

Article

Effect of Chlormequat Chloride and Trinexapac-Ethyl on Productivity and Selected Physiological Traits of Oats (*Avena sativa* L.) and Naked Oats (*Avena nuda* L.)

Renata Tobiasz-Salach 

Department of Crop Production, University of Rzeszów, Zelwerowicza 4, 35-601 Rzeszów, Poland; rtobiasz@ur.edu.pl

Abstract

Oats (*Avena sativa* L.) are a popular crop in Poland, used primarily for animal feed, human food, and biomass in the energy sector. A three-year field experiment was conducted in Poland between 2020 and 2022. The experimental factors included hulled oat (Bingo) and naked oat (Maczo) varieties as well as growth regulators: chlormequat chloride (CCC) and trinexapac-ethyl (TE). The aim of this study was to investigate the effect of growth regulators on yield, yield structure components, selected physiological processes, and canopy architecture indices. This study found that the use of growth regulators resulted in an average 7.2% increase in oat grain yield. The yield of the Bingo variety increased after TE application, while that of the Maczo variety increased after CCC and TE application. Growth regulators also had a beneficial effect on increasing the weight and number of grains per panicle. Growth regulators, particularly CCC, caused the shortening of the main shoot and panicle. Both CCC and TE increased the leaf area index (LAI). Among the physiological parameters, the relative leaf chlorophyll content (CCI) was 2.6% higher after CCC treatment than after TE treatment, while the photosynthetic index (PI) was higher after TE treatment (a 2.2% increase compared to CCC). The Bingo cultivar showed a more favorable response to growth regulators than the Maczo cultivar. The weather conditions during the oat growing season significantly influenced some of the obtained results.

Keywords: chlormequat chloride; trinexapac-ethyl; hulled oats; plant growth regulators; grain yield; yield components; chlorophyll; chlorophyll fluorescence

1. Introduction

Plant growth and development regulators (retardants) are synthetic or natural substances that significantly influence the growth and differentiation of various plant parts. Often called biostimulants or bioinhibitors, they act within plant cells, stimulating or inhibiting specific enzymes or enzyme systems and helping to regulate plant metabolism. Their activity depends on their concentration, environmental factors during the growing season, and the plant's physiological state. PGRs have the ability to influence cell division, cell structure, cell expansion, and cell function as well as to mediate environmental stress even at low concentrations [1]. Their role in modern agriculture has grown significantly due to the need to stabilize crop yields and quality and to improve plants' resilience to changing environmental conditions [2]. The use of plant growth regulators (PGRs) varies significantly depending on the cultivation system and plant type. In cereal and oil crops,



Received: 27 July 2026

Revised: 2 September 2026

Accepted: 5 September 2026

Published: 8 September 2026

Copyright: © 2026 by the author.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

these compounds are primarily used to modify plant architecture and improve yield stability. Retardants reduce the risk of lodging, improve light capture, and enhance assimilation, contributing to high-quality yields.

Studies have shown a reduction in plant shoots [3,4] as well as changes in the architecture of cereal crops [5–8] and oilseed crops [9] with the use of PGRs. The effectiveness of PGR application is closely related to the variety, dosage, and timing of application, the spraying method, the stage of growth and development, and other agrotechnical conditions [10,11].

Commonly used growth regulators include anti-gibberellins, such CCC and trinexapac-ethyl (TE). These compounds are used in crop production, particularly in intensive farming systems, to prevent lodging [11–13]. CCC inhibits gibberellin biosynthesis at an early stage, while trinexapac-ethyl does so at a later stage of growth (the onset of stem elongation and before the emergence of the flag leaf). CCC was introduced for cereal cultivation in the 1960s [14,15], while trinexapac-ethyl (TE) was developed several decades later as an acylcyclohexanedione inhibitor of gibberellic acid 3 β -hydroxylation [16,17]. Both growth regulators (CCC and TE) shorten the stem, limit growth, and reduce plant lodging. Their introduction into cereal agronomic practices has allowed for increased nitrogen fertilization and a significant increase in grain yield. It has been demonstrated that the application of growth regulators increases the number of grains produced per unit area in plants, while reducing biomass [11,12].

In addition to their growth-inhibiting effects, these compounds have a beneficial impact on other plant developmental processes, including photosynthesis. In small amounts, they modify the functioning of the photosynthetic apparatus and increase the number of productive lateral shoots in cereals [4,11,18,19] as well as stimulate root growth and development [20]. Studies indicate that under conditions of prolonged drought stress, meadow grasses treated with growth regulators maintain stable yield, photochemical activity, and cellular hydration [21–24]. A positive effect of growth regulators on the yields of cereals [25–27] and meadow grasses [12] has also been demonstrated.

Oats are a popular cereal crop grown in Poland. Poland is the third-largest producer of oats in the world, after Canada and Russia. In 2025, the area of oat cultivation in Poland was 0.515 million ha [28]. The popularity of oats stems from the fact that they are a phytosanitary crop and are competitive with weeds [29–31]. Oats serve as good preceding crops for cereals, which account for a very high percentage 64% of the crop structure in Poland [32]. The most suitable soils for oat cultivation are rye-type and mountain soils. Thanks to their well-developed root systems, oats can absorb nutrients from deeper soil layers and from forms that are difficult to access, which makes them more efficient in utilizing soil resources compared to other cereal species. However, the best oat yields are obtained on moderately fertile, loamy, or sandy-loamy soils with good drainage and moderate moisture content [33]. Favorable oat yields are achieved from soils with high water-holding capacity (the oat transpiration coefficient is high—500).

Oats are also a valuable food crop. The grain is high in dietary fiber, particularly the water-soluble fraction, including beta-glucans, which have a positive effect on lipid metabolism and blood glucose regulation [34,35].

Population growth means that cereal yields, including those of oats, should be increased by an average of 25–50% by 2050. Unfortunately, climate change is putting food security at risk. Grain yields significantly reduce if plants are exposed to unfavorable environmental factors for a long time, such as high and low temperatures, drought, salinity, and oxidative stress. Therefore, various methods are used to reduce the negative effects of environmental stress. One such method is the use of synthetic growth regulators in oat cultivation, which do not pose a significant environmental threat [36–39].

Currently, COBORU's variety selection in Poland includes 35 cultivars of hulled and 2 hull-less oats [40]. The use of growth regulators in cereal cultivation, including oats, results in shorter stalks, increased stalk diameter and thickness, and longer panicles, which in turn lead to an increase in the number of grains per panicle as well as the number of productive spikes [18,41]. Oats' response to growth regulators varies and depends on the variety and growing conditions. In Poland, there is a lack of information on the response of new oat varieties—particularly naked oats—to growth regulators. Therefore, a study was conducted using two forms of oats—hulled and hull-less—to evaluate the effects of two growth regulators, CCC and TE, on yield, yield components, the course of selected physiological processes, and crop architecture indicators.

The research hypothesis adopted in this study was that the use of CCC and TE preparations positively affects grain yield and its yield-forming characteristics, shortens the stem and improves physiological indicators, as well as increases the assimilation area of the canopy.

2. Materials and Methods

2.1. Characteristics of Field Experiment

This research was conducted between 2020 and 2022 as a rigorous field experiment. The experiment was established at the Experimental Station of the University of Rzeszów, Faculty of Technology and Life Sciences, in Krasne, near Rzeszów (50°03' N; 22°06' E) (Poland). It was a two-factor experiment conducted using the split-plot method with four replications.

The first factor in the experiment was the varieties recommended for cultivation in this region of Poland—Maczo (naked oats) and Bingo (hulled oats)—developed by the Strzelce Plant Breeding Station (IHAR Group, Kutno, Poland). The second factor in the experiment was the application of CCC (trade name Cycocel 750 SL—BASF, Ludwigshafen am Rhein, Germany) and TE (trade name Moddus 250EC—Syngenta, Basel, Switzerland), which were applied twice during the following plant growth stages: (33–35 BBCH) and (39–42 BBCH), along with a control plot where no growth regulators were applied. CCC was sprayed at a rate of 1500 g·ha^{−1} and TE at 100 g·ha^{−1} to the total dose during the growing season (according to manufacturer's recommendations) (Table 1).

Table 1. The characteristics of the growth retardants used in the experiment.

Growth Retardant	Active Substance	Composition	
Cycocel 750 SL	chlormequat chloride	750 g·L ^{−1}	65.56%
Moddus 250 EC	trinexapac ethyl	250 g·L ^{−1}	25.5%

Chemical sprayings were applied using a pressure sprayer in windless weather. Plant development stages were determined according to the BBCH scale (Bundesanstalt, Bundesortenamt und Chemische Industrie) used in the EU [42]. Oat grain was sown with a seeder in the second (in the years 2020 and 2021) and third week of March (2022), at a spacing of 12.5 cm and a sowing depth of 2.5–3 cm. The number of plants per 1 m² was 550, and the size of the harvest plots was 18 m². The forecrop was spring rapeseed. In spring, NPK mineral fertilizers were sown. Nitrogen rates were 30 kg·ha^{−1} (34% ammonium nitrate), phosphorus 60 kg·ha^{−1} (19% P₂O₅, superphosphate), and potassium 85 kg·ha^{−1} (60% KCl, potassium chloride). Plant protection treatments included spraying the leaf beetle (*Oscinella frit* L.) with Karate Zeon 050 CS (Syngenta) at a rate of 0.1 L·ha^{−1}.

Oat grain harvesting occurred in the second (years 2020, 2021) and third (2022) 10-day periods of August (BBCH 89). Panicle density per square meter was also determined before harvest.

Meteorological data are presented based on the results obtained from the Meteorological Station of the University of Rzeszów, Poland, located approximately 14 km from the planned experiment site.

2.2. Description of Soil Conditions

The experiment was established on medium soil. The soil was slightly acidic (pH KCl from 5.7 to 6.4). The soil organic carbon content ranged from 1.3 to 1.1%. The content of available nutrients was high for phosphorus (173–198 mg·kg^{−1} soil) and potassium (224–246 mg·kg^{−1} soil), and average for magnesium (Mg) (51–67 mg·kg^{−1} soil). The content of copper, manganese, and zinc was average across the study years, while iron was low in 2020 and average in 2021 and 2022 (Table 2).

Table 2. Soil conditions of field experiment.

Parameter	Unit	2020	2021	2022
pH in KCL	-	6.4	6.2	5.7
Humus	%	1.3	1.1	1.1
Phosphorus (P ₂ O ₅)	mg·kg ^{−1} soil	198	188	173
Potassium (K ₂ O)		246	239	224
Magnesium (Mg)		67	51	56
Copper (Cu)		4.6	5.1	4.3
Manganese (Mn)		158.1	168.2	165.3
Zinc (Zn)		8.6	10.6	9.6
Iron (Fe)		993.9	1008	1234

2.3. Plant Physiological Measurements and Canopy Architecture

During the growing season, in the morning hours after the dew had subsided, measurements of selected physiological indicators were carried out twice (BBCH 45–50 and 60–70) [42] (5 days after the application of retardants), and the canopy architecture was assessed. The results are presented as the average of the two measurement dates.

2.3.1. Measurement of Chlorophyll Fluorescence

Chlorophyll fluorescence parameters were measured using a Packet PEA (Plant Efficiency Analyzer) from Hansatech Instrument Ltd., Pentney, UK, which incorporates leaf clips for dark adaptation. Five randomly selected flag leaves were dark-adapted using the clips for 30 min. The following parameters were then measured using a fluorometer: maximum quantum yield of primary photochemistry (Fv/Fo), maximum photochemical efficiency of PSII (Fv/Fm) and the photosynthetic yield index (PI).

2.3.2. Measurement of Relative Chlorophyll Content

Leaf relative chlorophyll content indices (CCIs) were measured using a CCM-200plus instrument (Opti-Sciences, Hudson, NH, USA). Ten measurements were performed on flag leaves of randomly selected plants at each experimental site.

2.3.3. Measurement of Canopy Architecture

Measurements of canopy architecture indices, i.e., leaf area index (LAI) (m²/m²) and mean tilt angle (MTA), were performed using an LAI-2000 instrument (LI-COR, Lincoln, NE, USA). Measurements were performed four times on each plot.

2.4. Laboratory Analyses of Yield

Before harvest, 25 oat plants were randomly sampled from each plot to analyze biometric traits of plants and yield components. The following were analyzed: grain weight per panicle (g), number of grains per panicle (pcs), main stem length (cm), panicle length (cm), and 1000-grain weight (g). The 1000-grain weight was calculated using a grain counter (Sadkiewicz Instruments, Bydgoszcz, Poland) [43] at 15% grain moisture. Grain yield per plot was converted to yield per hectare, taking into account 15% grain moisture.

2.5. Statistical Analysis

The experimental results were analyzed statistically. Two-way analysis of variance (ANOVA) was performed using Statistica 13.3.0 (TIBCO Software Inc., Palo Alto, CA, USA). The fixed factors were cultivar and growth regulator. Year of study was treated as a random factor. Significance of differences between individual means was determined using Tukey's honestly significant difference (HSD) test at a significance level of $p \leq 0.05$.

Pearson's correlation coefficients (r) were also analyzed to assess the relationship between yield and physiological parameters and canopy architecture indices. Experimental variables were verified for conformity with a normal distribution.

3. Results and Discussion

Weather conditions during the growing season of cereals, including oats, influence yield and yield components. Adequate water supply affects traits such as plant height, productive tillering, ear length, and thousand-kernel weight [44–47]. Oats are sensitive to water shortages, especially during the stem elongation (BBCH 30–39) and heading (BBCH 41–49) stages [48–50]. In the experiments conducted, weather conditions varied across the study years (Figure 1).

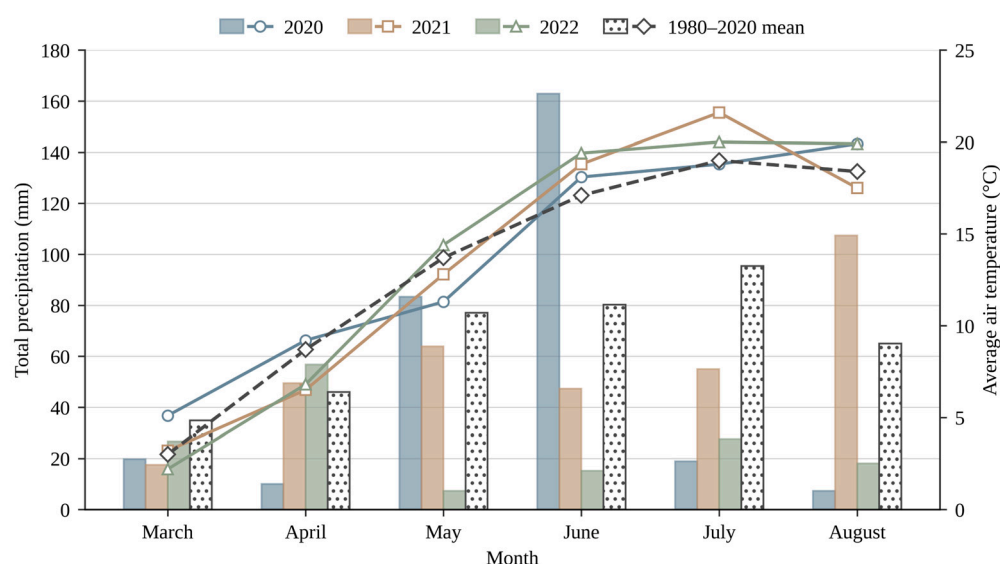


Figure 1. Weather conditions during growing season for oats in 2020–2022.

In 2020, the highest precipitation was recorded in June—more than twice the long-term average—but a drought was observed in July (precipitation was 76.5 mm below the long-term average). The year 2021 was characterized by the most evenly distributed precipitation during the growing season. Favorable precipitation was recorded in April and May. It was only slightly below the long-term average for this period. High soil moisture (though slightly below the long-term average) also persisted in June and July. The least favorable conditions for oat growth occurred in 2022. It was a dry year, with particularly

low precipitation observed in May, June, and July. Air temperatures during the oat growing season in 2020–2022 were high or close to the long-term average.

During the spring months, they were slightly lower. During the summer months, especially in June and July, they were higher than the long-term average (Table 3). Variations in yields were observed depending on the year of the experiment. The highest oat grain yields were obtained in 2021, when precipitation was highest and evenly distributed throughout the growing season. That year also yielded the most favorable values for thousand-kernel weight, as well as the number and weight of kernels per panicle, compared to 2020 and 2022. According to Szempliński et al. [50], oat yields are most strongly influenced by rainfall during the tillering and stem elongation stages, that is, in April and May, which was observed in 2021.

Table 3. Grain yield and yield components (average for 2020–2022).

Cultivar (A)	Growth Retardant (B)	Grain Yield [Mg·ha ⁻¹]	Panicle Density [pcs for m ²]	Weight of 1000 Grains [g]	Grain Weight per Panicle [g]	Number of Grains per Panicle [pcs]
Bingo	Control	6.70 ± 0.70 c	402.0 ± 25.7 b	36.7 ± 4.96 b	1.59 ± 0.21 cd	38.3 ± 3.73 a
	CCC	6.97 ± 0.66 c	419.3 ± 32.1 c	36.5 ± 4.41 b	1.62 ± 0.12 d	39.3 ± 4.69 a
	TE	7.31 ± 0.43 d	423.3 ± 31.9 c	36.7 ± 5.17 b	1.91 ± 0.11 e	43.6 ± 4.68 b
Maczo ^Y	Control	4.26 ± 0.68 a	374.9 ± 58.3 a	22.4 ± 2.99 a	1.27 ± 0.16 a	43.6 ± 4.69 c
	CCC	4.64 ± 0.20 b	423.7 ± 28.7 c	21.8 ± 2.83 a	1.40 ± 0.21 b	48.5 ± 6.33 c
	TE	4.61 ± 0.33 b	400.8 ± 67.6 b	22.5s ± 3.37 a	1.50 ± 0.22 c	50.4 ± 5.50 c
HSD _{p≤0.05} A × B		*** (0.0000)	*** (0.0000)	n. s.	*** (0.0000)	** (0.0114)
Mean	Bingo	7.00 ± 0.64 a	414.8 ± 30.9 b	36.6 ± 4.72 b	1.71 ± 0.20 b	40.3 ± 4.8 a
	Maczo	4.51 ± 0.47 b	399.8 a ± 56.2 a	22.2 ± 3.00 a	1.39 ± 0.21 a	49.0 ± 5.52 a
HSD _{p≤0.05} A		*** (0.0000)	*** (0.0001)	*** (0.0000)	*** (0.0000)	*** (0.0000)
Mean	Control	5.48 ± 1.41 a	388.40 ± 46.2 a	29.5 ± 8.34 a	1.43 ± 0.24 a	43.2 ± 6.63 a
	CCC	5.81 ± 1.28 b	421.5 ± 29.4 c	29.2 ± 8.32 a	1.51 ± 0.20 b	43.8 ± 7.27 a
	TE	5.96 ± 1.43 b	412.0 ± 53.0 c	29.6 ± 8.44 a	1.71 ± 0.27 c	46.9 ± 6.07 b
HSD _{p≤0.05} B		*** (0.0000)	*** (0.0000)	n. s.	*** (0.0000)	*** (0.0000)
Year (C)	2020	5.23 ± 1.26 a	359.2 ± 41.7 a	24.5 ± 6.33 a	1.53 ± 0.23 b	41.6 ± 5.1 a
	2021	6.16 ± 1.51 c	418.4 ± 16.9 b	32.5 ± 9.4 c	1.73 ± 0.18 c	50.3 ± 6.2 b
	2022	5.87 ± 1.91 b	444.4 ± 20.5 c	31.2 ± 6.54 b	1.39 ± 0.25 a	42.1 ± 5.27 a
HSD _{p≤0.05} C		*** (0.0000)	*** (0.0000)	*** (0.0000)	*** (0.0000)	*** (0.0000)
HSD _{p≤0.05}	C × A	*** (0.0001)	*** (0.0000)	*** (0.0000)	** 0.0221	*** (0.0000)
	C × B	** (0.0010)	*** (0.0000)	* (0.0128)	n. s.	*** (0.0000)
	C × A × B	n. s.	*** (0.0000)	n. s.	** 0.0017	*** (0.0000)
Mean		5.75 ± 1.37	407.3 ± 45.6	29.4 ± 8.26	1.55 ± 0.26	44.8 ± 6.79

^Y Naked cultivar, ± standard deviation; ***, **, * indicate significant differences at $p < 0.001$, $p < 0.01$, $p < 0.05$; n. s., non-significant, according to Tukey's honestly significant difference (HSD) test. Mean values with different letters in columns are statistically different.

In addition to weather conditions, experimental factors also influenced oat yield (Table 3).

Both varieties responded to the applied growth retardants with increased yields. For the Bingo variety, a significant increase of 9.1% compared to the control (without retardant application) was observed after applying TE. For the Maczo variety, yield increases were observed following the application of both CCC and TE by 8.2% and 7.6%, respectively.

Regardless of the variety used, growth retardants resulted in an average yield increase of 7.2% compared to the control (without CCC or TE application). The Bingo variety, due to its hull content, was characterized by a higher yield than the Maczo variety, by an average of 35.6%. A significant interaction was found between the year of study and the variety as well as the year of study and the growth regulator. This indicates that weather conditions influence oat yields. A positive response of growth regulators to increased yields and yield components in oats was reported by [51,52] and in wheat by [18]. In studies by Fernandes et al. [41] on white oats, the application of TE at a rate exceeding $100 \text{ g} \cdot \text{ha}^{-1}$ resulted in reduced lodging, an increase in the number of panicles per unit area, and higher grain yield, which was also confirmed in this study. Different results were obtained by Rajala and Peltonen-Sainio [53] and Fernandes [41] (up to a TE dose of $100 \text{ g} \cdot \text{ha}^{-1}$), who reported a decrease in oat yield following the application of growth retardants, which resulted from reductions in the number and weight of grains per ear. In this study, a positive effect of retardants on yield components was found in panicle density (an increase in the Bingo variety by an average of 4.8% after the application of both treatments and in the Maczo variety by 13.0% after the application of CCC and 6.9% after the application of TE). Grain weight and number per panicle increased in the Bingo variety after applying TE (by 20.1% and 14.0%, respectively, compared to the control). A more favorable effect of TE than CCC on these yield traits was also observed (significant increases in grain weight and number by 17.9% and 9.95% after applying TE). In the Maczo variety, such an increase (by 6.7%) was observed for panicle grain weight. Regardless of the varieties studied, both growth retardants used resulted in increases in panicle grain weight and number, and TE also produced a more favorable effect compared to CCC. The Bingo variety (regardless of the growth retardants used) achieved higher values for panicle density, 1000-grain weight, and panicle grain weight compared to the Maczo variety, which was most likely due to its genetic characteristics (naked-grain oat form). Analysis of variance revealed variation in yield components depending on the study year. Oat plants achieved the highest panicle density per square meter in 2022 and the lowest in 2020. The 1000-grain weight and the number of grains per panicle were the highest in 2021.

Growth retardants reduced the length of the main culm and the panicle length compared to the control (Table 4).

The CCC growth retardant was more effective at shortening the culm and panicle than TE. In the Maczo variety, greater reductions in main culm length (5.5%) and panicle length (10.4%) were observed after applying CCC compared to TE. A similar response in terms of stem and panicle shortening was observed in oats by Rajala and Peltonen-Sainio [53] and Raja [54], as well as in white oats [41] and rapeseed and winter rye [55,56]. The reductions in stem and panicle growth depended on weather conditions during the growing season. Interactions with year of study were found. The shortest stems were observed in 2022 and the shortest panicles in 2021 (Table 5). An influence of weather conditions on yield variability and yield-determining traits of oats and barley was also reported by Hakala et al. [49], Sadras and Slafer [57], and Juzoń-Sikora et al. [58] in winter wheat and Ngoune et al. [46].

During the study period, the effect of the growth retardants on the values of the stand architecture indices LAI and MTA (leaf tilt angle) was also analyzed (Table 5).

Most models for predicting plant growth and development are based on these indices, particularly LAI. The LAI and MTA indices are primarily used to assess the rate of growth and biomass accumulation [59,60]. They are influenced by the genetic characteristics of the variety, agrotechnical factors, and weather conditions during the growing season [61–63]. They are also influenced by growth retardants [53]. In the conducted studies, the LAI was higher in the Bingo variety than in the Maczo variety (variety factor). It also increased

(regardless of variety) after the application of both growth retardants compared to the control. In the Bingo variety, it was higher after TE application (an 11.8% increase compared to the control), while in the Maczo variety, it was higher after CCC application (an 18.6% increase). Variance analysis revealed variation across study years. The LAI index was highest in 2022. The lowest was recorded in 2021.

Table 4. Effect of growth retardant on length of main stem and oat panicle (average for 2020–2022).

Cultivar (A)	Growth Retardant (B)	Length of the Main Stem [cm]	Panicle Length [cm]
Bingo	Control	96.01 ± 14.3 d	14.35 ± 1.55 a
	CCC	90.25 ± 13.4 bc	13.47 ± 1.52 ab
	TE	90.58 ± 14.7 bc	14.7 ± 0.91 bc
Maczo ^Y	Control	94.63 ± 16.01 c	16.05 ± 0.89 d
	CCC	82.55 ± 15.96 a	15.43 ± 1.55 c
	TE	86.81 ± 15.43 b	15.96 ± 1.44 d
HSD _{p≤0.05} A × B		*** (0.0000)	** (0.0067)
Mean	Bingo	89.9 ± 14.17 b	14.17 ± 1.42 a
	Maczo	87.36 ± 15.81 a	15.81 ± 1.31 b
HSD _{p≤0.05} A		** (0.0011)	*** (0.0000)
Mean	Control	93.64 ± 15.2 c	15.20 ± 1.51 b
	CCC	85.70 ± 14.7 a	14.72 ± 1.96 a
	TE	87.6 ± 15.06 b	15.06 ± 1.23 b
HSD _{p≤0.05} B		*** (0.0000)	n. s.
Year (C)	2020	96.64 ± 15.46 a	15.46 ± 1.70 b
	2021	85.13 ± 13.66 c	13.66 ± 1.92 a
	2022	82.93 ± 15.86 b	15.86 ± 0.81 b
HSD _{p≤0.05} C		*** (0.0000)	*** (0.0000)
HSD _{p≤0.05}	C × A	*** (0.0000)	*** (0.0000)
	C × B	n. s.	n. s.
	C × A × B	*** (0.0000)	** (0.0075)
Mean		87.89 ± 14.99	14.9 ± 1.59

^Y Naked cultivar; ***, ** indicate significant differences at $p < 0.001$ $p < 0.01$; n. s. non-significant, according to Tukey's honestly significant difference (HSD) test. Mean values with different letters in columns are statistically different.

There are reports that growth retardants also regulate physiological processes in plants. Sattar et al. [64] found a positive effect of TE on increasing chlorophyll content in the leaves of wheat seedlings under laboratory conditions, as did studies on *Deschampsia cespitosa* [65], in sugarcane [66], and by Barányiová and Klem [67] in winter wheat under water deficit. In this study on oats, a positive effect of growth retardants on chlorophyll content in leaves (CCI) and chlorophyll fluorescence parameters (PI, Fv/Fo, and Fm/Fv) was found (Table 6).

The CCI index of both varieties (compared to the control) increased following the application of both CCC and TE. A slightly greater effect was observed after foliar application of CCC. The Bingo variety achieved a higher CCI index after treatment with both growth regulators compared to the control. In the Maczo variety, a significant increase (by 7.6%) was observed after treatment with CCC. Both varieties also responded with an increase in

the PI. The Bingo variety showed an average increase of 6.7% following the application of CCC and TE, while the Maczo variety showed an increase of 7.4% following the foliar application of TE. Regardless of the retardants used, the Bingo variety was characterized by a higher PI index (compared to the Maczo variety). Indeed, the highest PI was achieved by the plants in 2021.

Table 5. Oat stand architecture indices (average for 2020–2022).

Cultivar (A)	Growth Retardant (B)	Leaf Area Index (LAI) [m ² ·m ²]	Mean Tilt Angle (MTA) [°]
Bingo	Control	4.21 ± 0.3050 a	59.9 ± 6.049 ab
	CCC	4.63 ± 0.4970 b	57.5 ± 4.823 a
	TE	4.71 ± 0.276 b	58.2 ± 4.709 a
Maczo ^Y	Control	3.53 ± 0.5228 a	61.0 ± 4.945 bc
	CCC	4.19 ± 0.6180 b	63.3 ± 5.443 c
	TE	4.00 ± 0.4292 b	59.8 ± 4.812
HSD _{p≤0.05} A × B		*** (0.0000)	*** (0.0000)
Mean	Bingo	4.52 ± 0.422533 b	58.5 ± 5.184 a
	Maczo	3.91 ± 0.585370 a	61.4 ± 5.141 b
HSD _{p≤0.05} A		*** (0.0000)	*** (0.0001)
Mean	Control	3.87 ± 0.5453 a	60.5 ± 5.433 a
	CCC	4.41 ± 0.5927 b	60.4 ± 5.842 a
	TE	4.35 ± 0.5036 b	59.0 ± 4.724 a
HSD _{p≤0.05} B		*** (0.0000)	*** (0.0000)
Year (C)	2020	3.87 ± 0.5119 a	53.7 ± 2.431 a
	2021	4.16 ± 0.6702 b	64.4 ± 2.971 b
	2022	4.60 ± 0.302 c	61.7 ± 2.796 c
HSD _{p≤0.05} C		*** (0.0000)	*** (0.0000)
HSD _{p≤0.05}	C × A	*** (0.0000)	n. s.
	C × B	n. s.	n. s.
	C × A × B	n. s.	n. s.
Mean		4.21 ± 0.592383	60.0 ± 5.321

^Y Naked cultivar; ***, indicate significant differences at $p < 0.001$; n. s., non-significant, according to Tukey's honestly significant difference (HSD) test. Mean values with different letters in columns are statistically different.

Positive effects of CCC and TE were also observed in terms of an increase in the Fv/Fo ratio in the Maczo variety, but this was not statistically significant. Chlorophyll fluorescence measurement is one of the methods for detecting changes in the overall bioenergetic conditions of photosynthetic organisms, particularly under abiotic stress [21,68–71]. The PI and Fv/Fo increase under the influence of TE [67], a phenomenon also observed in this study. A significant interaction with the year of the study was identified. Oat plants in 2022 exhibited the highest chlorophyll content in their leaves, a result influenced by favorable weather conditions during the growing season, as also reported in studies by Murkowski [72].

Table 6. Physiological characteristics of oats (average for 2020–2022).

Cultivar (A)	Growth Retardant (B)	Chlorophyll Content Indices (CCI)	Photosynthetic Index (PI)	Maximum Quantum Yield of Primary Photochemistry Fv/Fo	Maximum Photochemical Efficiency of PS II Fv/Fm
Bingo	Control	43.7 ± 5.27 b	4.4 ± 0.21 b	3.50 ± 0.17 a	0.80 ± 0.013 a
	CCC	46.7 ± 5.23 c	4.7 ± 0.48 c	3.45 ± 0.13 a	0.81 ± 0.013 a
	TE	47.0 ± 5.30 c	4.8 ± 0.47 c	3.56 ± 0.20 a	0.81 ± 0.011 a
Maczo ^Y	Control	42.5 ± 4.77 a	4.1 ± 0.37 a	3.47 ± 0.18 a	0.81 ± 0.006 a
	CCC	46.0 ± 5.17 c	4.2 ± 0.51 a	3.63 ± 0.20 ab	0.80 ± 0.014 a
	TE	43.3 ± 4.95 ab	4.4 ± 0.50 b	3.62 ± 0.24 ab	0.81 ± 0.011 a
HSD _{p≤0.05} A × B		*** (0.0000)	** (0.0021)	n. s.	n. s.
Mean	Bingo	45.8 ± 5.32 b	4.7 ± 0.43 b	3.50 ± 0.17 a	0.81 ± 0.012 a
	Maczo	43.9 ± 5.06 a	4.2 ± 0.47 a	3.57 ± 0.22 a	0.81 ± 0.011 a
HSD _{p≤0.05} A		*** (0.0000)	*** (0.0001)	n. s.	n. s.
Mean	Control	43.1 ± 4.96 a	4.3 ± 0.34 a	3.49 ± 0.18 a	0.81 ± 0.012 a
	CCC	46.4 ± 5.10 c	4.5 ± 0.56 b	3.54 ± 0.19 a	0.81 ± 0.013 a
	TE	45.2 ± 5.36 b	4.6 ± 0.54 c	3.59 ± 0.22 a	0.81 ± 0.011 a
HSD _{p≤0.05} B		*** (0.0000)	*** (0.0000)	n. s.	n. s.
Year (C)	2020	39.3 ± 1.77 a	4.0 ± 0.32 a	3.44 ± 0.14 a	0.80 ± 0.010 a
	2021	44.4 ± 2.00 b	4.9 ± 0.37 c	3.58 ± 0.22 b	0.81 ± 0.011 a
	2022	51.0 ± 2.30 c	4.4 ± 0.28 b	3.59 ± 0.19 b	0.82 ± 0.013 a
HSD _{p≤0.05} C		*** (0.0000)	*** (0.0000)	** (0.0053)	* (0.024)
HSD _{p≤0.05}	C × A	*** (0.0000)	*** (0.0006)	n. s.	n. s.
	C × B	n. s.	** (0.0000)	** (0.0035)	n. s.
	C × A × B	n. s.	*** (0.0000)	n. s.	n. s.
Mean		44.8 ± 5.24	4.4 ± 0.50	3.54 ± 0.19	0.81 ± 0.012

^Y Naked cultivar; ***, **, *, indicate significant differences at $p < 0.001$, $p < 0.01$ and $p < 0.05$; n. s., non-significant, according to Tukey's honestly significant difference (HSD) test. Mean values with different letters in columns are statistically different.

This study also analyzed the correlations between yield and its components, crop architecture indices, and chlorophyll fluorescence parameters (Figure 2).

A very strong positive effect on yield was demonstrated for 1000-grain weight (0.95), a strong effect for panicle grain weight (0.67), and a strong effect for panicle length (0.59). A moderate effect was observed for the number of grains per panicle (0.50) and panicle density per 1 m² (0.39). Among the analyzed crop architecture indices, a high correlation with grain yield was observed for LAI (0.57). A positive effect was also observed for relative chlorophyll content ($r = 0.42$) and the PI (0.66). A high correlation was also found between panicle density per 1 m² and relative chlorophyll content ($r = 0.84$) as well as between 1000-grain weight and PI ($r = 0.68$). The results obtained confirm the hypothesis that oat grain yield is determined not only by yield-related traits (weight and number of grains per panicle) but also by physiological parameters such as relative chlorophyll content and certain chlorophyll fluorescence indices, as has also been reported by other researchers [73–76].

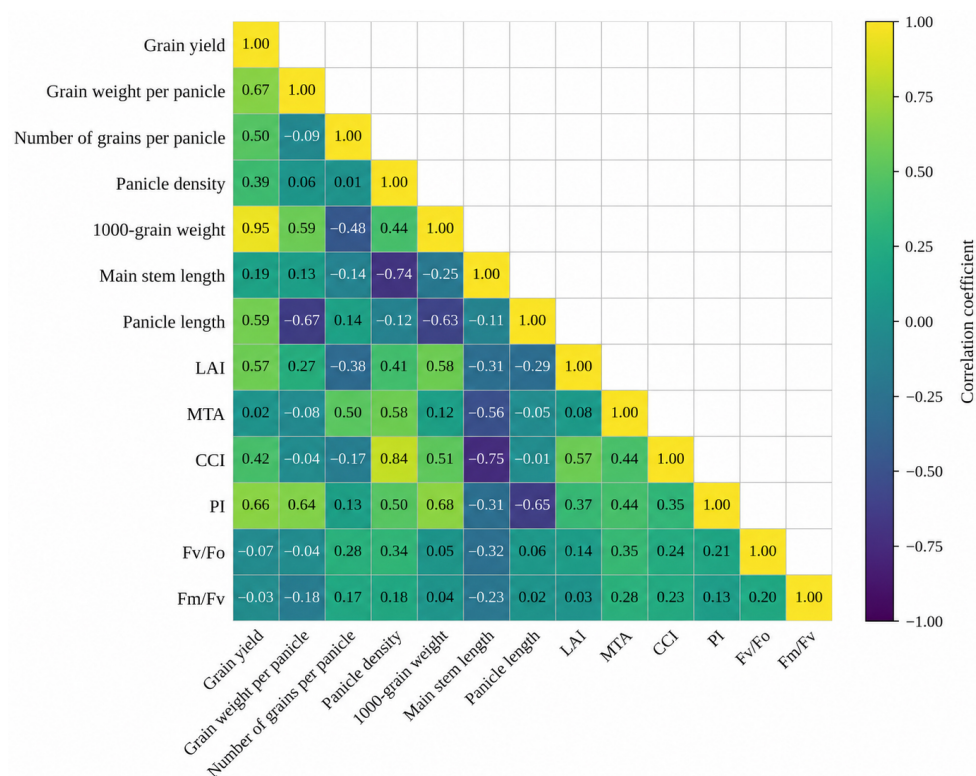


Figure 2. Correlation coefficients (r) between analyzed parameters ($n = 72$). (LAI—leaf area index, MTA—mean tilt angle, CCI—relative chlorophyll content, PI—photosynthetic yield index, Fv/Fo—maximum quantum yield of primary photochemistry, Fv/Fm—maximum photochemical efficiency of PSII).

4. Conclusions

The objective of this study was to evaluate the effect of growth regulators (CCC and TE) on yield, yield structure characteristics, crop architecture, and selected physiological parameters of two varieties of oats: hulled and hull-less oats. The results only partially confirm the hypothesis that CCC and TE use positively affect grain yield and some yield structure traits. Both regulators (regardless of the variety) increased grain yield, plant density per square meter, and grain weight per panicle. TE application also increased the number of grains per panicle. However, no effect of the growth regulators on 1000-grain weight was found. Both regulators shortened stem length and increased the LAI, with a stronger effect observed after CCC use. Among the analyzed physiological parameters, the beneficial effect of the growth regulators, regardless of oat variety, was confirmed only for the relative chlorophyll content (CCI) and the PI. The relative chlorophyll content in the leaves was higher after the application of CCC, while the photosynthetic yield index (PI) was higher after the application of TE. A varied varietal response to the action of growth regulators was also recorded.

The Bingo variety responded better to the growth regulator TE than to CCC in terms of yield, grain number, and grain weight per panicle. The Maczo variety achieved significantly higher panicle density per square meter after foliar spraying with CCC and grain weight per panicle after TE application. Compared to Bingo, the Maczo variety demonstrated greater stem and panicle shortening after CCC than after TE application. Of the physiological parameters analyzed, the Maczo variety had a significantly higher CCI after CCC application and a higher PI after TE. The Bingo variety (in terms of CCI and PI) responded similarly to CCC and TE. However, the results of this study do not fully reflect the response of oats to growth regulators. To thoroughly elucidate the complex phenomenon and the impact of retardants on oat yield, its components, and physiological

parameters, agronomists, breeders, physiologists, and geneticists should conduct further research to address this issue, particularly with new varieties. This will help optimize oat production and increase the efficiency of grain and straw production in the feed, food, and energy sectors.

Funding: This research was funded by financial resources of the Ministry of Science and Higher Education for statutory activity.

Data Availability Statement: The original contributions presented in this study are included in this article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The author declares no conflicts of interest.

References

1. Gujar, S.B.; Pathade, A.G.; Pathade, G.R. The plant growth regulators: Advances, their applications and potential uses in Agriculture—A review. *Ecol. Environ. Conserv.* **2024**, *30*, 271–280. [\[CrossRef\]](#)
2. Prisa, D.; Matsoukis, A.; Jamal, A.; Spagnuolo, D. Environmental Impacts of Plant Growth Regulators in Modern Agriculture: Advances, Risks, and Sustainable Perspectives. *Agrochemicals* **2026**, *5*, 14. [\[CrossRef\]](#)
3. Lukatkin, A.S.; Sokolova, A.S.; Lukatkin, A.A.; Cherepanov, I.A.; Kalganova, N.V.; Moiseev, S.K. Sydnone Imine: A Novel Class of Plant Growth Regulators. *Agrochemicals* **2023**, *2*, 203–219. [\[CrossRef\]](#)
4. Hozlar, P.; Valeuhova, D.; Ducsay, L.; Losak, T.; Wiśniowska-Kielian, B. The impact of morphoregulator on the productivity of common oats *Avena sativa* L. *Ecol. Chem. Eng. A* **2014**, *21*, 471–480. [\[CrossRef\]](#) [\[PubMed\]](#)
5. Bhattarai, S.; Khanal, N.; Anderson, N.P.; Yoder, C.L. Plant Growth Regulator Effects on Red Fescue Seed Crops in Diverse Production Environments. *Crop. Sci.* **2024**, *64*, 3608–3618. [\[CrossRef\]](#)
6. Shah, L.; Yahya, M.; Shah, S.M.A.; Nadeem, M.; Ali, A.; Ali, A.; Wang, J.; Riaz, M.W.; Rehman, S.; Wu, W.; et al. Improving Lodging Resistance: Using Wheat and Rice as Classical Examples. *Int. J. Mol. Sci.* **2019**, *20*, 4211. [\[CrossRef\]](#) [\[PubMed\]](#)
7. Sandhu, N.; Aggarwal, H.; Kumar, A.; Augustine, G.; Vishnoi, R.; Pandey, A.K.; Chauhan, H.; Chhuneja, P. Regulating Plant Architecture to Enhance the Future of Cereal Crop Production. *Physiol. Plant.* **2025**, *177*, e70367. [\[CrossRef\]](#) [\[PubMed\]](#)
8. Xu, T.; Wang, D.; Si, Y.; Kong, Y.; Shao, X.; Geng, Y.; Lv, Y.; Wang, Y. Plant Growth Regulators Enhance Maize (*Zea mays* L.) Yield under High Density by Optimizing Canopy Structure and Delaying Leaf Senescence. *Agronomy* **2024**, *14*, 1262. [\[CrossRef\]](#)
9. Shah, S.H.; Islam, S.; Parrey, Z.A.; Mohammad, F. Role of Exogenously Applied Plant Growth Regulators in Growth and Development of Edible Oilseed Crops Under Variable Environmental Conditions: A Review. *J. Soil Sci. Plant Nutr.* **2021**, *21*, 3284–3308. [\[CrossRef\]](#)
10. Sulistiono, W.; Sugihono, C.; Karim, A.A.; Wahab, A. *IOP Conference Series: Earth and Environmental Science*; IOP Publishing Ltd.: Bristol, UK, 2021; Volume 724, p. 012071. [\[CrossRef\]](#)
11. Rademacher, W. Chemical Regulators of Gibberellin Status and Their Application in Plant Production. In *Annual Plant Reviews Online*; Roberts, J.A., Ed.; John Wiley & Sons, Ltd.: Hoboken, NJ, USA, 2017. [\[CrossRef\]](#)
12. Anderson, N.P.; Monks, D.P.; Chastain, T.G.; Rolston, M.P.; Garbacik, C.J.; Ma, C.-H.; Bell, C.W. Trinexapac-ethyl effects on red clover seed crops in diverse production environments. *Agron. J.* **2015**, *107*, 951–956. [\[CrossRef\]](#)
13. Rademacher, W. Plant growth regulators: Backgrounds and uses in plant production. *J. Plant Growth Regul.* **2015**, *34*, 845–872. [\[CrossRef\]](#)
14. Tolbert, N.E. (2-Chloroethyl) trimethylammonium chloride and related compounds as plant growth substances.1. Chemical structure and bioassay. *J. Biol. Chem.* **1960**, *235*, 475–479. [\[CrossRef\]](#)
15. Hedden, P.; Sponsel, V. A century of gibberellin research. *J. Plant Growth Regul.* **2015**, *34*, 740–760. [\[CrossRef\]](#) [\[PubMed\]](#)
16. Green, C.F. Modifications to the growth and development of cereals using chlorocholine chloride in the absence of lodging: A synopsis. *Field Crops Res.* **1986**, *14*, 117–133. [\[CrossRef\]](#)
17. Castro-Camba, R.; Sánchez, C.; Vidal, N.; Vielba, J.M. Plant Development and Crop Yield: The Role of Gibberellins. *Plants* **2022**, *11*, 2650. [\[CrossRef\]](#) [\[PubMed\]](#)
18. Li, H.; Li, T.; Weng, W.; Cui, G.; Zhang, H.; Xing, Z.; Fu, L.; Liu, B.; Wei, H.; Zhang, H.; et al. Chlormequat Chloride and Uniconazole Regulate Lodging Resistance and Yield Formation of Wheat Through Different Strategies. *Agronomy* **2025**, *15*, 2475. [\[CrossRef\]](#)
19. Berry, P.M.; Sylvester-Bradley, R.; Berry, S. Ideotype for lodging resistant wheat. *Euphytica* **2007**, *154*, 165–179. [\[CrossRef\]](#)
20. Berry, P.M.; Spink, J.H.; Gay, A.P.; Craigan, J. A comparison of root and stem lodging risks among winter wheat cultivars. *J. Agric. Sci.* **2003**, *141*, 191–202. [\[CrossRef\]](#)
21. McCann, S.E.; Huang, B. Effects of trinexapac-ethyl foliar application on creeping bentgrass responses to combined drought and heat stress. *Crop Sci.* **2007**, *47*, 2121–2128. [\[CrossRef\]](#)

22. Etemadi, N.; Sheikh-Mohammadi, M.H.; Nikbakht, A.; Sabzalian, M.R.; Pessarakli, M. Wpływ trineksapaku etylu na poprawę odporności na suszę pszenicy i kostrzewy trzcinowej. *Acta Physiol. Plant.* **2015**, *37*, 53. [CrossRef]
23. Bian, X.; Merewitz, E.; Huang, B. Effects of trinexapac-ethyl on drought responses in creeping bentgrass associated with water use and osmotic adjustment. *J. Am. Soc. Hortic. Sci.* **2009**, *134*, 505–510. [CrossRef]
24. Burgess, P.; Huang, B. Effects of Sequential Application of Plant Growth Regulators and Osmoregulators on Drought Tolerance of Creeping Bentgrass (*Agrostis stolonifera*). *Crop Sci.* **2014**, *54*, 837–844. [CrossRef]
25. Peake, A.S.; Bell, K.L.; Fischer, R.A.; Gardner, M.; Das, B.T.; Poole, N.; Mumford, M. Cultivar $\times$ management interaction to reduce lodging and improve grain yield of irrigated spring wheat: Optimising plant growth regulator use, N application timing, row spacing and sowing date. *Front. Plant Sci.* **2020**, *11*, 401. [CrossRef] [PubMed]
26. Zhang, Y.; Su, S.; Tabori, M.; Yu, J.; Chabot, D.; Baninasab, B.; Wang, X.; Ma, B.; Li, C.; Khanizadeh, S. Effect of selected plant growth regulators on yield and stem height of spring wheat in Ontario. *J. Agric. Sci.* **2017**, *9*, 12. [CrossRef]
27. Studhalter, M.; Janovicek, K.; Kim, J.; Byker, H.; Mountain, N.; Nasielski, J. Row spacing, seeding depth, seeding rate, and trinexapac-ethyl effects on oat yield and lodging. *Crop Sci.* **2023**, *63*, 2509–2523. [CrossRef]
28. FAO. Crops and Livestock Products. Available online: https://www.fao.org/faostat/en/#rankings/countries_by_commodity (accessed on 27 July 2026).
29. Loskutov, I.G.; Shelenga, T.V.; Konarev, A.V.; Vargach, Y.I.; Porokhovinova, E.A.; Blinova, E.V.; Gnutikov, A.A.; Rodionov, A.V. Modern approach of structuring the variety diversity of the naked and covered forms of cultural oats (*Avena sativa* L.). *Ecol. Genet.* **2020**, *18*, 27–41. [CrossRef]
30. Vasilina, M.; Atanasova, D.; Savova, T. Phytosanitary status and grain quality of oat varieties grown in different farming systems. *Bulg. J. Crop Sci.* **2023**, *60*, 99–107.
31. Zhuikova, O.A.; Sheshegova, T.K.; Batalova, G.A. Bioresources of Oats for Use in Selection for Phytoimmunity to Fungal Diseases in Kirov Oblast. *Russ. Agric. Sci.* **2021**, *47*, 461–465. [CrossRef]
32. Statistics Poland. Available online: <https://dbw.stat.gov.pl/baza-danych> (accessed on 24 July 2026).
33. Mazurkiewicz, T. *Gleby i ich Właściwości/Soils and their Properties*; Wydawnictwo Uniwersyteckie: Kraków, Polska, 2011. (In Polish)
34. Lante, A.; Canazza, E.; Tessari, P. Beta-Glucans of Cereals: Functional and Technological Properties. *Nutrients* **2023**, *15*, 2124. [CrossRef] [PubMed]
35. Leszczyńska, D.; Wirkijowska, A.; Gasiński, A.; Średnicka-Tober, D.; Trafiałek, J.; Kazimierczak, R. Oat and Oat Processed Products—Technology, Composition, Nutritional Value, and Health. *Appl. Sci.* **2023**, *13*, 11267. [CrossRef]
36. Hunter, M.C.; Smith, R.G.; Schipanski, M.E.; Atwood, L.W.; Mortensen, D.A. Agriculture in 2050: Recalibrating targets for sustainable intensification. *Bioscience* **2017**, *67*, 386–391. [CrossRef]
37. Raza, A.; Razzaq, A.; Mehmood, S.S.; Zou, X.; Zhang, X.; Lv, Y.; Xu, J. Impact of Climate Change on Crops Adaptation and Strategies to Tackle Its Outcome: A Review. *Plants* **2019**, *8*, 34. [CrossRef] [PubMed]
38. Shah, K.; Chaturvedi, V.; Gupta, S. Climate change and abiotic stress-induced oxidative burst in rice. In *Advances in Rice Research for Abiotic Stress Tolerance*; Hasanuzzaman, M., Fujita, M., Nahar, K., Biswas, J.K., Eds.; Woodhead Publishing: Cambridge, MA, USA, 2019; pp. 505–535.
39. Kolmykova, T.S.; Lukatkin, A.S. Efficiency of plant growth regulators under abiotic stresses. *Agrochemistry* **2012**, *1*, 83–94. (In Russian)
40. COBORU. *Polish National List of Agricultural Plant Varieties*; Research Centre for Cultivar Testing: Słupia Wielka, Poland, 2026; pp. 60–61. (In Polish)
41. Fernandes, C.; Arruda, S.; Tejo, A.; Zucareli, P. Agronomic traits of white oat treated with the growth regulator trinexapac-ethyl. *Rev. Ceres* **2023**, *70*, 91–100. [CrossRef]
42. Meier, U. Growth stages of mono- and dicotyledonous plants. In *BBCH Monograph*; Federal Biological Research Centre for Agriculture and Forestry: Berlin/Braunschweig, Germany, 2018; p. 158. ISBN 978-3-95547-071-5. [CrossRef]
43. PN-68/R-74017; Cereals and Pulses—Determination of the Mass Od 1000 Grains. Polish Committee for Standardization: Warsaw, Poland, 1968.
44. Stewart, B.A.; Lal, R. Increasing world average yields of cereal crops: It's all about water. *Adv. Agron.* **2018**, *151*, 1–44. [CrossRef]
45. Ben Mariem, S.; Soba, D.; Zhou, B.; Loladze, I.; Morales, F.; Aranjuelo, I. Climate change, crop yields, and grain quality of C3 cereals: A meta-analysis of [CO₂], temperature, and drought effects. *Plants* **2021**, *10*, 1052. [CrossRef] [PubMed]
46. Ngoune, L.T.; Mutengwa, C.S. Factors affecting yield of crops. In *Agronomy-Climate Change & Food Security*; Amanullah, Ed.; IntechOpen: London, UK, 2020; Volume 2, pp. 1–16. [CrossRef]
47. Carrera, C.S.; Savin, R.; Slafer, G.A. Critical period for yield determination across grain crops. *Trends Plant Sci.* **2023**, *29*, 329–342. [CrossRef] [PubMed]
48. McCabe, C.P.; Burke, J.I. Oat (*Avena sativa* L.) yield and grain fill responses to varying agronomic and weather factors. *J. Agric. Sci.* **2021**, *159*, 90–105. [CrossRef]
49. Hakala, K.; Jauhiainen, L.; Rajala, A.A.; Jalli, M.; Kujala, M.; Laine, A. Different responses to weather events may change the cultivation balance of spring barley and oats in the future. *Field Crops Res.* **2020**, *259*, 107956. [CrossRef]

50. Szempliński, W.; Budzyński, W.; Bielski, S. Owies. In *Uprawa Roślin*; Kotecki, A., Ed.; Wydawnictwo Uniwersytetu Przyrodniczego we Wrocławiu: Wrocław, Poland, 2020; Volume 2, pp. 191–209. ISBN 9788377173411. (In Polish)
51. Berry, P.M. Lodging Resistance in Cereals. In *Crop Science*; Encyclopedia of sustainability science and technology series; Springer: Berlin/Heidelberg, Germany, 2019. [\[CrossRef\]](#)
52. Li, H.M.; Cui, G.G.; Li, G.Y.; Lu, H.; Wei, H.Y.; Zhang, H.P.; Zhang, H.C. Assessing the efficacy and residual impact of plant growth retardants on crop lodging and overgrowth. A review. *Eur. J. Agron.* **2024**, *159*, 127276. [\[CrossRef\]](#)
53. Rajala, A.; Peltonen-Sainio, P. Timing applications of growth regulators to alter spring cereal development at high latitudes. *Agric. Food Sci.* **2002**, *11*, 233–244. [\[CrossRef\]](#)
54. Rajala, A. Plant growth regulators to manipulate oat stands. *Agric. Food Sci.* **2004**, *13*, 186–197. [\[CrossRef\]](#)
55. Matysiak, K.; Kaczmarek, S.; Adamczewski, K. The influence of trinexapac-ethyl, chlorocholine chloride, metconazole and tebuconazole on plant morphology and yield of winter oilseed rape depending on time of application. *Oilseed Crops* **2010**, *31*, 361–371.
56. Matysiak, K.; Skrzypczak, W.; Kaczmarek, S. Porównanie sposobów stosowania regulatorów wzrostu i rozwoju w życie ozimym. *Fragm. Agron.* **2013**, *30*, 78–91. (In Polish)
57. Sadras, V.O.; Slafer, G.A. Environmental modulation of yield components in cereals: Heritabilities reveal a hierarchy of phenotypic plasticities. *Field Crops Res.* **2012**, *127*, 215–224. [\[CrossRef\]](#)
58. Juzoń-Sikora, K.; Laskoś, K.; Warchoń, M.; Czyczyło-Mysza, I.M.; Dziurka, K.; Grzesiak, M.; Skrzypek, E. Water Relations and Physiological Traits Associated with the Yield Components of Winter Wheat (*Triticum aestivum* L.). *Agriculture* **2024**, *14*, 1887. [\[CrossRef\]](#)
59. Chen, H.; Huang, W.; Li, W.; Niu, Z.; Zhang, L.; Xing, S. Estimation of LAI in Winter Wheat from Multi-Angular Hyperspectral VNIR Data: Effects of View Angles and Plant Architecture. *Remote Sens.* **2018**, *10*, 1630. [\[CrossRef\]](#)
60. Dereń, K.; Szewczyk, A.; Łuczycka, D.; Cieniawska, B. Deposition of copper depending on the spraying characteristics of winter oilseed rape. *J. Res. Appl. Agric. Eng.* **2018**, *63*, 13–17.
61. Chen, J.M.; Black, T.A. Defining leaf area index for non-flat leaves. *Plant Cell Environ.* **1992**, *15*, 421–429. [\[CrossRef\]](#)
62. Zou, X.; Haikarainen, I.; Haikarainen, I.P.; Mäkelä, P.; Möttus, M.; Pellikka, P. Effects of crop leaf angle on LAI-sensitive narrow-band vegetation indices derived from imaging spectroscopy. *Appl. Sci.* **2018**, *8*, 1435. [\[CrossRef\]](#)
63. Fang, H.; Baret, F.; Plummer, S.; Schaepman-Strub, G. An overview of global leaf area index (LAI): Methods, products, validation, and applications. *Rev. Geophys.* **2019**, *57*, 739–799. [\[CrossRef\]](#)
64. Sattar, A.; Cheema, M.A.; Sher, A.; Abbas, T.; Ijaz, M.; Ul-Allah, S.; Butt, M.; Qayyum, A.; Hussain, M. Exogenously Applied Trinexapac-ethyl Improves Photosynthetic Pigments, Water Relations, Osmoregulation and Antioxidants Defense Mechanism in Wheat under Salt Stress. *Cereal Res. Commun.* **2019**, *47*, 430–441. [\[CrossRef\]](#)
65. Bin, H.; Min, Z.; Yan-long, W.; Yu-Shou, M.; Ying, L. Effects of Four Plant Growth Regulators on Photosynthesis and Yield of *Deschampsia cespitosa*. *Russ. J. Plant Physiol.* **2023**, *70*, 151. [\[CrossRef\]](#)
66. Zhao, D.; Zhu, K.; LaBorde, C. Sugarcane growth, physiological and yield responses to application of trinexapac-ethyl (Moddus™) in grand growth phase. *J. Plant Growth Regul.* **2023**, *42*, 2813. [\[CrossRef\]](#)
67. Barányiová, K.; Klem. Effect of application of growth regulators on the physiological and yield parameters of winter wheat under water deficit. *Plant Soil Environ.* **2016**, *62*, 114–120. [\[CrossRef\]](#)
68. Park, B.; Wi, S.; Chung, H.; Lee, H. Chlorophyll Fluorescence Imaging for Environmental Stress Diagnosis in Crops. *Sensors* **2024**, *24*, 1442. [\[CrossRef\]](#) [\[PubMed\]](#)
69. Goltsev, V.N.; Kalaji, H.M.; Paunov, M.; Baba, W.; Horaczek, T.; Mojski, J.; Kociel, H.; Allakhverdiev, S.I. Variable chlorophyll fluorescence and its use for assessing physiological condition of plant photosynthetic apparatus. *Russ. J. Plant Physiol.* **2016**, *63*, 869–893. [\[CrossRef\]](#)
70. Brestic, M.; Zivcak, M. PSII fluorescence techniques for measurement of drought and high temperature stress signal in plants: Protocols and applications. In *Molecular Stress Physiology of Plants*; Rout, G.R., Das, A.B., Eds.; Springer: Dordrecht, The Netherlands, 2013; pp. 87–131.
71. Kalaji, H.M.; Jajoo, A.; Oukarroum, A.; Brestic, M.; Zivcak, M.; Samborska, I.A.; Cetner, M.D.; Łukasik, I.; Goltsev, V.; Ladle, R.J. Chlorophyll a fluorescence as a tool to monitor physiological status of plants under abiotic stress conditions. *Acta Physiol. Plant.* **2016**, *38*, 102. [\[CrossRef\]](#)
72. Murkowski, A. Oddziaływanie Czynn timerów Stresowych na Luminescencje Chlorofilu w Aparacie Fotosyntetycznym Roslin Uprawnych (Effects of Stress Factors on Chlorophyll Luminescence—Study of Plant Photosynthetic Apparatus), Monogr. 61; Instytut Agrofizyki im. Bohdana Dobrzańskiego: Lublin, Poland, 2002. (In Polish)
73. Maxwell, K.; Johnson, G.N. Chlorophyll fluorescence—A practical guide. *J. Exp. Bot.* **2000**, *51*, 659–668. [\[CrossRef\]](#) [\[PubMed\]](#)
74. Force, L.; Critchley, C.; van Rensen, J.J. Nowe parametry fluorescencji do monitorowania fotosyntezy u roślin. *Photosynth. Res.* **2003**, *78*, 17–33. [\[CrossRef\]](#) [\[PubMed\]](#)

75. Kalaji, H.M.; Baba, W.; Gediga, K.; Goltsev, V.; Samborska, I.A.; Cetner, M.D.; Dimitrova, S.; Piszcz, U.; Bielecki, K.; Karmowska, K.; et al. Chlorophyll fluorescence as a tool for nutrient status identification in rapeseed plants. *Photosynth. Res.* **2018**, *136*, 329–343. [[CrossRef](#)] [[PubMed](#)]
76. Bates, H.; Zavafer, A.; Szabó, M.; Ralph, P.J. The slow-phase of chlorophyll fluorescence induction curve reflects the electron transport rates of Photosystem II in vivo in *Chlorella vulgaris*. *J. Appl. Phycol.* **2023**, *35*, 109–116. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.