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Control of lodging and reduction in plant length in rice (*Oryza sativa* L.) with the treatment of trinexapac-ethyl and sowing density

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Abstract: In this study, the effects of the plant growth regulator trinexapac-ethyl (TE) combined with different sowing densities on field-grown rice (*Oryza sativa* L.) plant length, lodging, and grain yield were evaluated over 2 growing seasons. Two different rice cultivars (Karadeniz and Osmancik-97), 3 different sowing densities (400, 500, and 600 seeds m^{-2}), and 4 different doses of TE (0, 100, 200, and 300 g ai ha^{-1}) were compared. The experiments were designed in a randomized block design in factorial ordering with 3 replicates. An increase in sowing density led to an increase of lodging, but it did not have a significant impact on plant length and grain yield. There was a significant correlation between lodging and plant length. A sowing density of 500 seeds m^{-2} is the optimum value among all sowing densities, and the highest yield was obtained from Osmancik-97 among all the cultivars. Irrespective of genotype and sowing density, treatments with 100 and 200, but not 300, g TE ai ha^{-1} increased rice yield. All doses of TE reduced lodging and plant length. By regression analyses, the optimal TE dose was predicted to be 170 g ha^{-1}.

Key words: Lodging, plant length, rice (*Oryza sativa* L.), sowing density, trinexapac-ethyl, yield

1. Introduction

In terms of production and harvested area, rice (*Oryza sativa* L.) is the third cereal after maize and wheat, but it represents the staple food for more than half of the world's population. The global area of rice cultivation area is in the region of 1×10^6 ha producing 679×10^6 t, with yield averaging about 4.210 t ha^{-1}. The main region of cultivation is Asia, particularly China, India, and Indonesia, which produces 65% of the world's rice production. In Turkey, rice production and the area of cultivation is relatively limited compared to other countries, but Turkey achieves one of the highest yields at 7.776 t ha^{-1}. As a result, Turkey is ranked fourth out of 115 rice-cultivating countries in terms of rice productivity (FAO 2010). In a high-yielding environment, lodging is the most important constraining factor on yield for most cereals crops, including rice (Setter et al. 1997). Lodging negatively impacts both grain yield and quality (Day 1957; Weibel and Pendleton 1964), in part through a 60%–80% reduction in rice canopy photosynthesis (Setter et al. 1997). More practically, lodging reduces working efficiency by about 25% by making machine harvesting difficult (Lim et al. 1997). Lodging in rice may occur as a result of strong winds, heavy rain, water management, planting density, or an excessive use of fertilizer (Min and Fei 1984; Song et al. 1996; Back et al. 1998). The relative impact of any given factor can be exaggerated through a poor choice of cultivar being grown (Song et al. 1996; Back et al. 1998). In a study comparing semidwarf rice cultivars that were either held erect or allowed to naturally lodge, it was found that lodging led to a 35% reduction in yield (approximately 2 t ha^{-1}) (IRRI 1986). Jennings and Sornchai (1964) reported yield losses of up to 50% in the dry season and up to 80% in the wet season as a result of lodging in weak-culmed varieties grown under high nitrogen levels. Weather conditions, especially wind and rain near harvest time, appear to be a major factor influencing lodging and disease (Mobasser et al. 2009).

Given these data, there have been many efforts to reduce lodging through cultural practices and breeding as well as the use of phytoactive chemicals to influence plant development. Trinexapac-ethyl (TE) is a foliar absorbed cyclohexanedione plant growth regulator that can inhibit shoot growth in plants. It was registered as a plant growth inhibitor in 1998, and its particular potential

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in rice cultivation was noted (Fagerness and Penner 1998). In this study, we assessed the effect of sowing density and TE on lodging-related traits, plant height, and yield in 2 rice cultivars.

2. Materials and methods

These experiments were conducted in the paddy field experiment area of the Black Sea Agricultural Research Institute located in Samsun, Turkey (41°13′27″N, 36°30′08″E) in 2009 and 2010. The research area had a daily average temperature of 20.3 °C, relative humidity of 78.7%, and 399.4 mm m^{-2} rain during the rice-growing period from May to October in 2009 and 2010. The soil type was clay and at a neutral pH (pH 7.04). The nutrient values were as follows: 19.8 g kg^{-1} organic C, P_2O_{55} 19.1 mg kg^{-1} Olsen P, and 630.0 mg kg^{-1} extractable K. The soil tests were based on samples taken from the upper layer of soil (20 cm).

Two rice (*Oryza sativa* L.) cultivars, Osmancik-97 and Karadeniz, were grown. Osmancik-97 has a high grain yield (8.000–10.000 t ha^{-1}), medium plant length (95–100 cm), and moderately susceptible lodging. It is grown throughout Turkey and supplies 80% of the rice production of the country (Sürek 2009). Karadeniz has relatively moderate yields (6.900–9.000 t ha^{-1}), high plant length (120–130 cm), and is very susceptible to lodging. Nevertheless, it is considered to produce high-quality grain, especially in its size, and is considered to be an economically attractive cultivar. Various sowing densities were tested: 400, 500, and 600 seeds m^{-2}. As the plot size was 12 m^2, this required, respectively, 4800, 6000, and 7200 seeds. The number of seeds was calculated on the 1000-grain weight of each cultivar. Sowing density was determined according to the weight of seeds per plot. Clean seeds of each cultivar with a minimum of 90% germination rate were soaked in water for 48 h. Pregerminated seeds were then sown directly into plots on 20 May 2009 and 20 May 2010. The plot size was 12 m^2 (3 m × 4 m) and the harvested area was 10 m^2 (2.7 m × 3.7 m) to removing any edge effects. Nitrogen was applied at 40 kg N ha^{-1} in the form of ammonium sulfate at 3 different growth stages; at basal, midtillering, and panicle initiation (Li et al. 2010). After sowing, a 10-cm water depth was maintained over the experimental plots. Fifteen days before the harvest, the plots were drained to facilitate harvesting. Insects, diseases, and weeds were controlled to rule these factors out of any losses in yield. TE was applied as a wet powder (WP) to rice cultivars Osmancik-97 and Karadeniz. Both cultivars were treated with doses of 100, 200, and 300 g TE ai ha^{-1} using a hand-held sprayer. TE was applied at 17 and 7 days before heading, which designated Zadoks growth stages 31–32 (Zadoks et al. 1974).

Lodging severity was scored visually as a percentage of plants that lodged at maturity (growth stage 71). These was assessed on a 1–9 point scale where 1 was totally upright and 9 was totally lodged (lodging score: 1 = no lodging, 3 = 0%–10% lodging, 5 = 11%–25% lodging, 7 = 26%–50% lodging, 9 = >50% lodging) (TTSM 2003). Plant height was measured from the plant base to the tip of the panicle (or leaf, whichever was longer) in each plot (IRRI 1980). Harvest time was determined according to Sürek and Beşer (1998). Grain yield was determined from the 10 m^2 area in each plot and adjusted based on an assumed moisture content of 140 g H_2O kg^{-1}. Grain moisture content was measured with a digital moisture meter.

Data were analyzed using analysis of variance (SAS Institute 1982) and means of treatment were compared based on the least significant difference test (LSD) at a 0.05 probability level.

3. Results

3.1. Plant length

Plant length is an important factor for lodging for rice. Plant length ranged from 73.1 to 125.9 cm in this study. The analysis of variance revealed highly significant ($P < 0.01$) differences in plant length with each TE application rate and variety. The C × TE interaction was also significant ($P < 0.01$). However, there was no significant difference with sowing density in terms of plant length (Table 1).

The effects of TE and sowing density on rice plant length are given in Table 2. When evaluated in terms of the rate of TE application, the shortest mean plant length observed was 77.0 cm on the 300 g TE application plot. The highest mean plant length observed was 115.3 cm on the control plot (Table 2). The regression analysis (Figure 1) showed that TE application significantly negatively affected ($P < 0.01$) plant length. A quadratic relationship existed between the TE application rates and plant length, which was calculated as $y = 114.8164 - 0.22422x + 0.00033x^2$, where y = height and x = the rate of TE application. The R^2 coefficient was 0.64.

Considering each cultivar individually, mean plant length was 97.3 and 88.4 cm in Karadeniz and Osmancik-97, respectively, when the results of both years were combined. The mean of longest plant lengths for Karadeniz and Osmancik-97 were found in the control plots (0 g ai ha^{-1} TE) at, respectively, 124 and 106.6 cm. The shortest length means for Karadeniz and Osmancik-97 were found to be 80.2 and 73.8 cm in the 300 g TE application plot, respectively, representing 35.3% and 30.8% reductions in plant length. Sowing density had no significant effect on plant length with mean lengths of 97.2, 97.2, and 97.3 cm being respectively obtained in fields sown with 400, 500, and 600 seeds m^{-2}.

Table 1. Analysis of variance for rice plant characters in 2009 and 2010.

Source	DF	Plant length	Lodging	Grain yield
Cultivar (C)	1	2854.23**	136.11**	122,957.63**
Sowing density (D)	2	45.80	3.59**	1675.93
TE rates (TE)	3	9884.44**	211.63**	20,016.44**
TE-Linear	1	27,901.70**	547.76**	9834.89
TE-Quadratic	1	1591.35**	87.11**	43,064.10*
TE-Cubic	1	160.27	0.02	7150.30
Replication (R)	4	24.33	2.06	108,415.31
C × D	2	42.84	0.20	6478.79
C × TE	3	299.76**	46.26**	4974.32
D × TE	6	5.74	1.44	7317.83
C × D × TE	6	45.93	0.34	2487.67
Years (Y)	1	8622.67**	28.44**	29,978.65*
Y × C	1	79.36	5.44**	9.26
Y × D	2	9.78	0.70	7833.30
Y × TE	3	12.34	11.78**	8596.75
Y × C × TE	2	47.58	1.20	5911.50
Y × C × TE	3	14.20	3.00**	15,718.11*
Y × D × TE	6	22.52	0.25	7498.68
Y × C × D × TE	6	43.62	0.97	3770.95
Error	92	26.77	0.72	4426.55
General	143	319.91	7.64	9174.94

* , ** : Significant at 5% and 1% level, respectively.

Table 2. Effect of trinexapac-ethyl and sowing density on rice plant length.

Varieties	Sowing density (seeds m^{-2})	Trinexapac-ethyl rates (g ai ha^{-1})				
		Control	100	200	300	Mean
Osmancik-97	400	108.5	90.8	82.5	73.9	88.9
	500	106.9	95.1	84.7	73.1	89.9
	600	104.3	90.0	76.3	74.4	86.2
Mean		106.6 b	92.0 d	81.1 f	73.8 g	88.4 B
Karadeniz	400	123.5	97.7	88.3	79.7	97.3
	500	125.9	95.7	86.1	81.5	97.3
	600	122.7	96.5	90.3	79.5	97.2
Mean		124.0 a	96.6 c	88.2 e	80.2 f	97.3 A
General average		115.3 A	94.3 B	84.7 C	77.0 D	92.8
**	NS			**		

**: significant at the 1% level; NS: no significant differences.
Values followed by the same letter are not statistically significantly different.
$LSD_{variety}$ = 1.70; $LSD_{t\text{-}ethyl}$ = 2.41; $LSD_{variety \times t\text{-}ethyl}$ = 3.42; CV (%) = 5.57.

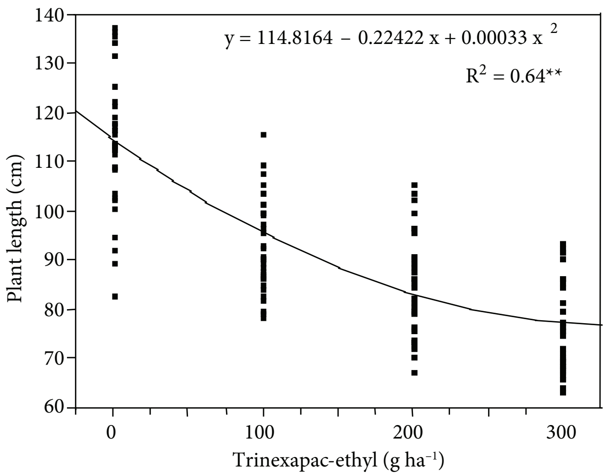

Figure 1. Correlating rice plant length with rates of trinexapac-ethyl application.

3.2. Lodging

The analysis of variance revealed highly significant ($P < 0.01$) differences in lodging with TE application rate, sowing density, and cultivars (Table 1). The cultivar × TE interaction was also significant ($P < 0.01$). Sowing density and lodging scores for rice treated with TE are presented in Table 3. In our 1–9 scale lodging score, the overall experimental average was 2.8. When evaluated in terms of TE doses, lodging was significantly affected by TE. Thus, lodging scores were progressively reduced from the controls (mean score: 6.2) with increasing doses of TE (100 g TE ha^{-1} = 2.9; 200 g TE ha^{-1} = 1.2; 300 g TE ha^{-1} = 1.0) (Table 3). The regression analysis is displayed in Figure 2 and shows that TE application significantly ($P < 0.01$) affected lodging. A quadratic relationship existed between the TE rates and lodging incidence, described by the following equation: $y = 6.22828 - 0.04078x + 0.00008x^2$, where y = lodging and x = application rate of TE. The R^2 coefficient was 0.58. Using this equation, the lowest lodging score (1.0) could be achieved with a dose of 260 g TE ha^{-1}.

Significant cultivar-specific differences ($P < 0.01$; Table 1) in the incidence of lodging were observed with different rates of TE application (Figures 3a and 3b). When focusing on the Karadeniz cultivar (Figure 3a), high mean lodging

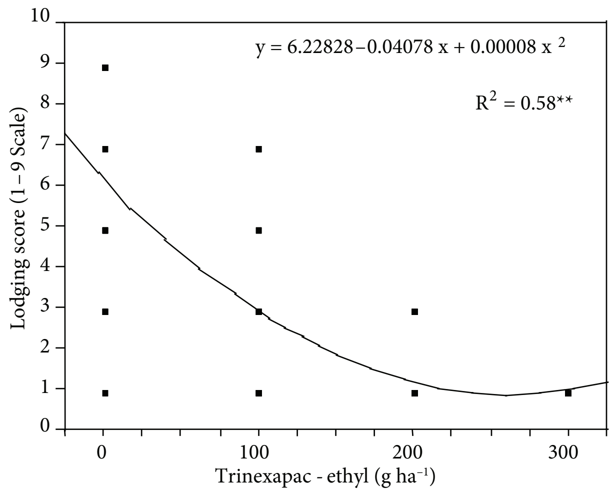

Figure 2. Correlating the lodging scores for rice with trinexapac-ethyl application rates.

Table 3. Effect of trinexapac-ethyl and sowing density on rice plant lodging score.

Varieties	Sowing density (seeds m^{-2})	Trinexapac-ethyl rates (g ai ha^{-1})				
		Control	100	200	300	Mean
	400	3.0	1.0	1.0	1.0	1.5
Osmancik-97	500	3.7	2.0	1.0	1.0	1.9
	600	4.7	2.0	1.0	1.0	2.2
Mean		3.8 b	1.7 c	1.0 d	1.0 d	1.9 B
	400	8.3	3.7	1.3	1.0	3.6
Karadeniz	500	8.7	4.7	1.0	1.0	3.8
	600	9.0	4.3	1.7	1.0	4.0
Mean		8.7 a	4.2 b	1.3 cd	1.0 d	3.8 A
General average		6.2 A	2.9 B	1.2 C	1.0 C	2.8
**	**			**		

**: significant at the 1% level. Values followed by the same letter are not statistically significantly different.
$LSD_{variety}$ = 0.28; $LSD_{density}$ = 0.34; $LSD_{t\text{-}ethyl}$ = 0.40; $LSD_{variety * t\text{-}ethyl}$ = 0.56; CV (%) = 19.68.
Lodging score ranges from 1 = no logging to 9 = all lodged. See Materials and methods for details.

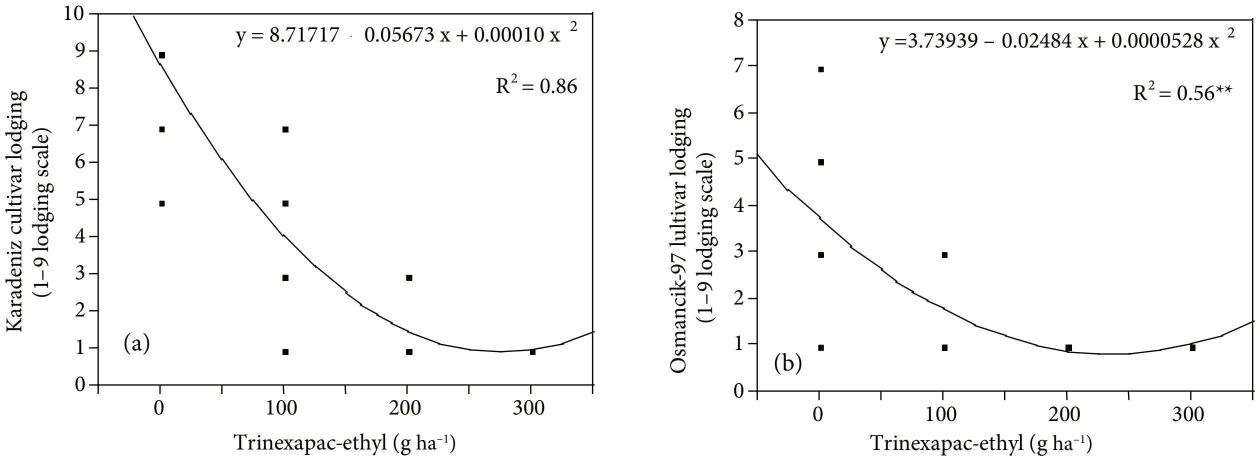

Figure 3. Correlating the lodging scores for rice cultivars Osmancik-97 and Karadeniz with trinexapac-ethyl application rates.

scores were obtained in control plots without TE (8.7) but were reduced through the application of TE, especially at rates of ≥200 g TE ha^{-1} (100 g TE ha^{-1} = 6.1; 200 g TE ha^{-1} = 1.7; 300 g TE ha^{-1} = 1.0). The regression analysis (Figure 3a) showed that TE application significantly ($P < 0.01$) reduced lodging. A quadratic relationship that described the relationship between the TE rates and lodging scores was derived, where $y = 8.71717 - 0.05673x + 0.00010x^2$, where y = lodging score and x = the TE application rates. Based on this equation, it was calculated that the lowest lodging score (0.9) for Karadeniz could be achieved with 280 g TE ha^{-1}. The lodging scores for the Osmancik-97 cultivar indicated that these were significantly ($P < 0.01$) improved by TE application, even though this cultivar is considered to be relatively lodging resistant (Figure 3b). From mean scores of 3.8 in control plots, lodging scores were decreased with TE (100 g TE ha^{-1} = 1.7; 200 g TE ha^{-1} = 1.0; 300 g TE ha^{-1} = 1.0). Regression analysis (Figure 3b) showed a quadratic relationship between the rates of TE application and lodging scores in Osmancik-97, described by the equation $y = 3.73939 - 0.02484x + 0.0000528x^2$, where y = lodging score and x = the TE application rates. Based on this equation, the lowest lodging score (0.8) was calculated to be 240 g TE ha^{-1} of TE. Lodging was significantly ($P < 0.01$; Table 1) affected by sowing density, with scores averaging 2.5, 2.9, and 3.1 in the plots of 400, 500, and 600 seeds m^{-2}, respectively. There was no statistically significant interaction between sowing density and TE application (Table 1). As an alternative method to describe lodging, lodging incidence was expressed as a ratio of plants that lodged to total population size (IRRI 1996). The analysis of variance of lodging incidence revealed highly significant ($P < 0.01$) differences with different TE application rates, sowing density, and cultivars for plant lodging incidences (Table 1). The C × TE interaction was also significant ($P < 0.01$).

3.3. Grain yield

Our ultimate aim was to increase rice productivity per unit hectare. The grain yield of rice treated with different rates of TE and sowing densities are presented in Table 4. Grain yield ranged from 5.635 t ha^{-1} to 7.009 t ha^{-1} with an overall mean of 6.483 t ha^{-1} (Table 4). Our experimental results indicated that cultivar and TE dose significantly ($P < 0.01$) affected yield (Table 1). However, this was not the case with sowing density.

Focusing on the effects of TE dose, the lowest seed productivity of 6.168 t ha^{-1} was obtained on control plots. Applying TE improved yields ($P < 0.05$) to 6.714 t ha^{-1} (100 g TE ha^{-1}), 6.598 t ha^{-1} (200 g TE ha^{-1}), and 6.453 t ha^{-1} (300 g TE ha^{-1}), although it should be noted that increasing the TE application rate reduced yield benefits. The regression analysis (Figure 4) suggested that the relationship between TE dose and grain yield could be described as $y = 6.19912 + 0.00593x - 0.0000173x^2$, where y = yield and x = the

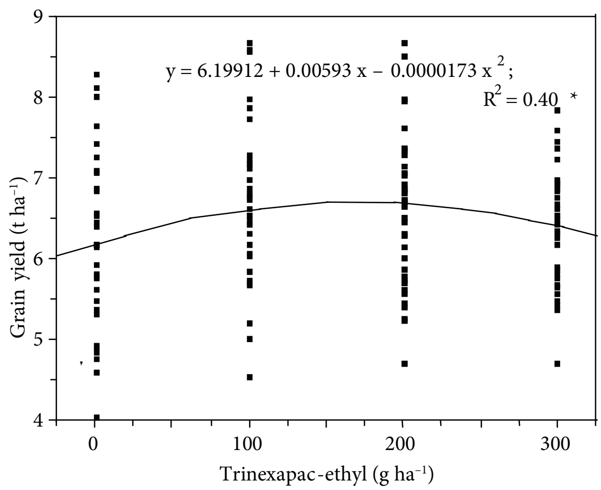

Figure 4. Correlating rice grain yield and trinexapac-ethyl application.

Table 4. Effect of trinexapac-ethyl and sowing density on rice grain yield (t ha^{-1}).

Varieties	Sowing density (seeds m^{-2})	Trinexapac-ethyl rates (g ai ha^{-1})				
		Control	100	200	300	Mean
Osmancik-97	400	6.635	7.009	6.730	6.730	6.776
	500	6.867	7.415	6.960	6.305	6.887
	600	6.223	6.807	6.867	6.756	6.663
Mean		6.575	7.077	6.852	6.597	6.775 A
Karadeniz	400	5.789	6.460	5.996	5.980	6.056
	500	5.635	6.498	6.369	6.174	6.169
	600	5.852	6.092	6.668	6.770	6.347
Mean		5.761	6.350	6.345	6.308	6.191 B
General average		6.168 B	6.714 A	6.598 A	6.453 AB	6.483
**	NS	**				

**: significant at the 1% level; NS: no significant differences. Values followed by the same letter are not statistically significantly different.
$LSD_{variety}$ = 0.223; $LSD_{t\text{-}ethyl}$ = 0.315; CV (%) = 10.26.

TE application rate. Using this equation, the maximum grain yield (6.707 t ha^{-1}) was predicted to be achieved with 170 g TE ha^{-1}. Considering the possible cultivar-specific effects of TE, we noted that C × TE interactions were statistically nonsignificant (Table 1). However, the data were suggestive of cultivar-specific TE effects. The average yield over the 2 assessed years was 6.775 t ha^{-1} for cultivar Osmancik-97 and 6.191 t ha^{-1} for Karadeniz. Compared to the yield on the control plot (5.761 t ha^{-1}), application of 100 g TE ha^{-1} to the Karadeniz cultivar raised its yield to 6.350 t ha^{-1}, representing a productivity increase of 0.589 t ha^{-1}. With the Osmancik-97 cultivar, there was an increase in productivity of 0.502 t ha^{-1} (from 6.575 t ha^{-1} on control plots to 7.077 t ha^{-1} following application of 100 g TE ha^{-1}). These values represented yield increases of 10.2% for Karadeniz and 7.6% for Osmancik-97 when applying TE at 100 g ha^{-1}. When examining sowing densities, perhaps somewhat surprisingly, these had no significant effect on yield (Table 1). Thus, yields of 6.416, 6.528, and 6.505 t ha^{-1} were obtained at sowing densities of, respectively, 400, 500, and 600 seeds m^{-2}.

3.4. Experimental variable correlations over the growing seasons

Table 1 indicates that the experimental year (Y) had a significant impact on the results of plant length, lodging, and yield. Furthermore, significant ($P < 0.01$) year (Y) × TE and also Y × cultivar (C) effects were observed. Thus, it was important to attempt to correlate pairs of variables in 2009 and 2010 (Table 5). Over the 2 tested years, the traits that significantly correlated with grain yield at a 0.01 level were plant length and lodging. The most important correlation was between lodging and plant length (r = 0.831**), but there were suggestions of reduced yield (r = –0.230). Increases in lodging reduced the yield (r = –0.259).

4. Discussion

With an increasing human population, it is essential to maximize crop yields. Rice is the staple food of much of humanity, and this paper examined a method of mitigating against a particular constraint on rice production, lodging. Lodging may cause the loss of grain yield and quality (Day 1957; Weibel and Pendleton 1964; Cooper 1971), and so it is vitally important to develop methods to reduce lodging. In this study, plant length, lodging, and yield

Table 5. Correlating plant length, lodging, and yield in rice plants.

	Yield	Plant length
Plant length	–0.230**	–
Lodging	–0.259**	0.831**

**: significant at 1% level.

were evaluated by using 2 rice cultivars (Karadeniz and Osmancik-97), 3 different sowing densities (400, 500, and 600 seeds m^{-2}), and 4 different TE rates (0, 100, 200, and 300 g ai ha^{-1}).

Some previous studies comparing plant length and grain yield in cereals have indicated a negative correlation (Köycü 1979; Anıl 2000), while others have found a positive correlation (Başar et al. 1998; Oktay 2006). In our study, a significant negative correlation was found between lodging and plant length ($r = 0.831^{**}$). Although sowing density did not affect plant length and yield, it did significantly affect lodging ($P < 0.01$).

TE application significantly affected plant length, lodging, and yield ($P < 0.01$). While the longest plant length was 115.3 cm on control plots, plant length fell to 77.0 cm when a TE dose of 300 g was applied. TE affected lodging at different doses in different cultivars. While 280 g of TE application to the Karadeniz type prevented lodging, a lower dose of 240 g on the Osmancik-97 type was sufficient to prevent lodging. TE application identically increased yield of both cultivars. It was calculated using the derived regression formula that the highest yield was achieved with 6.707 t ha^{-1} on 170 g TE, but decreases in yield were likely at higher doses. It was found that the sowing density of 500 seeds m^{-2} was the optimum, and the highest yield was obtained from Osmancik-97 among the cultivars. The TE results obtained in this present study were in agreement with the findings obtained by Im et al. (1993), Han et al. (1999), Ju et al. (1999), and Dunand (2004) for TE and Kaçar and Katkat (2006) and Şahin et al. (2009) for sowing density.

The presented results have demonstrated the potential of TE in preventing lodging in rice, thus increasing yield. This work is intended to inspire similar studies using other rice cultivars and also to encourage the wide-scale application of TE in rice cultivation.

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