-Sainio (2012) the response of barley to plant growth regulators depends on the crop cultivar.

There was no influence of trinexapac-ethyl and its mixtures with adjuvants or cirtic acid on crude protein and starch content in the grain of spring barley (Table 7) but some authors reported that the use of trinexapac-ethyl can modify cereal grain quality (Rajala and Peltonen-Sainio 2000; Matysiak 2006; Grijalva-Contreras *et al.* 2012).

Conclusions

The present study confirms that the effectiveness of trinexapac ethyl applied separately or with adjuvants is strongly influenced by weather conditions. Trinexapac-ethyl applied at a reduced rate in a mixture with organosilicone surfactant alone or organosilicone surfactant plus ammonium sulphate increased grain yield of spring barley by almost 1 · ha^{-1} in comparison to trinexapac-ethyl applied at the recommended rate without an adjuvant. The two year study did not show any phytotoxic symptoms, neither in the case of trinexapac ethyl applied individually, nor in the case of tank mixes with an organosilicone surfactant, ammonium sulphate and citric acid on the spring barley plants.

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