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ORIGINAL ARTICLE

Effect of plant growth regulator used with adjuvants in winter wheat (*Triticum aestivum* L.)

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Abstract

Crop yields depend not only on genetic traits, agronomic practices, and weather but also on effective crop protection. European agriculture aims to reduce the use of harmful chemicals while maintaining yields. Studies show that adjuvants can reduce the required doses of plant protection products. While their role in herbicide and fungicide applications is well documented, research on plant growth regulators remains limited. Field trials were conducted at the Institute of Plant Protection – National Research Institute in Poland to evaluate the impact of reduced doses of growth regulators, along with adjuvants, on the growth and yield of winter wheat. The study aimed to evaluate the potential and effectiveness of combining the plant growth regulators mepiquat chloride and prohexadione calcium with various adjuvants and additives in winter wheat under field conditions. The experimental treatments included a mixture of mepiquat chloride with prohexadione calcium (Medax Top 350 SC) applied together with citric acid; fertilizers such as urea and ammonium sulfate; and adjuvants—including heptamethyltrisiloxane-modified polyalkylene oxide (Slippa), 76% paraffin oil (Atpolan 80 EC), 80% rapeseed oil fatty acid methyl esters, surface-active agents (surfactants), and a pH buffer (Atpolan BIO 80 EC), as well as ammonium sulfate ($(NH_4)_2SO_4$ – 40%), a cationic surfactant (20%), and triethanolamine (5%) (AS 500 SL). The studies showed that it is possible to achieve the same results using half the standard doses of regulators, combined with adjuvants, as when using full doses. This also applied to plant height as well as qualitative and quantitative grain parameters. Additionally, the findings demonstrated that the effect of mepiquat chloride combined with prohexadione calcium and adjuvants varied depending on weather conditions during crop growth.

Keywords: ammonium sulfate, citric acid, chemical reduction, mepiquat chloride, prohexadione calcium, surfactants, urea

Introduction

Plant growth regulators (PGRs) are a commonly used group of plant protection products; they are natural or synthetic chemical substances that influence plant anatomical and physiological features through the action of plant hormones, mainly auxins, cytokinins, gibberellins, and ethylene. In cereals, these compounds are used primarily to shorten plant height and prevent crop lodging. Although biological progress and breeding already provide cultivars with anti-lodging resistance, in agricultural practice, PGRs remain a significant group of substances widely used in agriculture (Berry and Spink 2012; Miziniak and Piszczek 2014; Dahiya *et al.* 2018; Berry *et al.* 2019). The main task of PGRs is to reduce the length of internodes and increase the thickness of the stem to limit plant lodging. Lodging is an unfavorable phenomenon leading to significant yield losses and difficult harvesting. It is defined as the permanent displacement of plant stems from the vertical position due to internal and external factors and is a common problem in wheat. The factors that account for lodging include a high seed rate, inappropriate irrigation methods, soil type, crop husbandry practices, and crop disease. However, lodging is mainly favored by wind, rain, and high nitrogen fertilization. In most cases, weather conditions cannot be predicted. Therefore, growth regulators are usually used preventively. However, scientific research confirms that in addition to strengthening the stems (increasing the diameter) and reducing the height, many PGRs also increase the intensity of photosynthesis and chlorophyll concentration and increase the weight of grains and the number of grains in an ear. Therefore, these substances protect the crop and have a yield-forming effect (Rajala and Peltonen-Sainio 2000; Tams *et al*. 2004; Matysiak 2006; Souza *et al.* 2010; Rademacher 2015; Zhang *et al.* 2016, 2017; Swoish and Steinke 2017). Furthermore, some of the PGRs (e.g., trinexapac-ethyl) are also perceived as important factors that can protect against abiotic stresses, including drought and high temperatures (McCann and Huang 2007; Bian *et al.* 2009).

Plant growth regulators which are mainly used in cereals include chlormequat chloride, mepiquat chloride, trinexapac-ethyl, prohexadione-calcium, and ethephon. The mode of action of the first four compounds is based on the modification of the gibberellin biosynthesis pathway—gibberellins being key phytohormones responsible primarily for cell elongation and stem growth. Mepiquat chloride (N,N-dimethylpiperidinium methyl chloride) is an inhibitor of gibberellin biosynthesis and acts by disrupting the mevalonic acid (MVA) pathway. It inhibits the activity of enzymes responsible for converting gibberellin precursors, primarily ent-kaurene, into ent-kauren-16-ol.

Prohexadione calcium is a plant growth regulator belonging to the group of inhibitors that target the late stages of gibberellin biosynthesis. It functions as an inhibitor of 2-oxoglutarate-dependent dioxygenases and blocks the conversion of gibberellin GA20 to GA1 (the bioactive form) by inhibiting the enzyme GA 3β-dioxygenase, which is crucial for this transformation (Rademacher 2015; Rademacher 2016). Ethephon, on the other hand, functions through the release of ethylene, the only gaseous plant hormone, into the intercellular spaces, which subsequently inhibits shoot elongation (Burg *et al.* 1971). Recent studies on plant growth regulators suggest that combinations of two growth-retarding substances may be more beneficial to crop performance than applying each compound separately. This is attributed to the synergistic effect that can be achieved. Consequently, these compounds can be utilized at reduced dosages, which translates into both economic advantages and diminished environmental impact (Matysiak 2006; Miziniak and Piszczek 2014).

Conventional agriculture aims to reduce the use of plant protection products and fertilizers, mainly due to growing social awareness and the decline in ecological biodiversity. Various forms of replacing chemical substances are sought in integrated agriculture, including specialized cultivation procedures, crop rotation, pest and disease forecasting, biological protection, etc. (Jacquet *et al.* 2011; Brack *et al.* 2018). One way to reduce the amount of active substances applied to crops while maintaining their effectiveness is the use of adjuvants, substances that optimize active ingredient efficacy. The addition of adjuvants to spray liquid containing plant protection products improves the effectiveness of their action, and it allows the dose of growth regulators to be reduced by 25 to 50% without loss of effectiveness (Stachecki *et al.* 2004; Miziniak and Piszczek 2014).

The conditions for the effective operation of many plant protection products are adequate retention and penetration of the agent into the plant. The leaves of many plants are covered with thick cuticular waxes, which constitute the primary protective barrier against the deposition, retention, spread, and penetration of spray liquid droplets. Compounds that effectively overcome such a barrier are adjuvants that increase the adhesion of spray drops to leaves, prevent them from being washed off the leaf surface, and thus improve the penetration and absorption of substances by plants. Depending on the plant protection product type, there is a wide range of adjuvants (Xu *et al.* 2010). The effectiveness of plant protection products and the absorption rate largely depend on environmental factors; rain causes the preparation to be washed out; temperature and wind, in turn, cause the liquid drops to dry quickly; air humidity causes the drops to dry out and also changes their action. Adjuvants in the form of tank mixtures are used around the world to improve the effectiveness of foliar pesticides, especially if they are to be used in reduced doses, which also carries economic benefits (Zabkiewicz 2000; Holloway *et al.* 2000; Idziak *et al.* 2013). Some adjuvants are already included in the preparations, and others are intended for mixing with plant protection products. Using an adjuvant can possibly have adverse effects, primarily by reducing the activity of the active ingredient, hence it is thought that they are not universal products but must be adapted to a specific substance and conditions of use. Choosing a suitable adjuvant can, therefore, be a difficult task. One of the adjuvant groups is surfactants, which enhance emulsifying properties, evenly distribute the liquid on the leaf, increase penetration deep into the leaf, prevent crystallization of the agent, and inhibit the drying of drops. They contain large amounts of fatty acids with hydrophilic-lipid properties. Surfactants are divided into non-ionic surfactants (non-ionic surfactants, organic or silicone), readily biodegradable, and ionic surfactants. Another group is oil adjuvants, which increase the penetration of oil-soluble substances; they are mainly used for thick leaf cuticles during drought and high temperature. These include mineral or vegetable oils and do not have hydrophilic activity. Adjuvants also include ammonium salts, which, in addition to reducing surface tension and neutralizing ionic charges, also prevent the formation of deposits in the mixing tank or on the leaf surface (Hazen 2000; Stock and Briggs 2000; Castro *et al.* 2014).

The literature contains extensive data on mixing agrochemicals, including the beneficial effects of adding adjuvants to pesticides. Adjuvants can increase the effectiveness of herbicides and fungicides, which can lead to significant dose reductions (Bellinder *et al.* 2003; Kucharski 2003; Kudsk and Mathiassen 2007; Kwiatkowski *et al.* 2012; Devkota *et al.* 2016; Bhuiyan *et al.* 2024). Limited scientific information is available on using plant growth regulators (PGRs) in combination with other agrochemicals, particularly herbicides. Some studies that have been conducted include Miziniak *et al.* (2018), Miziniak and Matysiak (2019), Peppers *et al.* (2021), Sobiech *et al.* (2020), Kieloch and Domaradzki (2022), and Tkalich *et al.* (2022). However, the scientific literature does provide evidence of research conducted using PGRs with adjuvants such as chlormequat chloride (Stachecki *et al.* 2004), trinexapac-ethyl (Miziniak and Matysiak 2016; Miziniak *et al.* 2017) and prohexadione calcium (Osterholz *et al.* 2018).

This study aimed to assess the possibilities and effectiveness of combining plant growth regulators mepiquat chloride and prohexadione calcium with different kinds of adjuvants and supplies in winter wheat under field conditions. The hypothesis assumed that a combination of plant growth regulators applied in lower doses but with adjuvants will have the same effect as those used at full doses.

Materials and Methods

Trial conditions

The field experiments on winter wheat were conducted in 2020 and 2021 at the experimental station in Toruń (53°030894'N 18°343859'E), the Institute of Plant Protection – National Research Institute in Poznan (Poland). The research was conducted on winter wheat cv. 'Ozon' (KWS Łochów Polska). This variety was selected due to its good frost resistance, fast regeneration after winter, as well as very good resistance to stem base diseases and high yields in both intensive and extensive cultivation. Winter wheat was sown on October 15, 2019 and October 22, 2020 at a sowing rate 200 kg · ha^{-1}, thus obtaining 400 seeds · m^{-2}. The experimental design included a sowing rate of more than 10% compared to the recommended standard. Agrotechnical recommendations suggest sowing wheat cultivar KWS Ozon at a density of 280 to 320 seeds · m^{-2} corresponding to 150–180 · ha^{-1}. In the first and second years of the study, the forecrop was spring barley. The experiment was conducted in black soil, with a pH of 5.6 – 6.6 and an organic matter content of 1.04 –1.31%, depending on the year of the study. Mineral fertilization was used: N 140 kg · ha^{-1}, P_2O_5 40 kg · ha^{-1} and K_2O 60 kg · ha^{-1}. Plant protection against weeds, diseases, and pests was used in the entire experiment according to the recommendations for wheat. In the experiment, sodium mesosulfuron-methyl, iodosulfuron-methyl, amidosulfuron, prothioconazole + trifloxystrobin, and tebuconazole were applied. The crop was harvested on August 5, 2020 and August 8, 2021.

Experimental set-up

The experiment was conducted in four replications using a completely randomized design. The area of each plot was 12.0 m^2, and the inter-row width was 11.0 cm. Experimental treatments included: mepiquat chloride + prohexadione calcium (Medax Top 350 SC), citric acid (applied as a buffering agent to reduce the pH of the spray solution); fertilizers: urea, and ammonium sulfate, and adjuvants – heptamethyltrisiloxane modified polyalkylene oxide (Slippa), 76% paraffin oil (Atpolan 80 EC), 80% rapeseed oil fatty acid methyl esters, surface-active substances (surfactants) and pH buffer up to 100% (Atpolan BIO 80 EC), ammonium sulfate $(NH_4)_2SO_4$ – 40%, cationic surfactant 20% triethanolamine 5% (AS 500 SL).

These preparations were applied at crop growth stage BBCH 32 according to the following scheme:

Control (untreated plots);

Mepiquat chloride + prohexadione calcium (MC + PC) (375 a.i · ha^{-1} + 62.5 a.i · ha^{-1});

MC + PC (187.5 a.i · ha^{-1} + 31.2 a.i · ha^{-1});

MC + PC + citric acid (187.5 a.i · ha^{-1} + 31.2 a.i · ha^{-1} + 200 a.i · ha^{-1});

MC + PC + ammonium sulfate (187.5 a.i · ha^{-1} + 31.2 a.i · ha^{-1}+ 1050 N · ha^{-1});

MC + PC + urea (187.5 a.i · ha^{-1} + 31.2 a.i · ha^{-1}+ 2300 N · ha^{-1});

MC + PC + heptamethyltrisiloxane modified polyalkylene oxide (187.5 a.i · ha^{-1} + 31.2 a.i · ha^{-1} + 180 a.i · ha^{-1});

MC + PC + paraffin oil (187.5 a.i · ha^{-1} + 31.2 a.i · ha^{-1} + 1140 a.i · ha^{-1});

MC + PC + fatty acid methyl ester (187.5 a.i · ha^{-1} + 31.2 a.i · ha^{-1} + 1200 a.i · ha^{-1});

MC + PC (187.5 a.i · ha^{-1} + 31.2 a.i · ha^{-1} + 600 g $(NH_4)_2$ SO_4 ha^{-1}; cationic surfactant 300 g · ha^{-1}; triethanolamine 7.5 g · ha^{-1}.

Characteristics of the preparations

Medax Top 350 SC – mepiquat chloride 300 g · l^{-1} + prohexadione calcium 50 g · l^{-1}. Medax Top is produced by BASF SE. Citric acid 99.5% ($C_6H_8O_7$) is white, with pH 1.85, solubility – H_2O 1630 g · l^{-1} molecular weight – 210.14. Citric acid is produced by Chemart. Ammonium sulfate 21% N – $(NH_4)_2SO_4$, is white, with pH 5–6, solubility – H_2O 767 g · l^{-3} (25°C). Ammonium sulfate is produced by Grupa Azoty Tarnów (Tarnów, Poland). Urea 46% N – CH_4N_2O, is white, with solubility – H_2O 545 mg · l^{-3} (25°C). Urea is produced by Zakłady Azotowe Kędzierzyn (Kędzierzyn, Poland). Slippa – 90% heptamethyltrisiloxane is modified polyalkylene oxide. Slippa is produced by Interagro (UK) Ltd. Atpolan 80 EC – 76% paraffin oil. Atpolan 80 EC is produced by AGROMIX (Niepołomice, Poland). Atpolan BIO 80 EC is 80% rapeseed oil fatty acid methyl esters, surface-active substances (surfactants), and pH buffer up to 100%. Atpolan BIO 80 EC is produced by AGROMIX Niepołomice (Niepołomice, Poland). AS 500 SL ammonium sulfate $(NH_4)_2$ SO_4 40%, cationic surfactant 20% triethanolamine 5%. AS 500 SL is produced by AGROMIX Niepołomice (Niepołomice, Poland).

Spraying parameters

Treatments were conducted using a bicycle-mounted Victoria sprayer equipped with TeeJet 110 02 VP sprayers using 200 l of spray liquid per ha, with an operating pressure of 0.3 MPa. The treatment was applied at a velocity of 4.3 km · h^{-1}. The 3-meter-wide spray boom was equipped with six nozzles spaced 50 cm apart, with a suspension height of 50 cm above the crop canopy. The temperature during the applications varied between 16.6 and 18°C, and the air humidity was 54.5% and 46.1%, depending on the year of the study.

Observations

During the vegetation period, after reaching full grain maturity (BBCH 89), the number of ears · m^{-2} (D) and plant height (He) were assessed. The height was measured in a sample of 25 plants from each experimental plot before harvest. Harvesting was performed with a Wintersteiger plot combine. Next, the following parameters were determined: mass of a thousand grain(TGW), number of grains per ear (NG), and qualitative characteristics of the yield: protein (P), gluten (G), and starch content (S), sedimentation index (Z), and grain hardness (Ha). The number of grains per ear was calculated using a sample of 25 ears collected from each plot. The TGW from each plot was determined based on a random 1 kg sample, from which three subsamples of 200 seeds were taken. Qualitative analysis (P, G, S, Z and Ha) was conducted with an Infratec™ 1241 grain analyzer. Infratec™ 1241, produced by Foss (Denmark), is a whole grain analyzer that uses near-infrared transmission (NIT) technology to simultaneously determine multiple quality parameters. Samples from each plot were analyzed directly (without the need for grinding). Results from four replicates of each combination were averaged.

Weather conditions

Weather data were obtained from the Meteorological Station in Falęcin (53°13'54"N, 18°32'51"E). Weather conditions are presented in Table 1.

Weather conditions differed during the years of the study. In the winter of 2020/2021, after stable, moderate weather conducive to the continuation of winter wheat growth and development during this period, there was a sudden chill in January. As an immediate result of the frost, the winter wheat lost its foliage completely. In the ensuing situation, after a lengthy recovery period, the plants produced fewer tillers than in 2020.

Statistical analysis

The normal distributions of the observed traits (He, D, Y, TGW, NG, P, S, G, Z, and Ha) were established using the Shapiro-Wilk's normality test (Shapiro and Wilk 1965). A two-way (year and combination) analyses of variance (ANOVA) were carried out to determine the main effects of year and combination and year-by-combination interaction on the variability of observed traits. Mean values and standard deviations of individual characteristics were calculated. Tukey's honest significant difference (HSD) post hoc tests were used to determine differences for all traits at a significance level of $p < 0.05$ (starch content) and $p < 0.001$ (remaining traits). Tukey's HSD test is a single-step multiple comparison procedure and statistical test that can be used on raw data or in conjunction with an ANOVA (*post-hoc* analysis) to identify significantly different means. All the analyses were conducted using the GenStat 23.1 edition statistical software package (VSN International 2023).

Results

Crop height

Based on the variance analysis, the year (weather conditions) significantly affected the analyzed traits (Tab. 2, 3, Fig. 1). Regardless of the year of the study,

Table 1. Weather conditions in the years of experiment

Month	2019/2020		2020/2021	
	average temperature [°C]	rainfall [mm]	average temperature [°C]	rainfall [mm]
October	9.9	12.4	7.7	31.6
November	4.9	24.3	5.8	31.7
December	1.2	60.8	4.7	24.9
January	2.0	32.5	–2.7	24.0
February	1.6	15.0	3.8	26.2
March	6.3	34.5	5.1	16.3
April	8.9	18.1	10.3	32.1
May	12.7	35.0	16.1	57.0
June	15.7	47.3	18.0	73.7
July	18.9	121.5	18.6	128.5
August	21.7	7.5	17.7	52.8
Sum	–	408.9	–	498.8

Table 2. Mean squares from two-way analysis for observed traits

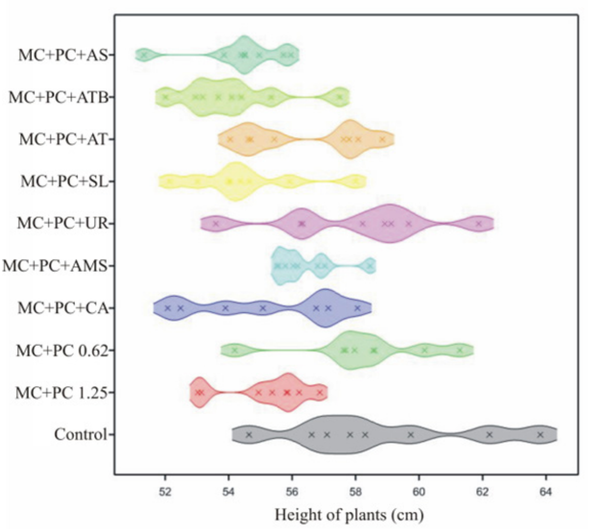
Source of variation	Year	Combination	Year × Combination	Residual
d.f.	1	9	9	60
Height of plants – He	45.032***	23.38***	4.445	3.219
Number of heads – D	416017***	1298	1505	1181
Grain yield – Y	97.6928***	0.3284	0.2014	0.1986
Thousand-grain weight – TGW	638.202***	2.692	3.348*	1.375
Number of grains per ear – NG	114.108***	1.297	2.28	1.635
Protein content – P	54.1205***	0.1747	0.1205	0.2181
Starch content – S	2.178*	0.2919	0.3586	0.3682
Gluten – G	253.947***	1.403	1.102	1.684
Zeleny sedimentation index – Z	2833.39***	10.65	5.44	12.78
Grain hardness – Ha	3738.75***	3.74	13.31	13.54

* $p < 0.05$; *** $p < 0.001$

Table 3. Influence of a mixture of plant growth regulators with adjuvants on winter wheat height and number of heads per square meter

Treatments	Dose [g · ha^{-1}]	Height of plants [cm] – He		Number of heads · m^{-2} – D	
		experimental years			
		2020	2021	2020	2021
Control	–	59.74 a ± 2.93**	57.83 ab ± 3.21	606.0 a ± 11.31	444.5 c ± 50.45
MC + PC*	375 + 62.5	54.94 cd ± 1.27	55.37 bcd ± 1.68	602.5a ±3 4.42	479.2 abc ± 38.31
MC + PC	187 + 31.2	57.97 ab ± 0.45	58.55 a ± 3.12	615.2 a ± 46.66	514.5 a ± 43.34
MC + PC + citric acid	187 + 31.2 + 200	56.76 bc ± 1.25	53.90 cd ± 2.3	620.0 a ± 21.6	458.0 bc ± 27.47
MC + PC + ammonium sulphate	187 + 31.2 + 1050	56.81 bc ± 1.18	56.04 abc ± 0.7	605.2 a ± 41.52	453.2 bc ± 18.36
MC + PC + urea	187 + 31.2 + 2300	59.67 a ± 1.59	56.33 abc ± 2.26	617.2 a ± 32.43	500.5 ab ± 44.46
MC + PC + polyalkylene oxide	187 + 31.2 + 180	54.66 d ± 0.89	54.38 cd ± 2.59	636.5 a ± 13.2	438.5 c ± 25.37
MC + PC + paraffin oil	187 + 31.2 + 1140	58.09 ab ± 0.54	54.70 cd ± 0.57	611.2 a ± 39.2	464.0 abc ± 22.09
MC + PC + fatty acid methyl ester	187 + 31.2 + 1200	55.33 cd ± 1.54	52.96 d ± 0.7	614.0 a ± 28.33	467.2 abc ± 28.16
MC + PC + ammonium salts of polybasic and hydroxy carboxylic acids	187 + 31.2 + 300	54.96 cd ± 0.71	53.85 cd ± 1.85	595.2 a ± 21.75	461.2 abc ± 54.9

*mepiquat chloride + prohexadione calcium; **mean values ± standard deviation. Means with different letters in the column are significantly different according to Tukey's test at $p < 0.05$



MC + PC 1.25 – mepiquat chloride + proheksadione calcium (full dose); MC + PC 0.62 – mepiquat chloride + proheksadione calcium (half dose); MC + PC + CA – mepiquat chloride + proheksadione calcium (half dose) + citric acid; MC + PC + AMS – mepiquat chloride + proheksadione calcium (half dose) + ammonium sulphate; MC + PC + UR – mepiquat chloride + proheksadione calcium (half dose) + urea; MC + PC + SL – mepiquat chloride + proheksadione calcium (half dose) + polyalkylene oxide; MC + PC + AT – mepiquat chloride + proheksadione calcium (half dose) + paraffin oil; MC + PC +ATB – mepiquat chloride + proheksadione calcium (half dose) + fatty acid methyl ester; MC + PC + AS – mepiquat chloride + proheksadione calcium (half dose) + ammonium salts of polybasic and hydroxy carboxylic acids

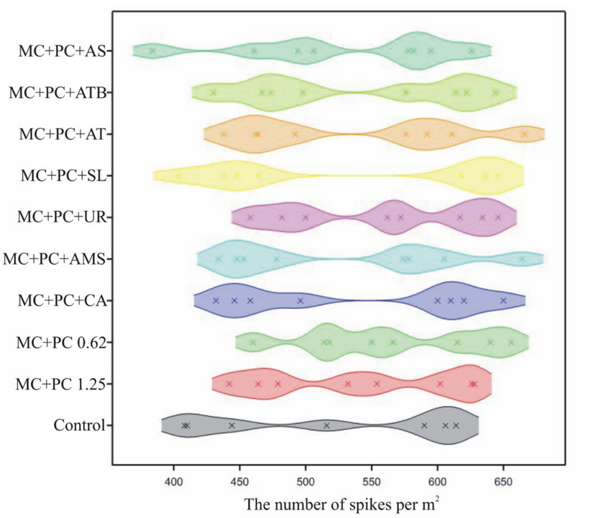
Fig. 1. Density charts showing the distribution of the height of plants

a factor affecting the height of the wheat canopy was the method of applying mepiquat chloride. Among the analyzed variants of the study, a significant reduction of the wheat canopy compared to the control was obtained using both the full dose and mixtures of reduced doses of mepiquat chloride by 50% with citric acid, organosilicone adjuvant, fatty acid methyl ester or with ammonium salt of polybasic and hydroxycarboxylic acids. Adding urea to the spray liquid containing a growth retardant did not affect the canopy height. In the mixtures of mepiquat chloride with ammonium sulfate or mineral oil, ambiguous results were obtained. In 2020, mixtures with ammonium sulfate reduced plant height compared to the control, while in the second year, they showed a negligible effect. Inverse relationships were obtained when evaluating the impact of the combined application of mepiquat chloride with mineral oil.

It should be noted that the addition of retardant, organosilicone adjuvant, fatty acid methyl ester, as well as ammonium salt of polybasic and hydroxycarboxylic acids to the spray liquid in 2020 reduced the growth of wheat in the same range as the full dose of the agent. In the second year, however, they showed better efficiency in the range of 1.8% (organosilicone adjuvant), 2.7% (hydroxycarboxylic acids), and 4.3% (fatty acid methyl ester) about above the recommended retardant dose. Statistical analyses showed no significant differences between the analyzed study variants (Tab. 3).

Number of heads per m²

Applying mepiquat chloride alone or with adjuvants in most of the analyzed combinations did not significantly affect individual elements of the yield structure (Tables 2, 3, Fig. 2). In 2020, the number of heads ranged from 595.2 to 636.5, while in 2021, it was much lower and oscillated between 438.5 and 500.5 heads $\cdot$ m^{-2}. In the first year of the research, regardless of the retardant application method, the density of winter wheat heads in individual experimental variants was equal. Different reports were recorded in 2021. In the objects where a lower dose or a mixture with urea was applied, a significantly greater number of ear-bearing stems was recorded than in the control. The above relationships were only visible in the second year of the study.



MC + PC 1.25 – mepiquat chloride + proheksadione calcium (full dose); MC + PC 0.62 – mepiquat chloride + proheksadione calcium (half dose); MC + PC + CA – mepiquat chloride + proheksadione calcium (half dose) + citric acid; MC + PC + AMS – mepiquat chloride + proheksadione calcium (half dose) + ammonium sulphate; MC + PC + UR – mepiquat chloride + proheksadione calcium (half dose) + urea; MC + PC + SL – mepiquat chloride + proheksadione calcium (half dose) + polyalkylene oxide; MC + PC + AT – mepiquat chloride + proheksadione calcium (half dose) + paraffin oil; MC + PC +ATB – mepiquat chloride + proheksadione calcium (half dose) + fatty acid methyl ester; MC + PC + AS – mepiquat chloride + proheksadione calcium (half dose) + ammonium salts of polybasic and hydroxy carboxylic acids

Fig. 2. Density charts showing the distribution of the number of heads

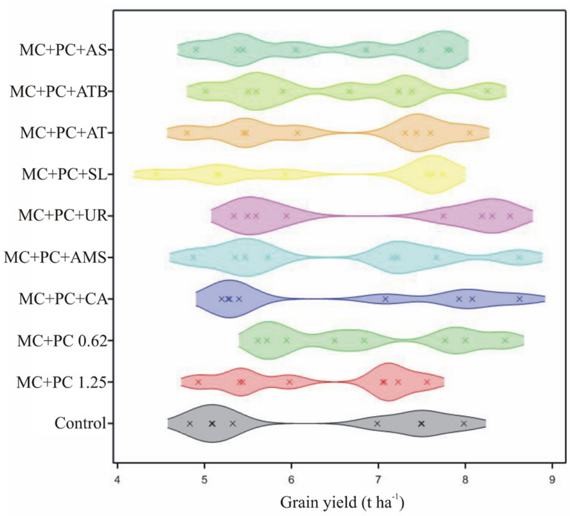
Weight of 1000 grains

The thousand-grain weight (TGW) was mainly factor-affected by the year of research (Tab. 2, 4, Fig. 3). There was also a significant effect of the interaction of year

Table 4. Influence of a mixture of plant growth regulators with adjuvants on the characteristics of winter wheat grain

Treatments	Dose [g · ha⁻¹]	Thousand-grain weight [g] – TGW		Number of grains per ear – NG	
		experimental years			
		2020	2021	2020	2021
Control	–	41.55 ab ± 0.81**	36.23 ab ± 2.22	29.66 bc ± 0.57	31.80 a ± 0.64
MC + PC*	375 + 62.5	40.15 bc ± 1.61	34.66 bc ± 0.32	29.93 bc ± 0.46	32.81 a ± 2.23
MC + PC	187 + 31.2	41.87 ab ± 0.61	34.63 c ± 1.07	30.12 b ± 0.67	33.43 a ± 0.97
MC + PC + citric acid	187 + 31.2 + 200	42.16 a ± 1.69	35.60 abc ± 0.33	30.29 ab ± 0.93	32.52 a ± 1.27
MC + PC + ammonium sulphate	187 + 31.2 + 1050	42.51 a ± 0.72	35.47 abc ± 0.94	29.76 bc ± 0.47	33.27 a ± 0.52
MC + PC + urea	187 + 31.2 + 2300	42.44 a ± 1.85	35.92 abc ± 0.88	31.33 a ± 1.09	31.27 a ± 2.2
MC + PC + polyalkylene oxide	187 + 31.2 + 180	41.45 ab ± 1	36.25 a ± 0.54	28.90 c ± 0.18	32.41 a ± 1.68
MC + PC + paraffin oil	187 + 31.2 + 1140	41.72 ab ± 0.73	36.68 a ± 1.88	29.85 bc ± 0.89	32.01 a ± 1.91
MC + PC + fatty acid methyl ester	187 + 31.2 + 1200	39.35 c ± 1.37	36.57 a ± 0.17	30.54 ab ± 1.35	32.19 a ± 0.29
MC + PC + ammonium salts of polybasic and hydroxy carboxylic acids	187 + 31.2 + 300	41.18 ab ± 1.28	35.89 abc ± 0.46	30.55 ab ± 0.8	33.12 a ± 2.57

*mepiquat chloride + prohexadione calcium; **mean values ± standard deviation. Means with different letters in the column are significantly different according to Tukey's test at $p < 0.05$



MC + PC 1.25 – mepiquat chloride + proheksadione calcium (full dose); MC + PC 0.62 – mepiquat chloride + proheksadione calcium (half dose); MC + PC + CA – mepiquat chloride + proheksadione calcium (half dose) + citric acid; MC + PC + AMS – mepiquat chloride + proheksadione calcium (half dose) + ammonium sulphate; MC + PC + UR – mepiquat chloride + proheksadione calcium (half dose) + urea; MC + PC + SL – mepiquat chloride + proheksadione calcium (half dose) + polyalkylene oxide; MC + PC + AT – mepiquat chloride + proheksadione calcium (half dose) + paraffin oil; MC + PC +ATB – mepiquat chloride + proheksadione calcium (half dose) + fatty acid methyl ester; MC + PC + AS – mepiquat chloride + proheksadione calcium (half dose) + ammonium salts of polybasic and hydroxy carboxylic acids

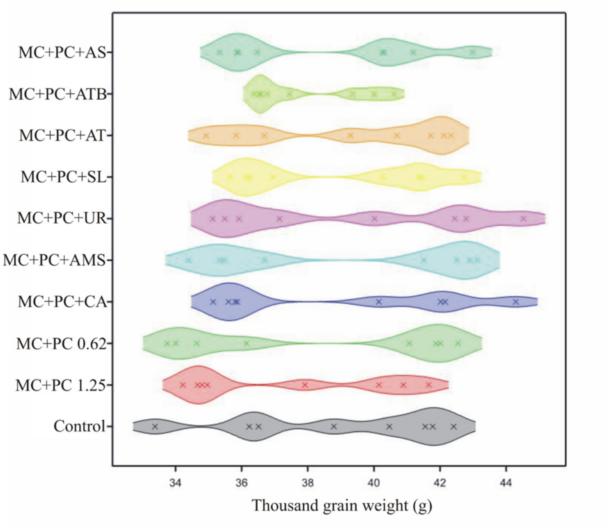
Fig. 3. Density charts showing the distribution of the grain yield

and experimental combination on this feature (3.348; $p < 0.05$). In 2020, winter wheat grain collected from individual experimental plots was more substantial and heavier than grain samples collected in the next growing season. In the first year of the study, the thousand-grain weight ranged from 39.35 to 42.51 g (2020), while in the second year, it was lower and oscillated between 34.63 and 36.68 g. According to the research, the method of application of mepiquat chloride (retarder alone or a mixture with adjuvants) in most of the analyzed variants did not significantly impact the discussed feature. Nevertheless, depending on the year of field observations, a decrease in TGW was observed in plots where mepiquat chloride was combined with an adjuvant based on fatty acid methyl ester – Atpolan BIO 80 EC (2020) or half of the retardant dose (2021) compared to control plots. Similar relationships were found in both years of research after treatment with a full dose of mepiquat chloride. The conducted statistical analyses showed no correlation between the discussed averages.

Number of grains per ear, yield and grain hardness

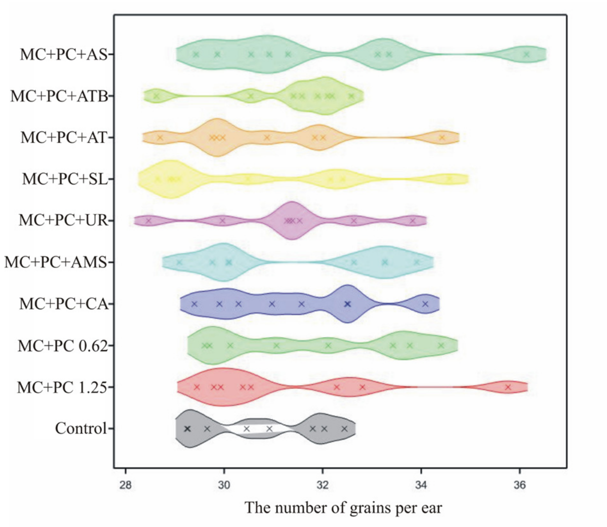
In both years of research, the method of applying the plant growth regulators did not significantly affect the average number of grains per ear (Tab. 2, 4, Fig. 4). However, there was a noticeable tendency in both years for a higher number of grains after the application of mepiquat chloride and its mixtures, than in the control.

The yield of winter wheat depended on the weather conditions in particular years of the study (Tab. 1). In January 2021, winter wheat lost all its foliage after a sharp cooling. Consequently, that year, the plants produced a smaller number of tillers, which directly translated into the yield of cereals (Tab. 4). In the first



MC + PC 1.25 – mepiquat chloride + proheksadione calcium (full dose); MC + PC 0.62 – mepiquat chloride + proheksadione calcium (half dose); MC + PC + CA – mepiquat chloride + proheksadione calcium (half dose) + citric acid; MC + PC + AMS – mepiquat chloride + proheksadione calcium (half dose) + ammonium sulphate; MC + PC + UR – mepiquat chloride + proheksadione calcium (half dose) + urea; MC + PC + SL – mepiquat chloride + proheksadione calcium (half dose) + polyalkylene oxide; MC + PC + AT – mepiquat chloride + proheksadione calcium (half dose) + paraffin oil; MC + PC +ATB – mepiquat chloride + proheksadione calcium (half dose) + fatty acid methyl ester; MC + PC + AS – mepiquat chloride + proheksadione calcium (half dose) + ammonium salts of polybasic and hydroxy carboxylic acids

Fig. 4. Density charts showing the distribution of the thousand-grain weight



MC + PC 1.25 – mepiquat chloride + proheksadione calcium (full dose); MC + PC 0.62 – mepiquat chloride + proheksadione calcium (half dose); MC + PC + CA – mepiquat chloride + proheksadione calcium (half dose) + citric acid; MC + PC + AMS – mepiquat chloride + proheksadione calcium (half dose) + ammonium sulphate; MC + PC + UR – mepiquat chloride + proheksadione calcium (half dose) + urea; MC + PC + SL – mepiquat chloride + proheksadione calcium (half dose) + polyalkylene oxide; MC + PC + AT – mepiquat chloride + proheksadione calcium (half dose) + paraffin oil; MC + PC +ATB – mepiquat chloride + proheksadione calcium (half dose) + fatty acid methyl ester; MC + PC + AS – mepiquat chloride + proheksadione calcium (half dose) + ammonium salts of polybasic and hydroxy carboxylic acids

Fig. 5. Density charts showing the distribution of the number of grains per ear

year of the study, the yields harvested from individual variants oscillated between 7.38 and 8.19 t · ha^{-1}, while in 2021, they were much lower and ranged from 5.08 to 5.94 t · ha^{-1}. Irrespective of the year of field observations, the method of application of mepiquat chloride (preparation alone or a mixture with adjuvants) had no significant effect on the collected grain weight from the individual test variants.

It was found that in the first year of the study, the grain yield from the treatment where the MC + PC mixture was applied at the full dose, as well as from the treatment where the mixture was applied at a reduced dose combined with fatty acid methyl ester, was significantly lower than the yield from the control and other experimental treatments (see Tab. 2, 5, Fig. 5). In the same year, plants treated with the MC + PC mixture in combination with urea showed an increase in yield of over 9% compared to the control, and more than 13% compared to the treatment where only the MC + PC mixture was applied.

In the second year of the study, a significantly higher yield than the control was observed in the treatment where MC + PC was applied at a reduced dose without adjuvants, with an increase of 17%. The plants from the other experimental treatments displayed similar yields with statistically insignificant differences; however, a trend toward increased yield was noted when the mixture of growth regulators was applied with adjuvants. No significant differences in grain hardness were found between the treatments examined (Fig. 6)..

Grain quality parameters

The analysis of variance showed a significant effect of the year of research (weather conditions) on the quality parameters of wheat grain (Tab. 2, 5, 6, 7, Fig. 7, 8, 9, 10). Grain harvested from the experimental plots in 2020 was characterized by a lower protein, gluten, and Zelen index content than in 2021. Inverse relationships were recorded in the case of grain hardness. Despite the differences in content in both years of research, the method of application of mepiquat chloride had no significant effect on the characteristics mentioned above. Among the analyzed grain quality parameters, only the starch content was modified to the most minor extent by weather conditions. Depending on the year of research, the starch content ranged from 67.52 to 68.05 (2020) and from 67.1 to 68.22 (2021).

Table 5. Influence of a mixture of application of growth regulators with adjuvants on yield parameters

Treatments	Dose [g · ha⁻¹]	Grain yield – Y [t · ha⁻¹]		Grain hardness – Ha	
		experimental years			
		2020	2021	2020	2021
Control	–	7.491 ab ± 0.41**	5.084 b ± 0.2	79.00 a ± 4.82	65.28 a ± 4.03
MC + PC*	375 + 62.5	7.227 b ± 0.24	5.439 ab ± 0.43	79.38 a ± 1.01	64.40 a ± 7.49
MC + PC	187 + 31.2	7.767 ab ± 0.68	5.944 a ± 0.39	78.18 a ± 1.86	67.75 a ± 5.1
MC + PC + citric acid	187 + 31.2 + 200	7.928 ab ± 0.64	5.289 b ± 0.08	80.10 a ± 2.68	67.10 a ± 5.19
MC + PC + ammonium sulphate	187 + 31.2 + 1050	7.668 ab ± 0.67	5.355 b ± 0.36	79.17 a ± 2.39	66.22 a ± 1.33
MC + PC + urea	187 + 31.2 + 2300	8.191 a ± 0.33	5.593 ab ± 0.26	81.22 a ± 1.17	62.48 a ± 4.28
MC + PC + polyalkylene oxide	187 + 31.2 + 180	7.624 ab ± 0.08	5.172 b ± 0.6	78.15 a ± 1.01	66.80 a ± 3.96
MC + PC + paraffin oil	187 + 31.2 + 1140	7.599 ab ± 0.32	5.450 ab ± 0.52	79.10 a ± 3.63	68.03 a ± 5.82
MC + PC + fatty acid methyl ester	187 + 31.2 + 1200	7.388 b ± 0.66	5.503 ab ± 0.37	79.95 a ± 1.03	66.10 a ± 2.51
MC + PC + ammonium salts of polybasic and hydroxy carboxylic acids	187 + 31.2 + 300	7.493 ab ± 0.45	5.445 ab ± 0.47	80.10 a ± 2.58	63.48 a ± 2.43

*mepiquat chloride + prohexadione calcium; **mean values ± standard deviation. Means with different letters in the column are significantly different according to Tukey's test at $p < 0.05$

Table 6. Influence of a mixture of plant growth regulators with adjuvants on some winter wheat grain quality characteristics

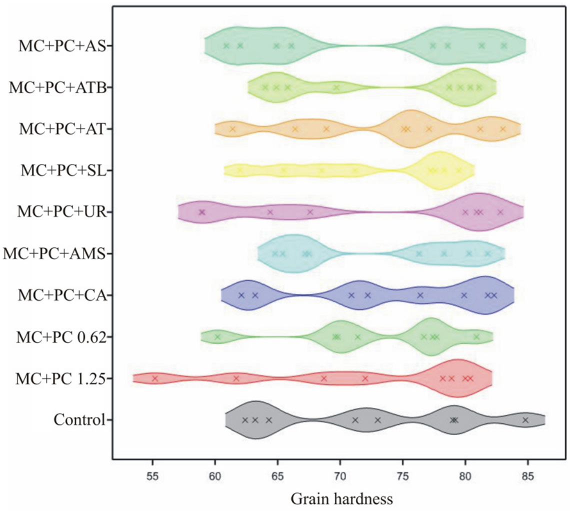
Treatments	Dose [g · ha⁻¹]	Protein content [%] – P		Starch content [%] – S	
		experimental years			
		2020	2021	2020	2021
Control	–	13.25 a ± 0.5**	14.88 a ± 0.61	67.90 a ± 0.43	67.50 ab ± 1.1
MC + PC*	375 + 62.5	13.55 a ± 0.19	15.02 a ± 0.61	67.52 a ± 0.25	67.33 ab ± 0.74
MC + PC	187 + 31.2	12.97 a ± 0.24	14.85 a ± 0.52	68.00 a ± 0.45	67.10 b ± 0.57
MC + PC + citric acid	187 + 31.2 + 200	12.9 a ± 0.24	14.67 a ± 0.34	68.01 a ± 0.29	67.72 ab ± 0.35
MC + PC + ammonium sulphate	187 + 31.2 + 1050	12.88 a ± 0.46	14.75 a ± 0.21	68.15 a ± 0.47	67.40 ab ± 0.14
MC + PC + urea	187 + 31.2 + 2300	13.07 a ± 0.45	14.77 a ± 0.22	67.83 a ± 0.78	67.27 b ± 0.51
MC + PC + polyalkylene oxide	187 + 31.2 + 180	13.18 a ± 0.26	14.80 a ± 0.37	67.78 a ± 0.35	67.60 ab ± 0.37
MC + PC + paraffin oil	187 + 31.2 + 1140	13.17 a ± 0.13	14.55 a ± 0.51	68.00 a ± 0.29	68.22 a ± 0.83
MC + PC + fatty acid methyl ester	187 + 31.2 + 1200	13.35 a ± 0.71	14.53 a ± 0.33	67.58 a ± 0.88	68.02 ab ± 0.42
MC + PC + ammonium salts of polybasic and hydroxy carboxylic acids	187 + 31.2 + 300	13.1a ± 1.1	15.05 a ± 0.13	68.05 a ± 0.98	67.35 ab ± 0.75

*mepiquat chloride + prohexadione calcium; **mean values ± standard deviation. Means with different letters in the column are significantly different according to Tukey's test at $p < 0.05$

Table 7. Influence of a mixture of plant growth regulators with adjuvants on some winter wheat grain quality characteristics

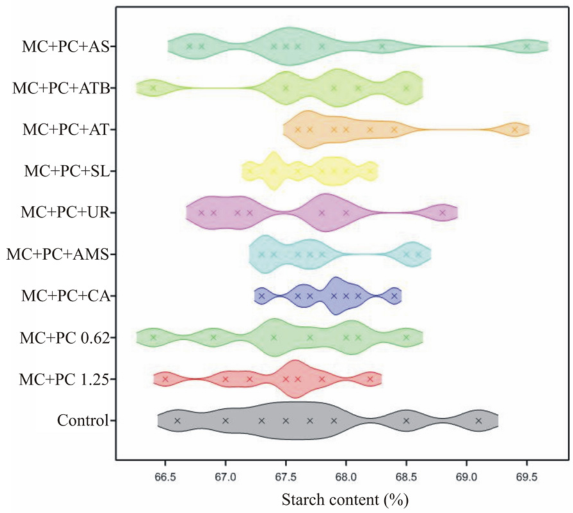
Treatments	Dose [g · ha⁻¹]	Gluten [%] – G		Zeleny sedimentation index – Z	
		experimental years			
		2020	2021	2020	2021
Control	–	32.97 a ± 1.12**	36.55 a ± 2.07	44.90 a ± 3.45	55.83 ab ± 3.69
MC + PC*	375 + 62.5	33.65 a ± 0.34	36.90 a ± 1.5	46.67 a ± 1.95	57.65 a ± 3.8
MC + PC	187 + 31.2	32.15 a ± 0.69	36.45 a ± 1.6	41.67 a ± 2.42	55.72 ab ± 3.37
MC + PC + citric acid	187 + 31.2 + 200	32.01 a ± 0.5	35.80 a ± 1.12	41.85 a ± 2.31	54.40 ab ± 2.33
MC + PC + ammonium sulphate	187 + 31.2 + 1050	31.87 a ± 1.12	36.15 a ± 0.58	42.20 a ± 4.32	55.77 ab ± 1.57
MC + PC + urea	187 + 31.2 + 2300	32.50 a ± 1.22	36.12 a ± 0.85	43.27 a ± 3.73	54.70 ab ± 0.95
MC + PC + polyalkylene oxide	187 + 31.2 + 180	32.83 a ± 0.8	36.35 a ± 1.08	43.60 a ± 2.24	56.55 ab ± 2.75
MC + PC + paraffin oil	187 + 31.2 + 1140	32.77 a ± 0.34	35.17 a ± 1.25	43.55 a ± 1.54	54.45 ab ± 2.84
MC + PC + fatty acid methyl ester	187 + 31.2 + 1200	33.10 a ± 1.7	35.45 a ± 0.93	45.08 a ± 6.3	53.65 b ± 1.98
MC + PC + ammonium salts of polybasic and hydroxy carboxylic acids	187 + 31.2 + 300	32.32 a ± 3.15	36.85 a ± 0.51	43.73 a ± 8.98	56.83 ab ± 0.87

*mepiquat chloride + prohexadione calcium; **mean values ± standard deviation. Means with different letters in the column are significantly different according to Tukey's test at $p < 0.05$



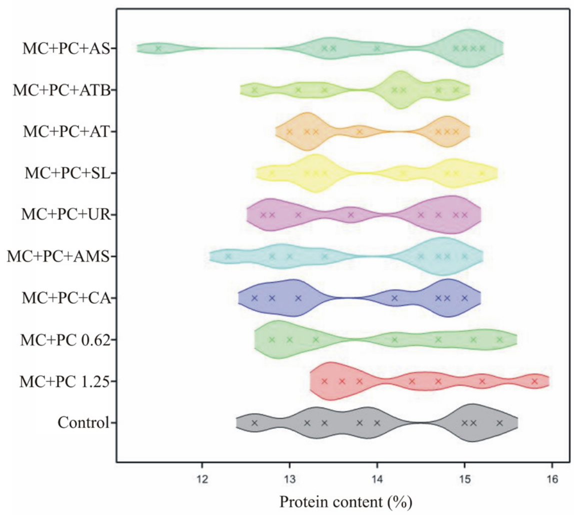
MC + PC 1.25 – mepiquat chloride + proheksadione calcium (full dose); MC + PC 0.62 – mepiquat chloride + proheksadione calcium (half dose); MC + PC + CA – mepiquat chloride + proheksadione calcium (half dose) + citric acid; MC + PC + AMS – mepiquat chloride + proheksadione calcium (half dose) + ammonium sulphate; MC + PC + UR – mepiquat chloride + proheksadione calcium (half dose) + urea; MC + PC + SL – mepiquat chloride + proheksadione calcium (half dose) + polyalkylene oxide; MC + PC + AT – mepiquat chloride + proheksadione calcium (half dose) + paraffin oil; MC + PC +ATB – mepiquat chloride + proheksadione calcium (half dose) + fatty acid methyl ester; MC + PC + AS – mepiquat chloride + proheksadione calcium (half dose) + ammonium salts of polybasic and hydroxy carboxylic acids

Fig. 6. Density charts showing the distribution of the grain hardness



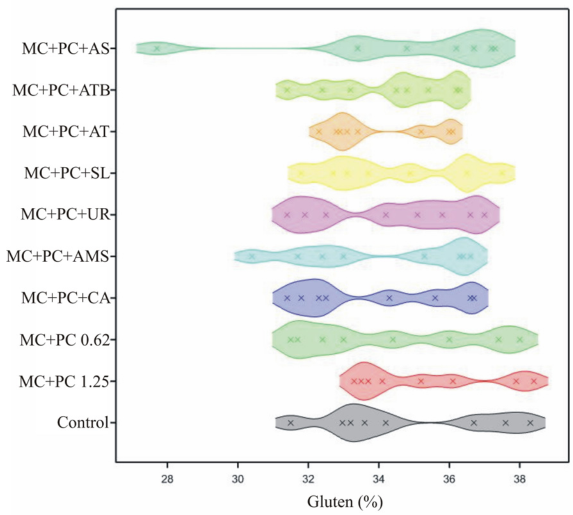
MC + PC 1.25 – mepiquat chloride + proheksadione calcium (full dose); MC + PC 0.62 – mepiquat chloride + proheksadione calcium (half dose); MC + PC + CA – mepiquat chloride + proheksadione calcium (half dose) + citric acid; MC + PC + AMS – mepiquat chloride + proheksadione calcium (half dose) + ammonium sulphate; MC + PC + UR – mepiquat chloride + proheksadione calcium (half dose) + urea; MC + PC + SL – mepiquat chloride + proheksadione calcium (half dose) + polyalkylene oxide; MC + PC + AT – mepiquat chloride + proheksadione calcium (half dose) + paraffin oil; MC + PC +ATB – mepiquat chloride + proheksadione calcium (half dose) + fatty acid methyl ester; MC + PC + AS – mepiquat chloride + proheksadione calcium (half dose) + ammonium salts of polybasic and hydroxy carboxylic acids

Fig. 8. Density charts showing the distribution of the starch content



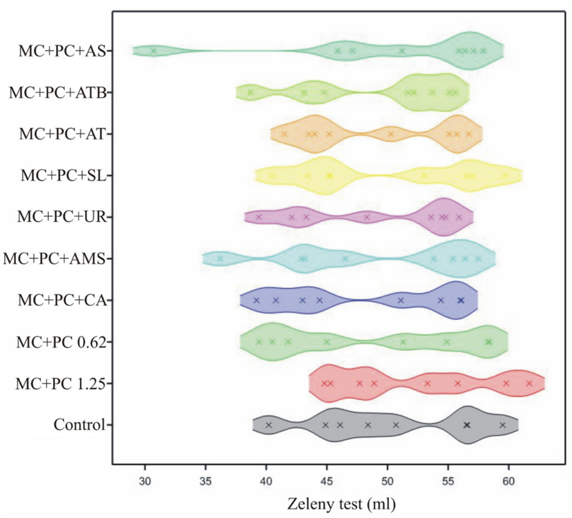
MC + PC 1.25 – mepiquat chloride + proheksadione calcium (full dose); MC + PC 0.62 – mepiquat chloride + proheksadione calcium (half dose); MC + PC + CA – mepiquat chloride + proheksadione calcium (half dose) + citric acid; MC + PC + AMS – mepiquat chloride + proheksadione calcium (half dose) + ammonium sulphate; MC + PC + UR – mepiquat chloride + proheksadione calcium (half dose) + urea; MC + PC + SL – mepiquat chloride + proheksadione calcium (half dose) + polyalkylene oxide; MC + PC + AT – mepiquat chloride + proheksadione calcium (half dose) + paraffin oil; MC + PC +ATB – mepiquat chloride + proheksadione calcium (half dose) + fatty acid methyl ester; MC + PC + AS – mepiquat chloride + proheksadione calcium (half dose) + ammonium salts of polybasic and hydroxy carboxylic acids

Fig. 7. Density charts showing the distribution of the protein content



MC + PC 1.25 – mepiquat chloride + proheksadione calcium (full dose); MC + PC 0.62 – mepiquat chloride + proheksadione calcium (half dose); MC + PC + CA – mepiquat chloride + proheksadione calcium (half dose) + citric acid; MC + PC + AMS – mepiquat chloride + proheksadione calcium (half dose) + ammonium sulphate; MC + PC + UR – mepiquat chloride + proheksadione calcium (half dose) + urea; MC + PC + SL – mepiquat chloride + proheksadione calcium (half dose) + polyalkylene oxide; MC + PC + AT – mepiquat chloride + proheksadione calcium (half dose) + paraffin oil; MC + PC +ATB – mepiquat chloride + proheksadione calcium (half dose) + fatty acid methyl ester; MC + PC + AS – mepiquat chloride + proheksadione calcium (half dose) + ammonium salts of polybasic and hydroxy carboxylic acids

Fig. 9. Density charts showing the distribution of gluten



MC + PC 1.25 – mepiquat chloride + proheksadione calcium (full dose); MC + PC 0.62 – mepiquat chloride + proheksadione calcium (half dose); MC + PC + CA – mepiquat chloride + proheksadione calcium (half dose) + citric acid; MC + PC + AMS – mepiquat chloride + proheksadione calcium (half dose) + ammonium sulphate; MC + PC + UR – mepiquat chloride + proheksadione calcium (half dose) + urea; MC + PC + SL – mepiquat chloride + proheksadione calcium (half dose) + polyalkylene oxide; MC + PC + AT – mepiquat chloride + proheksadione calcium (half dose) + paraffin oil; MC + PC +ATB – mepiquat chloride + proheksadione calcium (half dose) + fatty acid methyl ester; MC + PC + AS – mepiquat chloride + proheksadione calcium (half dose) + ammonium salts of polybasic and hydroxy carboxylic acids

Fig. 10. Density charts showing the distribution of the Zeleny sedimentation index

Discussion

Contemporary agriculture places significant emphasis on minimizing the negative impact of pesticides on the environment and human health. One of the practical solutions is the use of adjuvants, which enhance the efficiency of chemical application by reducing losses and increasing the penetration of active substances into plant tissues (de Oliveira *et al.* 2013; Baek *et al.* 2024; Hewitt 2024). Research on adjuvants also highlights their potential to reduce groundwater contamination and pesticide drift, which is crucial for sustainable agriculture and protecting natural ecosystems (Holka and Kowalska 2023). Plant growth regulators are still widely used chemical agents primarily aimed at preventing plant lodging. Lodging creates favorable conditions for fungal diseases, significantly complicates harvest, and ultimately reduces the yield's quality and quantity. Plant height plays a key role in lodging resistance – the taller the plants, the more susceptible they are to lodging. As a result, plant growth regulators continue to be commonly utilized in agriculture (Li *et al.* 2011; Na *et al.* 2011; Shah *et al.* 2017; Wang *et al.* 2012).

There is limited research on the combined application of plant growth regulators (PGRs) and adjuvants; however, examples of such applications can be found in the scientific literature (Stachecki *et al.* 2004; Echer and Rosolem 2012; Miziniak and Matysiak 2016; Miziniak *et al.* 2017). The presented studies align with the current trend of reducing pesticide use by integrating them with adjuvants. The obtained results confirm that the application of mepiquat chloride and prohexadione calcium in winter wheat cultivation affects canopy height and yield structure, with the effectiveness of growth regulators being dependent on weather conditions in a given year. The results of this research indicated that both full and reduced doses of PGRs, when applied in combination with adjuvants such as citric acid, methyl esters of fatty acids (Atpolan BIO 80 EC), or ammonium salts of polybasic and hydroxycarboxylic acids (AS 500 SL), effectively reduced wheat canopy height. These results are consistent with previous studies demonstrating that the mixture of mepiquat chloride and prohexadione calcium effectively controls excessive shoot elongation. However, the literature presents mixed findings—some studies report a beneficial effect of PGR mixtures (Supronienė 2006; Spitzer *et al.* 2015), while others indicate that the mixtures were less effective than the separate application of the tested substances (Haguewood *et al.* 2013). The tested PGRs did not significantly impact the number of heads per unit area, although in one year – characterized by slightly higher temperatures and increased spring precipitation – a significantly higher number of heads was observed in plots treated with a lower dose of growth regulator or its mixture with urea. Studies have reported similar observations showing that mepiquat chloride can influence plant architecture and tillering, leading to a more significant number of fertile tillers under favorable soil and weather conditions (Zhao *et al.* 2019). This suggests that adding adjuvants may enhance the effectiveness of the mepiquat chloride and prohexadione calcium mixture under less favorable weather conditions. This is a crucial finding, as the performance of growth regulators is highly dependent on climatic conditions, a factor confirmed by other researchers (Sliman and Ghandorah 1992; Rademacher 2015). An essential aspect of the analysis was the effect of the plant growth regulator (PGR) mixture on the thousand-grain weight and grain quality characteristics. However, weather conditions strongly influenced these traits, particularly precipitation levels. The close relationship between these parameters and climatic conditions has been confirmed in studies by Miziniak and Matysiak (2019) and Tung *et al.* (2020), who suggest that PGRs, including mepiquat chloride, may affect carbohydrate and protein content in grains. Notably, in the present study, combining PGRs with adjuvants did not significantly influence grain quality parameters. A similar opinion was presented by Harasim and Wesołowski (2013), demonstrating that ethephon (trinexapac-ethyl) applied alone or in combination with an adjuvant does not affect the quality parameters of grain and can be used in the cultivation of technological wheat varieties. Despite the lack of significant differences, the authors noted in most cases a tendency for an increase in indicators (protein, gluten, Zeleny sedimentation index) and a deterioration in the gluten index as the dose of the growth retardant was reduced. In the present study, opposite relationships were observed. Reducing the dose of the mixture of mepiquat chloride and prohexadione calcium resulted in a slight decrease in protein content, gluten, and the Zeleny index compared to the object where the full dose of the growth regulator was applied.

The presented findings confirm that mixing mepiquat chloride with prohexadione calcium effectively reduced winter wheat height. However, its final effect is dependent on weather conditions. These results align with previous research on the influence of mepiquat chloride on cereal development and confirm its potential for optimizing canopy architecture and winter wheat yield. Some studies suggest that applying PGRs may enhance wheat grain production (Shekoofa and Emam 2008). However, in some instances, growth regulators do not impact grain yield and may even reduce it (Espindula *et al.* 2009; Espindula *et al.* 2011). In the present study, applying a half-dose mixture of mepiquat chloride and prohexadione calcium with adjuvants yielded results comparable to those obtained with the full-dose application of PGRs. The tested adjuvants exhibited similar effects. These findings demonstrate that mepiquat chloride and prohexadione calcium can be effectively applied at significantly reduced doses in combination with adjuvants. Since lodging did not occur in the present study, it is not possible to conclude about the effect of reduced growth regulator doses on this trait. Additional research is needed under intensive cultivation conditions that increase the risk of lodging, primarily involving high nitrogen fertilization and the selection of a wheat cultivar with greater susceptibility to lodging.

The results of this study, which integrate the analysis of weather effects, plant growth regulator (PGR) application methods, and the role of adjuvants, confirm the complexity of interactions between environmental and agronomic factors. The literature emphasizes that the effectiveness of applied formulations is highly dependent on cultivar specificity, plant developmental stage, and variability in weather conditions (Sliman and Ghandorah 1992; Shah *et al.* 2017, 2019). Therefore, further research should focus on optimizing doses and application methods, considering interactions between adjuvants and environmental conditions. A crucial aspect is investigating the mechanisms of agrochemical mixture penetration through leaves, which may contribute to better utilization of active substances and a reduction in environmental impact (Jordan *et al.* 2000; Rademacher and Kober 2003; Castro *et al.* 2014; Osterholz *et al.* 2018).

Conclusions

In conclusion, this study confirmed that weather conditions are the primary factor shaping the morphology, yield structure, and grain quality of winter wheat. The application of a mepiquat chloride and prohexadione calcium mixture, especially when combined with carefully selected adjuvants, enabled canopy height modification without negatively impacting key yield structure components.

Funding

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