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Effect of trinexapac-ethyl application rate and timing on the yield and physiological quality of white oat seeds

Efeito da dose e época de aplicação de trinexapac-ethyl na produtividade e qualidade fisiológica de sementes de aveia branca

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Highlights

Trinexapac-ethyl application affected the physiological quality of white oat seeds.
Application timing had a strong impact on all examined variables.
This study presents important findings for the management of oat crops.

Abstract

Growth regulators can mitigate lodging damage. However, their effects on the physiological quality of seeds are not widely known. This study aimed to assess the effects of trinexapac-ethyl application rate and timing on the yield and physiological quality of white oat seeds. The experiment was conducted in Londrina, Paraná, Brazil, in the 2019 and 2020 cropping seasons using a randomized block design with a 4 × 3 factorial arrangement and four replications. Treatments consisted of four trinexapac-ethyl rates (0, 50, 100, and 150 g ha^{-1}) and three application timings (E_1, first node detectable; E_2, stem elongation phase from first node visible to second node detectable; and E_3, second node visible to third node detectable). Seed yield, thousand seed weight, germination rate, seedling length, seedling dry weight, accelerated aging, electrical conductivity, and seedling emergence in sand were evaluated. The results showed that trinexapac-ethyl at 100 and 150 g ha^{-1} at E_2 and E_3 increased seed yield in white oat IPR Artemis. However, all rates negatively affected thousand seed weight, germination rate, and seed vigor, reducing the establishment capacity and initial development of white oat plants.

Key words: *Avena sativa* L. Germination. Growth reducer. Lodging. Vigor.

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Resumo

Uso de reguladores de crescimento podem mitigar danos provocados pelo acamamento. No entanto, seus efeitos na qualidade fisiológica de sementes não são amplamente conhecidos. O objetivo deste trabalho foi avaliar o efeito de diferentes doses e épocas de aplicação do trinexapac-etil na produtividade e na qualidade fisiológica de sementes de aveia branca. O experimento foi conduzido no município de Londrina-PR, nas safras 2019 e 2020, sob o delineamento experimental de blocos ao acaso com quatro repetições, em esquema fatorial 4 x 3, sendo quatro doses de trinexapac-etil (0, 50, 100 e 150 g ha^{-1}) e três épocas de aplicação (E_1: plantas com o 1º nó perceptível; E_2: plantas na fase de elongação do colmo, entre o 1° nó visível e o 2° nó perceptível e E_3: plantas com o 2º nó visível e 3º nó perceptível). Foram avaliados: produtividade de sementes, massa de mil sementes, germinação, comprimento e massa seca de plântulas, envelhecimento acelerado, condutividade elétrica e emergência de plântulas em areia. Ao término do estudo verificou-se que a aplicação do trinexapac-etil nas doses de 100 e 150 g ha^{-1} nas épocas de aplicação E_2 e E_3 aumentou a produtividade de sementes da cultivar IPR Artemis, porém todas as doses de trinexapac-etil afetou a massa de mil sementes, a porcentagem de germinação e o vigor destas, reduzindo a capacidade de estabelecimento e desenvolvimento inicial das plantas.
Palavras-chave: *Avena sativa* L. Acamamento. Germinação. Redutor de crescimento. Vigor.

Introduction

White oat (Avena sativa L.) genotypes have been selected over several years for rapid growth in the early stages of development, favoring competition against weeds (Kaspary et al., 2015). However, when grown at high densities and under high rates of nitrogen fertilizer, oat crops frequently experience lodging, adversely impacting seed yield and physiological quality (Barbosa et al., 2022; Silva et al., 2014). When lodging occurs in the maturation phase, negative effects include exposure to disease-causing conditions, germination losses, and seed rotting, as well as difficulties related to mechanized harvesting. Therefore, application of growth regulators has become a common practice to control lodging (Bazzo et al., 2018). Growth regulators reduce plant height and minimize the risk of lodging throughout the crop cycle, potentially contributing to the production of seeds with high physiological quality (Fernandes et al., 2023; McMillan et al., 2020).

One of the main growth regulators applied to winter cereals is trinexapac-ethyl. It reduces internode elongation, increases stem diameter, and alters leaf architecture. The molecule inhibits the enzyme 3β-hydroxylase, acting at the end of the biosynthetic pathway of gibberellic acid, a hormone that induces internode elongation. The effect is a drastic reduction in the levels of active gibberellic acid (GA1), accompanied by an increase in the levels of its immediate biosynthetic precursor GA20. This drop in GA1 levels is responsible for the inhibition of plant growth (Rademacher, 2000).

In addition to reducing crop height and lodging damage, growth regulators are applied to modify plant architecture. A notable effect of this class of compounds is observed in the flag leaf, which grows more upright, improving the use of environmental resources, particularly solar radiation (Penckowski & Fernandes, 2010). Ultimately, these effects can alter the partitioning of photoassimilates, improving seed filling and the physiological quality of seeds (Fernandes et al., 2023).

A study carried out by Carvalho and Nakagawa (2012) reported that all batches of white oat seeds treated with trinexapac-ethyl exceeded the minimum germination rate requirement for sale (80%) set by the Brazilian Ministry of Agriculture, Livestock, and Food Supply (MAPA). By contrast, Bazzo et al. (2018) reported that 100 g ha−1 trinexapac-ethyl applied to white oat crops between the first visible node and the second detectable node stages reduced the seed vigor of cultivars IPR Afrodite and IPR Artemis grown respectively in Londrina and Mauá da Serra, Paraná, Brazil. In a study investigating the effects of trinexapac-ethyl on wheat, Zagonel and Fernandes (2007) observed that application rate and timing must be specifically determined for each cultivar, particularly in the case of crops with high susceptibility to lodging. Nevertheless, the authors concluded that the best results are obtained when the growth regulator is applied between the first and second detectable node stages at a rate of 100 g ha^{-1}. This recommendation does not take into account the unique characteristics of each cultivar and growing environment but may serve as a general guideline to minimize the negative effects of lodging and enhance seed yield and physiological quality.

In view of the above, this study aimed to examine the effects of application rate and timing of trinexapac-ethyl on the yield and physiological quality of white oat seeds.

Material and Methods

The experiment was conducted in the 2019 and 2020 cropping seasons at the Experimental Station of the Paraná Institute of Rural Development (IDR-Paraná), Paraná Agricultural Institute (IAPAR), Technical Assistance and Rural Extension Agency of Paraná State (EMATER), Londrina, Paraná, Brazil (23°23'S 51°11'W, 610 m a.s.l.). The soil was an eutroferric Red Latosol. The climate is of the Cfa type (Köppen system), classified as humid subtropical with hot summers (Empresa Brasileira de Pesquisa Agropecuária [EMBRAPA], 2018). The maximum and minimum temperatures and rainfall during the experiment are shown in Figure 1.

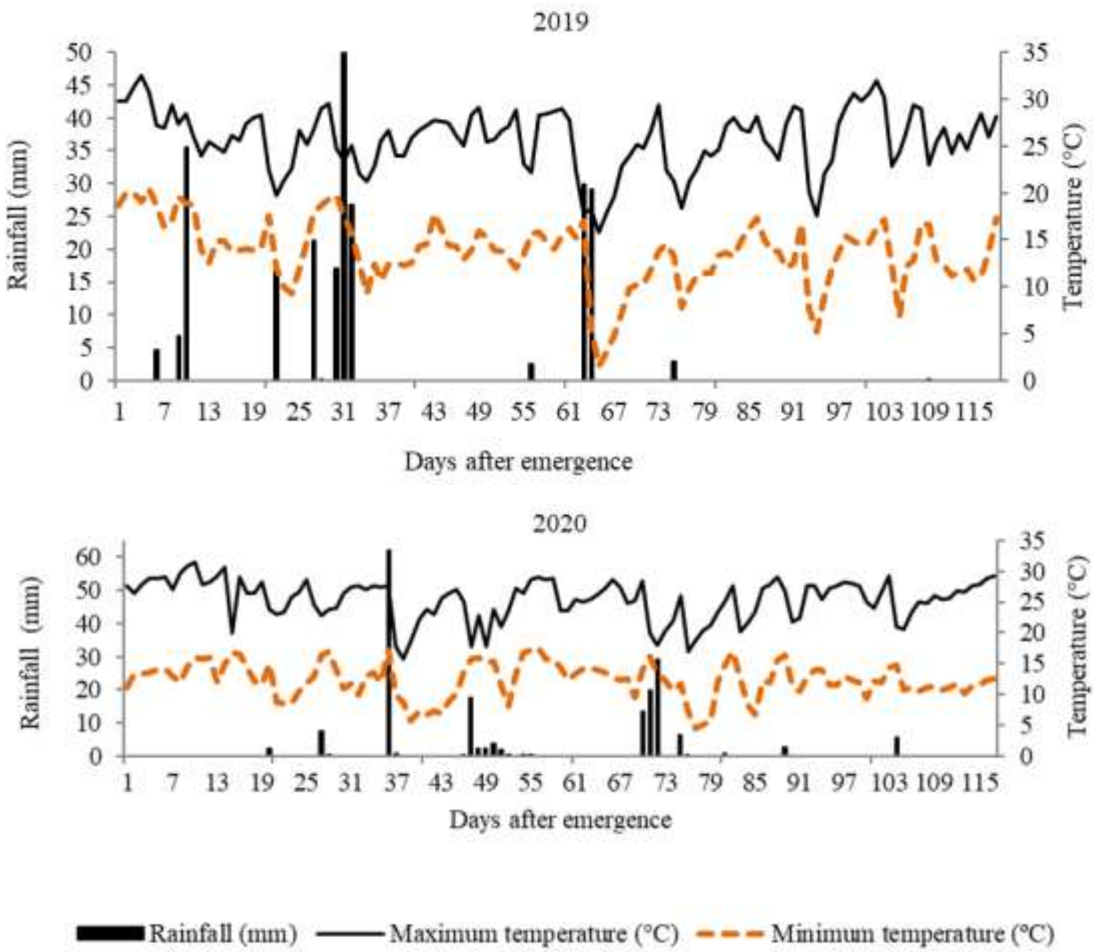

Figure 1. Daily temperature and rainfall in Londrina, PR, Brazil during the experimental period (2019 and 2020 cropping seasons).

Soil chemical properties in the 0–20 cm layer were determined before installation of the experiments. In 2019, chemical analysis showed the following results: pH ($CaCl_2$) 5.00, 5.21 $cmol_c$ dm^{-3} H + Al^{3+}, 5.31 $mmol_c$ dm^{-3} Ca^{2+}, 0.98 $mmol_c$ dm^{-3} Mg^{2+}, 0.59 $mmol_c$ dm^{-3} K^+, 29.33 mg dm^{-3} P, and 16.98 g dm^{-3} organic matter. In 2020, soil properties were as follows: pH ($CaCl_2$) 4.85, 5.96 $cmol_c$ dm^{-3} H + Al^{3+}, 5.76 $mmol_c$ dm^{-3} Ca^{2+}, 0.65 $mmol_c$ dm^{-3} Mg^{2+}, 0.61 $mmol_c$ dm^{-3} K^+, 31.09 mg dm^{-3} P, and 15.92 g dm^{-3} organic matter.

The experiment was conducted using the grain oat cultivar IPR Artemis, launched by IAPAR in 2016. This cultivar has a medium cycle (117 days on average), moderate resistance to lodging, and a mean height of 100 cm. Mechanized sowing was carried out under a no-tillage system, in succession to soybean (*Glycine max* L.) crops in both years. The first crop was sown on May 3, 2019, emerged on May 14, 2019, and was harvested on August 28, 2019. The second crop was sown on April 17, 2020, emerged on April

25, 2020, and was harvested on August 11, 2020. Basal fertilization consisted of applying 200 kg ha^{-1} NPK (10-30-10). Nitrogen top dressing was carried out at a rate of 54 kg ha^{-1}, split between two applications, namely 27 kg ha^{-1} applied 10 days after emergence and 27 kg ha^{-1} applied 5 days later. Nitrogen fertilizer was broadcast manually. Control of leaf diseases and cultural treatments were carried out as needed, according to the technical recommendations of IDR-Paraná for oat crops.

Each experimental unit (plot) consisted of six 5 m long rows spaced 0.17 m apart. Plants were sown at a density of 300 viable seeds m^{-2}. The four central rows of each plot were treated as useful area. Treatments followed a randomized block design with a 4 × 3 factorial arrangement and four replications. The levels were four trinexapac-ethyl rates (0, 50, 100, and 150 g a.i. ha^{-1}, Moddus®, Syngenta) and three application timings (E_1, first node detectable; E_2, stem elongation phase from first node visible to second node detectable; and E_3, second node visible to third node detectable). The growth regulator was applied at a spray volume of 200 L ha^{-1} by using a CO_2-pressurized backpack sprayer at constant pressure (30 lb in^{-2}) equipped with two flat fan jet nozzles (XR 110-020).

Plants were harvested at seed maturity using a self-propelled harvester. The seed maturity stage is characterized by the hardening of the caryopsis, a dry appearance in plants, and seeds with a moisture content below 20%. Subsequently, seeds were cleaned and evaluated for the following parameters:

- Seed yield: determined by harvesting all seeds from plants in the useful area of each plot (3.4 m^{-2}). After mechanical threshing, the seeds were weighed, and the data transformed to kg ha^{-1} at 13% moisture.
- Thousand seed weight (TSW): determined by counting and weighing eight replicates of 100 seeds per plot. The average value was multiplied by 10 to obtain TSW.
- Germination rate: analyzed on eight replications of 50 seeds each. Seeds were placed on Germitest® paper and moistened with distilled water at a ratio of 2.5:1 (water/substrate). The germination papers were rolled into a cylinder and placed in a germinator at 20 °C. Germinated seedlings were counted at 5 (first count) and 10 (second count) days after sowing. The results are presented as percentage.
- Seedling length: evaluated on four replications of 20 seeds per treatment. Seeds were sown in the upper third part of a Germitest® paper and moistened with distilled water at a ratio of 2.5:1 (water/substrate). The paper rolls containing oat seeds were placed in a germinator for 5 days at 20 °C, after which normal seedlings were measured for length by using a millimeter ruler. Normal seedlings were defined as seedlings having all essential organs well developed and without abnormalities, including the primary root, epicotyl, and primary leaves. Results are presented as the mean of replicates and expressed in centimeters.

- Seedling dry weight: determined together with seedling length. After length measurements were taken, normal seedlings were cut and separated from the remaining tissues (storage tissues). Shoots were placed in paper bags and dried in a forced-circulation oven at 80 °C for 24 h. At the end of this period, shoot dry weight was measured to the nearest 0.0001 g. Results are expressed in milligrams.
- Accelerated aging: analyzed on four replications per treatment in 250 mL germination boxes measuring 11 × 11 × 3.5 cm and containing 40 mL of water and an aluminum screen, on which 240 seeds per treatment were evenly distributed. The boxes were kept in an accelerated aging chamber at 42 °C for 48 h. Then, seeds were subjected to a germination test at 20 °C. The number of normal seedlings was counted 5 days after sowing.
- Electrical conductivity: analyzed on four replications of 50 seeds each. Seeds were weighed, placed in plastic cups containing 75 mL of deionized water, and incubated at 25 °C. After 24 h, the electrical conductivity of the solution was determined. Results are expressed in μS cm^{-1} g^{-1}.
- Seedling emergence in sand: determined on four replications of 50 seeds per treatment. Prior to its use in the experiment, the sand substrate was washed and distributed in plastic trays. Then, seeds were sown and covered with a 3 cm layer of sand. Trays were placed in a greenhouse. Irrigation was performed according to crop requirements. The number of normal seedlings was counted at 15 days after sowing.

The data were tested for normality and homogeneity of variance. Subsequently, the data were subjected to analysis of variance. Means were compared by Tukey's test and subjected to regression analysis up to the second order at $p < 0.05$. All statistical analyses were performed using Genes software (Cruz, 2013).

Results and Discussion

Analysis of variance showed that IPR Artemis was affected by the interaction of trinexapac-ethyl rate and timing in 2019, influencing thousand seed weight, germination, SDW, accelerated aging, electrical conductivity, and seedling emergence in sand. Additionally, the main effects of trinexapac-ethyl application timing and rate influenced seed yield, first count, and seedling length. In the 2020 season, a significant interaction effect was observed on germination, first count, shoot length, accelerated aging, electrical conductivity, and seedling emergence. Seed yield and SDW were influenced by the main effects of trinexapac-ethyl application timing and rate. Thousand seed weight was not significantly affected by any of the factors or their interaction. The estimated environmental variation coefficients in 2019 and 2020 ranged from 2.19 to 13.41, indicating good to moderate experimental accuracy (Table 1).

Table 1
Analysis of variance and coefficient of variation for yield and growth variables of white oat IPR Artemis as a function of trinexapac-ethyl application rate and timing in Londrina, PR, Brazil, in the 2019 and 2020 cropping seasons

Season	Variable	Mean square					CV (%)	Overall mean
		Block	Rate (R)	Timing (T)	R × T	Residuals		
2019	SY	16474.5^{ns}	177299.78**	145372.58*	59373.36^{ns}	28014.07	3.23	5175.72
	TSW	0.61^{ns}	22.05**	3.51**	4.57**	0.44	2.19	30.5
	GR	6.38^{ns}	429.28**	120.89**	52.09^{ns}	11.34	3.72	90.42
	FGC	10.58^{ns}	348.74**	29.44^{ns}	37.4^{ns}	19.44	5.37	82.06
	SL	14.09^{ns}	14.82**	5.59^{ns}	4.71^{ns}	2.08	6.46	22.28
	SDW	0.00ns	0.00*	0.00**	0.00^{ns}	0.00	7.72	0.18
	AA	52.69^{ns}	394.13**	136.27**	81.38**	15.38	4.8	81.64
	EC	393.03^{ns}	3312.41**	1332.88**	696.91**	87.75	5.33	175.45
	SE	27.47^{ns}	217.03**	97.64**	69.01**	15.37	4.58	85.54
2020	SY	378794.31^{ns}	130429.97^{ns}	641315.66*	183394.04^{ns}	126793.39	6.17	5764.77
	TSW	2.64^{ns}	12.95^{ns}	9.10^{ns}	3.64^{ns}	5.51	7.31	32.11
	GR	31.64^{ns}	855.64**	589.75**	186.3**	11.69	3.85	88.62
	FGC	12.08^{ns}	1502.97**	789.75**	260.64**	18.26	8.23	51.88
	SL	1.64^{ns}	10.19**	7.21**	2.83^{ns}	0.52	4.77	15.18
	SDW	0.00^{ns}	0.00*	0.00**	0.00**	0.00	13.41	0.12
	AA	29.41^{ns}	267.85**	143.91**	57.89**	11.04	4.11	80.72
	EC	51.97^{ns}	895.21**	410.98**	260.49**	50.46	6.91	102.88
	SE	5.35^{ns}	302.91**	59.77*	48.49*	16.51	4.86	83.48

* $p < 0.05$ and ** $p < 0.01$ (*F*-test); ns, not significant; SY, seed yield (kg ha^{-1}); TSW, thousand seed weight (g); GR, germination rate (%); FGC, first germination count (%); SL, seedling length (cm); SDW, seedling dry weight (mg); AA, accelerated aging (%); EC, electrical conductivity (μS cm^{-1} g^{-1}); SE, seedling emergence in sand (%).
Degrees of freedom: block, 3; rate, 3; timing, 2; R × T, 6; residuals, 33.

Trinexapac-ethyl rate positively influenced the seed yield of IPR Artemis in 2019 (Table 2 and Figure 2A). Application of 150 g ha^{-1} trinexapac-ethyl at E_2 led to an increase in seed yield. However, for plants treated at E_3, the increase in seed yield was observed from a rate of 100 g ha^{-1} and higher. On the other hand, in the 2020 season, plants treated at E_3 showed a higher seed yield than those treated at E_1 and E_2, regardless of trinexapac-ethyl rate (Table 2 and Figure 2B). The mean seed yields in 2020 were 5927, 5541, and 5826 kg ha^{-1} in E_3, E_1, and E_2 groups, respectively. Bazzo et al. (2019) observed similar results in studying different cultivars of white oat treated with varying trinexapac-ethyl and nitrogen rates in two cultivation environments (Mauá da Serra and Londrina, Paraná State). White oat IPR Afrodite treated with trinexapac-ethyl exhibited increased seed yield. Hawerroth et al. (2015) analyzed the effect of trinexapac-ethyl rate and timing on white oat 'Barbarasul' grown in different environments under different nitrogen rates. The authors observed that yield showed a positive or insignificant response to trinexapac-ethyl application depending on the locality. Overall, the increase in yield observed here may be attributed to the reduction in plant height and lodging and the increase in the number of panicles per square meter. Furthermore, the growth regulator may induce positive changes in leaf architecture (Penckowski & Fernandes, 2010).

Table 2

Seed yield, germination rate, thousand seed weight, accelerated aging, electrical conductivity, and seedling emergence of white oat IPR Artemis as a function of trinexapac-ethyl application rate and timing in Londrina, PR, Brazil, in the 2019 and 2020 cropping seasons

Variable	Application timing	2019				2020			
		Trinexapac-ethyl rate (g ha^{-1})				Trinexapac-ethyl rate (g ha^{-1})			
		0	50	100	150	0	50	100	150
SY (kg ha^{-1})	E_1	5062 a	5078 a	5090 b	5090 b	5621 a	5525 a	5781 a	5235 b
	E_2	5095 a	5067 a	5104 b	5436 a	5772 a	5609 a	5838 a	6084 a
	E_3	5090 a	5093 a	5419 a	5480 a	5791 a	5772 a	5989 a	6154 a
GR (%)	E_1	95.0 a	96.0 a	91.3 a	91.5 a	95.5 a	96.0 a	95.0 a	93.0 a
	E_2	96.0 a	94.5 a	89.5 ab	79.0 b	95.5 a	96.5 a	84.0 b	77.0 b
	E_3	95.0 a	94.5 a	85.0 b	77.8 b	95.0 a	94.0 a	78.0 c	64.0 c
SDW (mg)	E_1	0.18 a	0.20 a	0.18 a	0.20 a	0.14 a	0.15 a	0.13 a	0.13 a
	E_2	0.18 a	0.19 a	0.17 a	0.16 b	0.14 a	0.14 a	0.14 a	0.09 b
	E_3	0.18 a	0.18 a	0.17 a	0.16 b	0.14 a	0.15 a	0.10 b	0.08 b
AA (%)	E_1	87.0 a	85.0 a	82.5 a	85.5 a	84.5 a	85.0 a	85.0 a	81.8 a
	E_2	85.5 a	86.5 a	76.5 ab	72.5 b	84.5 a	83.5 a	79.0 b	72.5 b
	E_3	87.0 a	88.5 a	73.3 b	70.0 b	87.0 a	83.0 a	72.0 c	71.0 b
CE (µS cm^{-1} g^{-1})	E_1	167.0 a	160.9 a	167.8 b	172.1 b	97.8 a	96.9 a	97.3 b	97.3 b
	E_2	160.5 a	161.2 a	169.9 b	205.7 a	93.3 a	97.7 a	104.5 ab	120.5 a
	E_3	162.9 a	162.2 a	201.6 a	213.6 a	98.2 a	92.6 a	113.6 a	124.5 a
SE (%)	E_1	88.5 a	88.0 a	87.5 a	88.3 a	88.0 a	87.0 a	83.0 a	84.5 a
	E_2	88.0 a	90.0 a	86.3 a	77.5 b	88.7 a	90.5 a	81.0 a	75.5 b
	E_3	89.5 a	88.5 a	79.0 b	74.5 b	89.5 a	86.5 a	78.0 a	73.5 b

Means within columns followed by the same lowercase letter are not significantly different by Tukey's test ($p < 0.05$). E_1, first node detectable; E_2, stem elongation phase from first node visible to second node detectable; and E_3, second node visible to third node detectable; SY, seed yield; GR, germination rate; SDW, seedling dry weight (mg); AA, accelerated aging; EC, electrical conductivity; SE, seedling emergence in sand (%).

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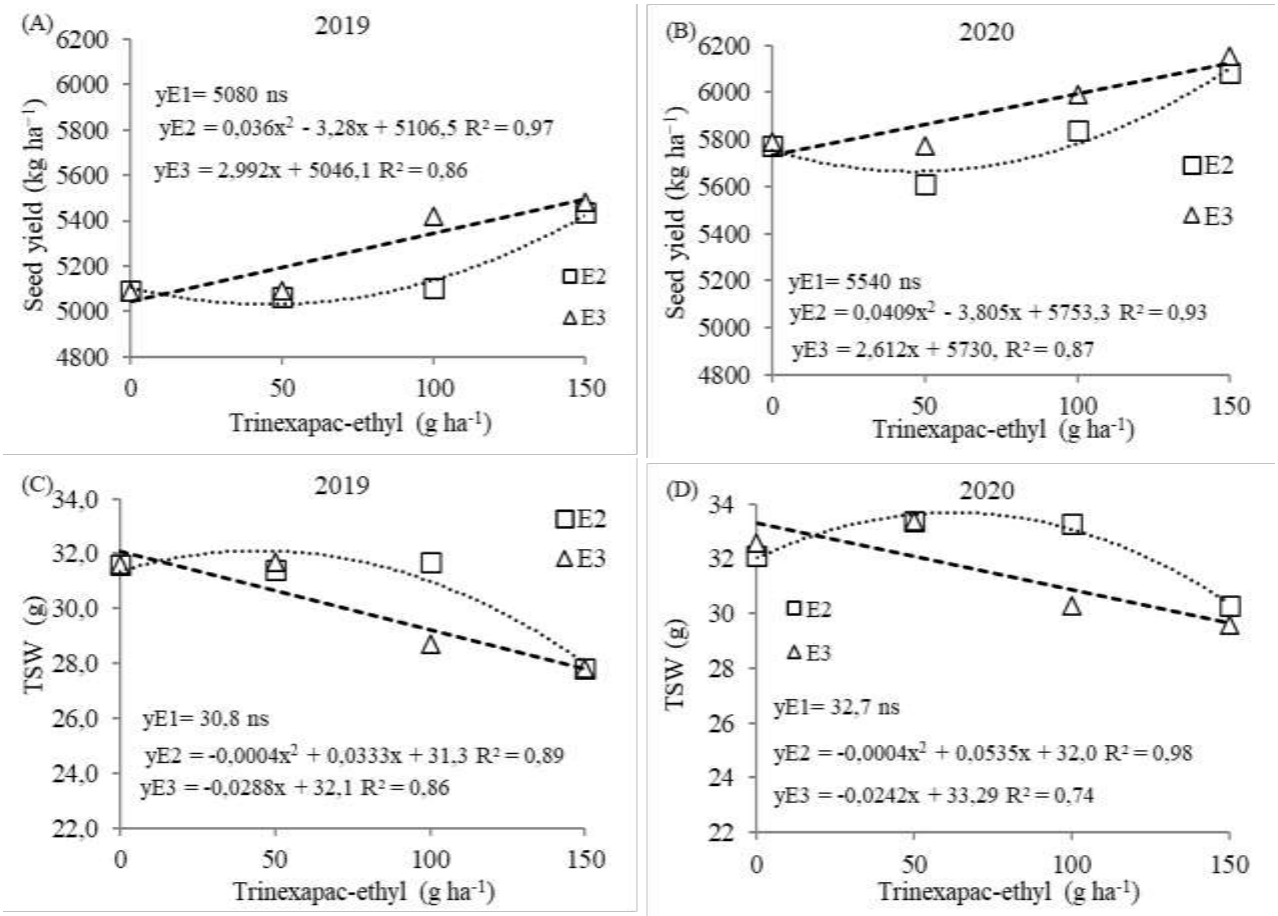

Figure 2. Seed yield and thousand seed weight (TSW) of white oat IPR Artemis as a function of trinexapac-ethyl application rate and timing in Londrina, PR, Brazil, in the 2019 and 2020 cropping seasons. ns, not significant; E1, first node detectable; E2, stem elongation phase from first node visible to second node detectable; and E3, second node visible to third node detectable.

Thousand seed weight was negatively influenced by trinexapac-ethyl application in the 2019 season (Table 3 and Figure 2C). Trinexapac-ethyl application at E_2 and a rate of 150 g ha^{-1} provided a reduction of 11.54% in thousand seed weight compared with 0 g ha^{-1} trinexapac-ethyl. Plants treated with 100 g ha^{-1} at E_3 showed a 10.11% reduction in the parameter. Bazzo et al. (2019) found that IPR Artemis grown in Mauá da Serra exhibited a reduction in thousand seed weight with trinexapac-ethyl application. Kaspary et al. (2015) reported that 150 g ha^{-1} trinexapac-ethyl affected thousand seed weight in white oat cultivars. The reduction in thousand seed weight indicates lower amounts of reserves in seeds, which may affect germination and vigor. Generally, seeds with more vigor can germinate and emerge more quickly under adverse conditions (Vieira & Krzyzanowski, 1999).

Table 3
Thousand seed weight of white oat IPR Artemis as a function of trinexapac-ethyl application rate and timing in Londrina, PR, Brazil, in the 2019 cropping season

Variable	Application timing	Trinexapac-ethyl rate (g ha^{-1})			
		0	50	100	150
Thousand seed weight (g)	E_1	31.1 a	31.1 a	31.1 a	30.1 a
	E_2	31.6 a	31.4 a	31.7 a	27.8 b
	E_3	31.6 a	31.7 a	28.7 b	27.8 b

Means within columns followed by the same lowercase letter are not significantly different by Tukey's test ($p < 0.05$).
E_1, first node detectable; E_2, stem elongation phase from first node visible to second node detectable; and E_3, second node visible to third node detectable.

The physiological quality of seeds produced from plants treated with different trinexapac-ethyl rates showed that seed potential decreased linearly with increasing application time. Germination rate (Table 2 and Figure 3A and B) had an inverse relationship with trinexapac-ethyl rate. In 2019, germination rate was influenced by trinexapac-ethyl rate and timing (Table 2 and Figure 3A). Among plants treated at E_1, the effect of trinexapac-ethyl rate on germination was nearly non-significant, not modifying the characteristic. However, trinexapac-ethyl application at E_2 and E_3 resulted in a marked reduction in germination at 100 g ha^{-1} and even more so at 150 g ha^{-1}. Similar patterns were observed in 2020 (Table 2 and Figure 3B).

The lower performance of seeds from plants treated with the growth regulator may be attributed to the reduction in seed filling. Gustafson et al. (2004) underscored that rapid development and initial establishment are essential for white oat to gain competitive advantages for the use of environmental resources. This may help minimize competition with weeds, allowing the crop to achieve its productive potential. Thus, the negative effects of trinexapac-ethyl on white oat seed vigor may impact initial crop development.

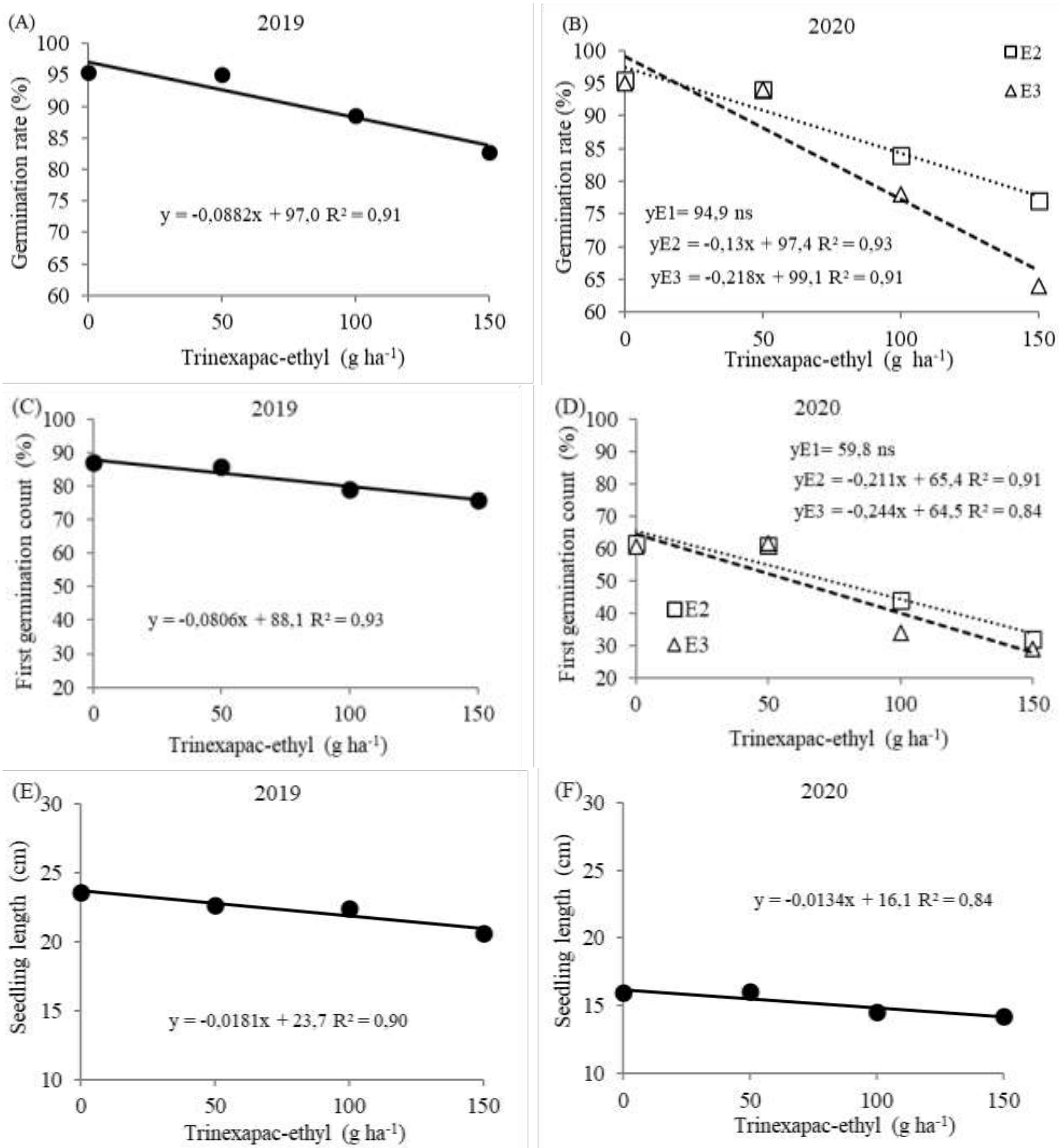

Figure 3. Germination rate, first germination count, and seedling length of white oat IPR Artemis as a function of trinexapac-ethyl application rate and timing in Londrina, PR, Brazil, in the 2019 and 2020 cropping seasons. E_1, first node detectable; E_2, stem elongation phase from first node visible to second node detectable; and E_3, second node visible to third node detectable.

The relationship of first germination count with trinexapac-ethyl rate in 2019 was explained by a decreasing linear equation for the three application timings (Figure 3C). As depicted in Table 4, in the 2020 season, among plants treated at E_1, first count was not influenced by trinexapac-ethyl rate. However, for the E_2 group, first count reduced drastically with trinexapac-ethyl rate, being 60.7% in the control and 32.0% in the 150 g ha^{-1} treatment. A similar behavior was observed for E_3. Therefore, it can be said that high rates of trinexapac-ethyl result in less vigorous seeds. Seedling length data in 2019 were explained by a decreasing linear function (Figure 3E and F). In 2020, seedling length reduced more markedly from trinexapac-ethyl rates of 100 g ha^{-1} and higher applied at E2 or E3. Increasing rates of the growth regulator led to increasing reductions in seedling length.

Table 4

First germination count and seedling length of white oat IPR Artemis as a function of trinexapac-ethyl application rate and timing in Londrina, PR, Brazil, in the 2020 cropping season

Variable	Application timing	Trinexapac-ethyl rate (g ha^{-1})			
		0	50	100	150
First germination count (%)	E_1	60.0 a	63.5 a	58.0 a	57.5 a
	E_2	61.5 a	61.0 a	44.0 b	32.0 b
	E_3	60.5 a	61.5 a	34.0 c	29.0 b
Seedling length (cm)	E_1	15.8 a	16.2 a	15.9 a	15.8 a
	E_2	15.9 a	16.1 a	14.5 b	13.4 b
	E_3	16.2 a	15.8 a	13.2 c	13.5 b

Means within columns followed by the same lowercase letter are not significantly different by Tukey's test ($p < 0.05$).
E_1, first node detectable; E_2, stem elongation phase from first node visible to second node detectable; and E_3, second node visible to third node detectable.

SDW was negatively affected by trinexapac-ethyl rates of 100 g ha^{-1} or greater at E_2 or E_3 in 2019 (Table 2 and Figure 4A). In 2020, the SDW of plants treated with 150 g ha^{-1} at E_2 decreased by 35.71% compared with the control. For the E_3 group, reductions in SDW were observed from 100 g ha^{-1} onward, being similar to the results obtained in the E_2 treatment at 150 g ha^{-1} (Table 2 and Figure 4B). Bazzo et al. (2018) also found that trinexapac-ethyl negatively influenced SDW in white oat. Martins et al. (2021), in studies on the effects of TE in upland rice cultivars, verified that doses above 75 g ha^{-1} cause a reduction in the thousand grain weight, associated with the application period. Kaspary et al. (2015) reported that the use of 150 g of TE ha^{-1} interfered in the thousand grain weight of white oat cultivars.

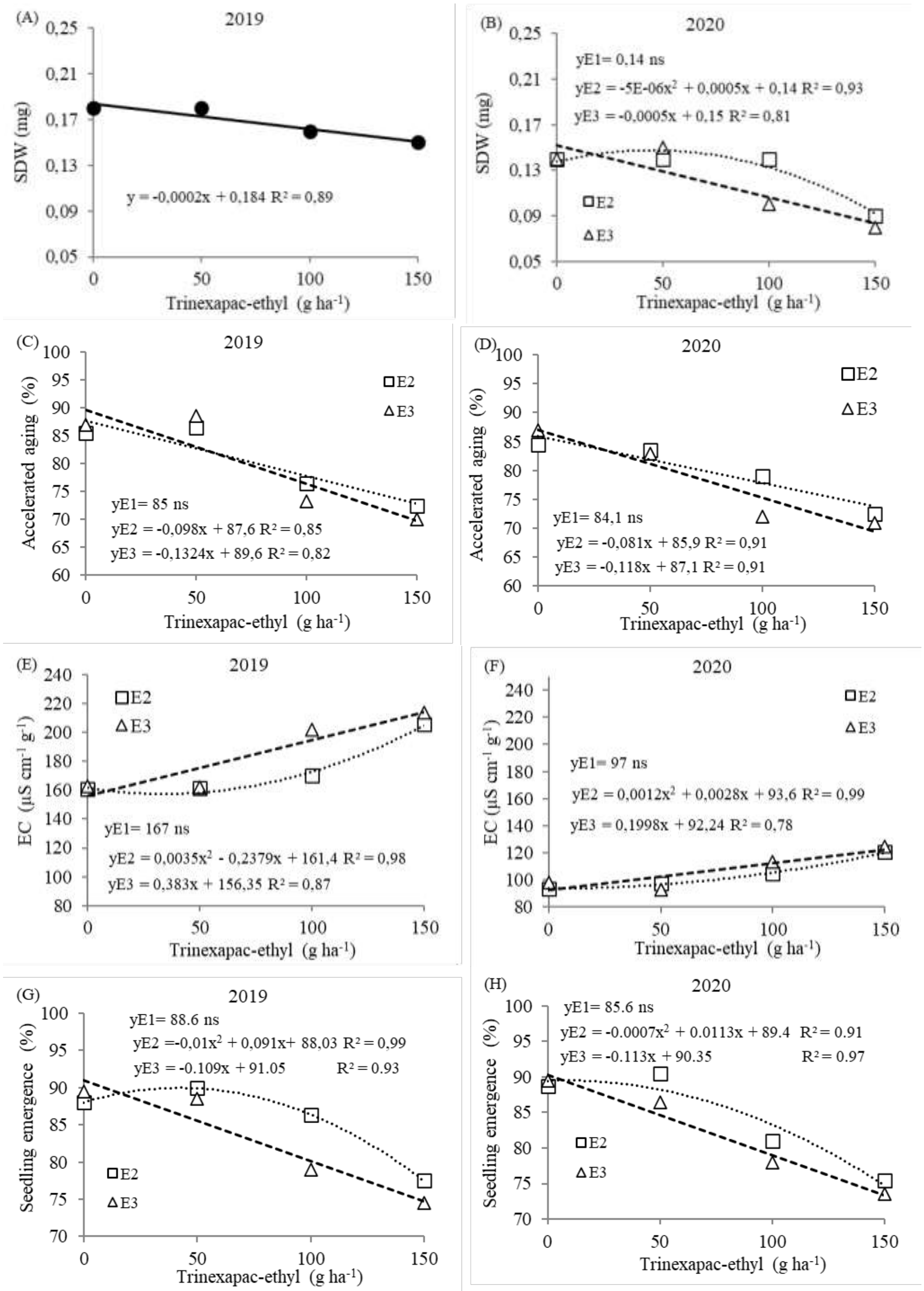

Figure 4. Seedling dry weight (SDW), accelerated aging, electrical conductivity, and seedling emergence in sand of white oat IPR Artemis as a function of trinexapac-ethyl application rate and timing in Londrina, PR, Brazil, in the 2019 and 2020 cropping seasons. E_1, first node detectable; E_2, stem elongation phase from first node visible to second node detectable; and E_3, second node visible to third node detectable.

In the 2019 season, accelerated aging (Table 2 and Figure 4C) decreased with trinexapac-ethyl application (≥100 g ha^{-1}) at E_2 and E_3. However, in 2020, accelerated aging decreased, by 15.04%, only in plants treated at E_2 at a rate of 150 g ha^{-1}. With trinexapac-ethyl application at E_3, there was a reduction of 16.21% in accelerated aging from 100 g ha^{-1} onward (Table 2 and Figure 4D). With this, the ability of seeds to withstand adverse conditions and germinate early decreased. Kaspary et al. (2015) reported similar results of accelerated aging with trinexapac-ethyl rates of 100 and 150 g ha^{-1}. Bazzo et al. (2018) found that accelerated aging is closely related to genotype: TC had a negative impact on white oat IPR Afrodite but a positive one on URS Corona.

Electrical conductivity was negatively influenced by trinexapac-ethyl application in 2019 and 2020 (Table 2 and Figure 4E and F). For the E2 group, electrical conductivity was higher at a trinexapac-ethyl rate of 150 g ha^{-1} in both years. Trinexapac-ethyl application at E3 at rates of ≥100 g ha^{-1} led to a significant increase in electrical conductivity in both years. These findings demonstrate that trinexapac-ethyl is disadvantageous when the aim is to produce seeds with high physiological quality. It can be said that seeds with increased electrical conductivity will undergo malformation, resulting in disorganized cell walls. The cell membrane is the last structure to organize itself before physiological maturity and the first to exhibit the changes characterizing seed deterioration. A lack of membrane integrity entails leaching of sugars, amino acids, electrolytes, and other water-soluble substances (Sponchiado et al., 2014). Thus, trinexapac-ethyl application at E_2 and E_3 to IPR Artemis caused a reduction in the rate of membrane restoration during imbibing, leading to greater leaching of solutes into the external environment (Marcos, 2005). These effects resulted in seeds with low physiological quality, less vigorous, and high deterioration. Bazzo et al. (2018) found that white oat cultivars treated with trinexapac-ethyl exhibited an increase in seed electrical conductivity compared with the control.

Similarly, seedling emergence in sand had a negative response to the increase in trinexapac-ethyl rate (Table 2 and Figure 4G and H). In 2019, in the E_1 group, the parameter was not influenced by trinexapac-ethyl rate. However, in the E_2 group, a trinexapac-ethyl rate of 150 g ha^{-1} led to a 12.92% reduction in seedling emergence. Seedling emergence in sand was 89% in the control, 77.50% with 150 g ha^{-1} at E_2, and 76.75% with 100 g ha^{-1} at E_3 (Table 2 and Figure 4G). Similar findings were observed in the 2020 season, with a reduction in seedling emergence with trinexapac-ethyl rates of ≥100 g ha^{-1} at E_2 and E_3 (Table 2 and Figure 4H).

Overall, seed germination exceeded the minimum required for sale (80%) in plants treated with 0 or 50 g ha^{-1} trinexapac-ethyl at all application timings, as determined by the Brazilian Ministry of Agriculture, Livestock, and Food Supply. Nevertheless, given that trinexapac-ethyl negatively influenced germination variables and seed vigor, seedling emergence and crop establishment in the field are likely to be affected, possibly resulting in production losses.

Conclusion

Application of trinexapac-ethyl at 100 or 150 g ha^{-1} at E_2 or E_3 increased seed yield in white oat IPR Artemis. However, the growth regulator affected thousand seed weight, germination percentage, and vigor, regardless of the rate, negatively affecting the crop's initial development and establishment in the field.

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