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Effect of Wheat Stem Morphological and Chemical Characteristics on Lodging

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ABSTRACT

The simplest and most effective method for solving the lodging problem, which causes serious yield losses in the production of wheat (*Triticum* L.), has been the use of shorter varieties. However, this situation eventually creates pressure on yield increases and decreases straw production. Thus, the determination of stem traits that impart lodging resistance and the development of nonlodging varieties has gained importance. This study examined the relationship between stem characteristics and lodging in 16 common and local wheat varieties. The lodging rate and angle were positively correlated with plant height, center of gravity length, potassium-calcium ratio, and plant weight, and negatively correlated with the second internode stem diameter, stem-bending strength, stem potassium content, and stem calcium content. A plant height that exceeded 104 cm increased the probability of lodging to 95%. The probability of lodging also increased considerably when the stem center of gravity was greater than 80 cm and the diameter of the second internode was smaller than 3.3 mm. A stem potassium content above 8500 mg kg^{-1} and a calcium content above 420 mg kg^{-1} were important for increasing lodging resistance. The local Gökala and Zerun wheat varieties showed high lodging resistance despite their tall heights.

Keywords: lodging rate, stem strength, wheat stem diameter.

INTRODUCTION

Although the yield losses in wheat (*Triticum aestivum* L.) have been reduced in recent years from 61% to 43% (Acreche and Slafer, 2011) with the use of new and shorter varieties (Wilhelm et al., 2013), persistent lodging continues to be an important problem that reduces yield and quality in wheat, as in many other crops (Berry et al., 2007). Depending on the time of lodging (Laidig et al., 2021) and the wheat variety, yield losses can vary across a wide range, from 8% (Tripathi et al., 2004) to 60-75% (Berry and Spink, 2012). Lodging also causes nutrient content decreases, harvesting difficulties, disease susceptibility, grain germination in the spike, cooking quality deterioration, and decreases in 1000 grain weight (Khobra et al., 2019; Ageeva et al., 2020).

Lodging, which is generally defined as the displacement of the stem or the whole plant from its vertical position, occurs in two ways: root lodging and stem lodging (stem bending or breaking) (Khobra et al., 2019). Root lodging, which occurs when the roots are not sufficiently firmly anchored in the soil (Packa et al., 2015), has been viewed as the main problem in the agricultural sector (Berry et al., 2003a). Increases in yield also increase the weight at the top of the wheat plant, forcing the plant to bend. Therefore, stalk lodging represents a serious obstacle to further increases in yield as it continuously worsens as yield increases (Wu et al., 2019). Consequently, any new varieties that are developed must have increased resistance to stem lodging along with increases in yield. The use of short varieties has also led to a decrease in straw yield. Worldwide, 650-900 million metric tons of wheat straw are produced annually (Montero et al., 2018). Wheat stalks are staples of animal nutrition in many developing countries.

Sustaining the achieved yield increases will require the development of lodging-resistant varieties without shortening, or perhaps even slightly increasing, plant height. Lodging resistance is related to stem strength

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vigor (Kelbert et al., 2004), and differences are evident in lodging resistance among tall wheat cultivars (Navabi et al., 2006). Tall and strong-stemmed varieties will be important for overcoming the limitations imposed by short-stature lodging resistance on grain and straw yields. The aim of this study was to determine the relationship between some of the physical and chemical properties of wheat stems and stem lodging and to explore which wheat varieties display lodging resistance.

MATERIAL AND METHODS

The data were obtained from samples taken from plots established using a randomized complete block design with three replications. Plants were sown on 21 October 2022 on 2 m^2 plots with a row spacing of 20 cm at 400 seeds m^{-2}. The experimental field had a sandy, silty soil structure. Super Ekin™ (13-25-5 NPK +10×SO_3+0.5×Zn) fertilizer was applied at 200 kg ha^{-1} during sowing. Ammonium nitrate fertilizer was used as a top-dressing fertilizer at a rate of 150 kg ha^{-1} at Feekes 3 and 5. The plots were irrigated throughout the growing season, except during rainy periods. Weeds were controlled by spraying with 2,4-D ethylhexyl ester at Feekes 4. Table 2 shows the wheat varieties used in the experiment and abbreviations in manuscript. The climate of the test field is cold and wet in winter and hot and dry in summer. The climatic data for the growing period are given in Table 1 and Figure 1.

Table 1. Climate data during the wheat growing period (2022-2023)

	Year / Month	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July
Temp. (°C)	2022/23	16.1	11.3	7.9	6.0	3.4	8.8	10.4	15.3	19.8	26.1
	Long term	13.4	7.9	3.7	1.8	3.0	6.0	10.8	15.5	19.9	23.5
RH (%)	2022/23	50.3	58.6	74.3	68.2	56.7	66.2	65.0	69.3	63.7	37.1
	Long term	62.4	68.2	73.9	72.0	68.1	65.0	62.0	58.1	52.2	47.6

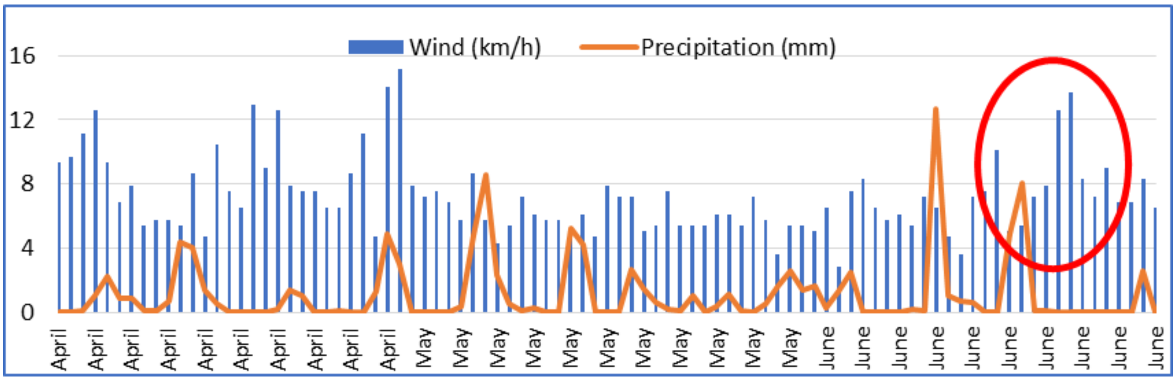

Figure 1. Daily rainfall and wind data during the critical wheat growing season for lodging and the period when lodging occurred (red line)

Samples for measurement, taken at anthesis and maturity, consisted of five intact main culms (main culms, without roots) from plants at the center of each plot (Berry et al., 2003a). The plants were measured at both periods when the stems were completely dry (6% moisture). Data were taken between the 2nd and 3rd internodes and after separation from the leaves (Zhang et al., 2016). The stem diameters were measured at the midpoint of the internode with calipers to a precision of one-tenth of a millimeter. Lodging angles were determined by measuring the angle of the upright plant to the horizontal (surface), and the lodging rate was established by observing how many plants in the plot were lodged (Xiao et al., 2015). The center of gravity was determined as the distance from the base to the point at which the plant could be balanced on an index finger (Bian et al., 2016).

Wheat stem bending strength was measured on the second internode from the bottom by separating the leaves and using the three-point bending test method (Peng et al., 2014). The center of the internode was pushed toward breaking, and the load when the internode broke was measured in Newtons (N) (bending force) and as the energy at maximum load (mJ) (shearing energy) (Zhang et al., 2016; Luo et al., 2019). A universal testing machine (LF Plus, LLOYD Instruments, Ametek Inc., England) was used for the measurements, with the following measurement specifications: spacing between the two metal supports, 5 cm; height, 5 cm; speed, 30 mm min^{-1}; and blunt blade thickness, 3 mm (Luo et al., 2019; Gökduman and Yılmaz, 2021).

The stem N, K, and Ca contents were analyzed after removal of the leaves and spike. The nitrogen content of the stem samples was analyzed using a semi-micro Kjeldahl method (Bremner, 1960). Wet-ashed plant digests were analyzed for K and Ca by atomic absorption spectrometry (AAS; Varian 240 FS) and for P spectrophotometrically using an ascorbic acid method (Murphy and Riley, 1962) at a wavelength of 882 nm. IBM SPSS version 29.0 and R 4.4.2 for Windows package programs were used to evaluate the data. Descriptive statistics are given as means and standard deviations.

Table 2. Abbreviations and wheat varieties

Abbreviation	Description	Abbreviation	Description
…M	physiological Maturity (harvest time)	…A	Anthesis stage (late flowering time)
PLM	Percentage of lodged plants (%)	NM	Stem nitrogen content (%)
ALM	Angle of lodging from the vert. (degree)	KM	Stem potassium content (mg kg^{-1})
PHM	Plant height at maturity (cm)	CaM	Stem calcium content (mg kg^{-1})
CGA	Center of gravity (cm)	KMtoCaM	Ratio of potassium to Ca content
CGMtoPHM	Ratio of CGM to PHM	PHA	Plant height at anthesis (cm)
PWM	Plant weight (g)	CGA	Center of gravity (cm)
SWM	Spike weight (g)	CGAtoPHA	Ratio of CGA to PHA
GWM	Grain weight per spike (g)	PWA	Plant weight (g)
HIM	Harvest index (%)	DSIA	Diameter of the second internode (mm)
DSIM	Diameter of the second internode (mm)	BFA	Bending force (strength) (N) (2. Internode)
BFM	Bending force (strength) (N) (2. Internode)	BEA	Shearing energy (mJ) (2. Internode)
BEM	Shearing energy (mJ) (2. Internode)		
W2ItoDM	Weight of the 2nd internode 1 cm long / Diameter at dought stage (cm.g/mm)	W3ItoDM	Weight of the 3nd internode 1 cm long / Diameter at dought stage (cm.g/mm)
Wheat varieties			
Bez	Bezostaja-1 (*T. aestivum* L.) (Registered)	Ein	Einkorn (*T. monococcum* L.) (Landraces)
EmW	Emmer *(T. dicoccon* Shrank) (White spike) (Landraces)	Alb	Albostan (*T. aestivum*) (Landraces)
Ger	Gerek-79 (*Triticum aestivum* L.) (Registered)	Cum	Cumhuriyet-75 (*T. aestivum* L.) (Registered)
Gok	Gökala (*T. durum* Desf.) (Landraces)	Alt	Altın buğday (*T.durum* Desf.) (Landraces)
Tir	Tir (*T. aestivum*) (Landraces)	Tos	Tosunbey (*T. aestivum* L.) (Registered)
Sah	Şahman (*T. aestivum*) (Landraces)	Kay	Kayra (*T. aestivum* L.) (Registered)
EmB	Emmer *(T. dicoccon* Shrank) (Brown spike) (Landraces)	Zer	Zerun (*T. aestivum* L.) (Landraces)
Sar	Sarı Buğday (*T. durum* Desf.) (Landraces)	Koc	Koç 2015 (*T. aestivum* L.) (Registered)

RESULTS AND DISCUSSION

All the tested wheat varieties showed differences (P>0.05) in terms of the examined traits, except CGAtoPHA. Among the lodged varieties, the PL of Alb, Emb, Emw, Sar, and Tir were between 60 and 93%, while those of Gök and Zer were approximately 30%. In our study, naturally occurring lodging was observed in mid-June.

Rainfall and wind were the climatic events that triggered lodging; however, the greatest effect was induced when these events occurred at the same time or when rain preceded the wind. The distribution of rainfall was as important as the amount. Although the total monthly rainfall was low compared to the long-term average (Table 1), short-term excess rainfall followed by strong winds caused lodging (Figure 1).

The mean values, statistical groups and standard deviations of traits are given in Table 3. The average PHM of the cultivars varied between 79 and 143 cm, with the highest plant height observed for the landrace genotypes (Gök, Sar, Zer, Emb, and Alb). The average height of the common cultivars was approximately 90-100 cm. The CGM was similar to the PHM, and the varieties with high PHM also had high CGM. The highest CGM occurred in the Gök variety (97 cm). The ratio of the CGM to PHM varied between 0.6-0.8, and the ratio was somewhat higher in the new varieties than in the landraces. The PWM varied over a wide range, from 1.2 to 7.9, although the landraces (except Gök) had relatively low values, and common cultivars had average values between 4 and 6. The SWM and GWM were proportionally similar to the PWM on a cultivar basis. The HIM ranged from 30 to 48%, and the lowest HI was determined in the Ein (*T. monococcum* L.) genotype. The DSIM of the cultivars varied between 2.17 and 4.0, and of the 5 cultivars with values below 3, all (except Ein) were lodged. Lodging was observed in 3 varieties (Gök, Sar, and Tir) with values above 3.

Three-point bending tests were performed to determine the resistance of the stem. The BFM and BEM varied from 3.5-23.5 N and 7.7-66.7 mJ, respectively. In general, the resistance of the new varieties was more homogeneous and higher, whereas the landraces had more irregular values. Stalk samples taken at anthesis (after drying) had smaller resistance values. The lowest W2ItoDM and W3ItoDM values were found in the Ein genotype and the highest in the Zer genotype.

Evaluation of the relationship between the N, K, and Ca contents of the stems and lodging rates revealed lodging in varieties with stem N contents above 0.22% and below 0.17%. No lodging occurred in varieties with stem K content above 8500 mg kg^{-1}, whereas some varieties with K contents below 8500 mg kg^{-1} lodged and some did not. For Ca content, the critical value appeared to be 420 mg kg^{-1}. Two varieties that had Ca values less than 420 mg kg^{-1} did not lodge. Among all the lodged varieties, the stem Ca content was lower than 420 mg kg^{-1}. The KMtoCaM ratio had values between 8.1 and 24.9. This ratio was relatively low in most of the nonlodging varieties. In general, the results of the samples taken during the anthesis period were similar to the results of the samples taken during the harvest period.

Multiple regression analysis models of the relationship between PLM and ALM and the examined traits in all varieties and lodged varieties are given in Table 5. Since the dependent variable angle was zero in the nonlodging varieties, a multiple regression model could not be constructed. In the analysis in which all varieties were included, a positive relationship was found between PLM and PHM, whereas a negative relationship was found between PLM and DSIA. These two variables explained 62% (R2: 0.623) of the model. In lodged varieties, PLM, and DSIA showed a negative relationship, whereas PLM and BFA showed a positive relationship. The predictive power of the model with these two traits was 74% (R2: 0.74). ALM showed a positive relationship with PHM and NM in all varieties but a negative relationship with DSIA and CGM. These four variables explained 65% (R2: 0.650) of the model. In lodged varieties, ALM showed a negative relationship with CGM and KM. These two traits explained 48% (R2: 0.483) of the model.

Table 3. Descriptive and Multivariate ANOVA statistics of the studied variables

Variety	PL		AL		PHM			CGM			CGMtoPHM			PWM			SWM			GWM			HIM			DSIM			BFM			BEM			W2ItoDM		
	Mean		Mean		Mean		Std. Dev.	Mean		Std. Dev.	Mean		Std. Dev.	Mean		Std. Dev.	Mean		Std. Dev.	Mean		Std. Dev.	Mean		Std. Dev.	Mean		Std. Dev.	Mean		Std. Dev.	Mean		Std. Dev.	Mean		Std. Dev.
Alb	88	b	82	b	120	cd	2.5	70	bc	8.5	0.58	d	0.06	2.8	hı	0.34	1.32	hı	0.27	0.91	hı	0.30	32.70	cd	9.22	2.80	de	0.36	11.40	cd	2.2	16.80	e	1.07	6.80	ab	0.85
Alt	0	f	0	e	79	ı	4.0	58	e	4.0	0.74	ab	0.03	3.6	fgh	0.25	2.15	d-g	0.11	1.60	efg	0.08	45.10	ab	0.93	3.07	cde	0.21	9.50	cd	0.45	13.70	e	4.49	5.60	bcd	0.79
Bez	0	f	0	e	101	e	6.4	70	bc	6.0	0.69	bc	0.02	4.7	def	0.67	2.54	c-f	0.33	1.92	def	0.29	41.60	ab	5.28	4.00	a	0.62	16.60	abc	5.93	26.70	cde	9.53	5.00	cd	0.57
Cum	0	f	0	e	80	hı	3.6	60	de	3.8	0.74	ab	0.01	5.0	cde	0.84	3.01	bc	0.54	2.31	cd	0.39	45.80	a	1.37	4.00	a	0.2	22.00	ab	9.19	66.70	a	15.13	5.00	cd	0.33
Ein	0	f	0	e	99	ef	4.0	64	bcd	3.9	0.64	cd	0.03	1.2	j	0.17	0.48	j	0.09	0.37	j	0.11	30.30	e	5.05	2.20	f	0.1	3.50	d	0.14	11.00	e	6.36	4.50	d	0.71
EmB	93	a	87	a	127	bc	7.0	88	a	10.2	0.69	bc	0.06	3.0	hı	0.67	1.47	ghı	0.29	1.24	ghı	0.24	41.50	ab	3.45	2.60	ef	0.36	6.50	cd	1.4	8.30	e	4.17	5.00	cd	1.15
EmW	93	a	80	b	113	d	5.9	76	b	3.5	0.67	bc	0.02	2.3	ı	0.16	1.12	ıj	0.07	0.85	ıj	0.10	36.90	bcd	4.00	2.17	f	0.06	6.40	cd	1.27	7.70	e	0.98	7.40	a	1.11
Ger	0	f	0	e	98	ef	4.0	72	bc	2.7	0.74	ab	0.01	4.5	def	0.88	2.65	cde	0.5	1.90	def	0.48	41.80	ab	2.77	3.93	a	0.21	12.30	bcd	2.56	31.10	b-e	15.51	4.60	d	0.51
Gok	32	e	37	c	143	a	7.9	97	a	3.1	0.68	bc	0.02	7.9	a	0.79	4.08	a	0.8	3.17	a	0.25	40.20	abc	1.64	3.93	a	0.35	23.40	a	6.41	61.10	abc	22.26	6.50	abc	1.1
Kay	0	f	0	e	92	efg	4.4	63	bcd	3.0	0.68	bc	0.00	4.9	cde	0.5	3.15	bc	0.2	2.33	cd	0.27	47.20	a	4.45	3.87	a	0.31	13.90	abc	3.22	29.00	cde	16.36	5.30	bcd	1.16
Koc	0	f	0	e	90	fgh	3.6	70	bcd	3.1	0.78	a	0.00	6.2	b	0.84	3.95	a	0.59	2.90	ab	0.41	46.90	a	2.79	3.87	a	0.15	13.80	a-d	4.25	23.00	de	19.32	5.90	abc	1.16
Sah	0	f	0	e	80	hı	4.0	54	e	2.7	0.68	bc	0.00	5.5	bcd	0.91	3.47	ab	0.55	2.53	bc	0.31	46.50	a	2.94	3.67	ab	0.15	15.40	abc	3.43	57.20	a-d	40.23	5.50	bcd	0.79
Sar	78	c	82	b	140	a	12.5	91	a	6.1	0.65	c	0.05	5.8	bc	0.26	2.83	bcd	0.28	1.88	def	0.36	32.30	cd	6.35	3.50	abc	0.3	23.50	a	15	64.30	abc	47.58	6.60	abc	1.51
Tir	60	d	80	b	100	ef	8.5	63	bcd	4.6	0.63	cd	0.07	4.3	d-g	0.99	2.75	bcd	0.53	2.06	cde	0.45	48.00	a	3.35	3.13	b-e	0.4	8.70	cd	2.81	10.40	e	6.03	5.60	bcd	0.12
Tos	0	f	0	e	86	gh	1.0	59	e	0.6	0.69	bc	0.01	3.3	ghı	0.21	1.89	fgh	0.28	1.43	fgh	0.22	43.00	ab	6.81	3.20	bcd	0.00	12.00	bcd	1.77	16.10	e	5.32	6.50	abc	0.32
Zer	32	e	20	d	135	ab	1.2	94	a	9.8	0.70	bc	0.07	3.9	e-h	0.27	1.93	e-h	0.15	1.42	fgh	0.17	36.80	bcd	2.24	2.93	de	0.25	11.40	cd	1.97	21.30	e	10.98	7.50	a	0.58
Mean	30		29		105			72			0.69			4.3			2.42			1.80			41.04			3.30			13.14			29.03			5.83		

Table 3. (Continued)

Variety	W3ItoDM			NM			KM			CaM			KMtoCaM			PHA			CGA			CGAtoPHA			PWA			DSIA			BFA			BEA		
	Mean		Std. Dev.	Mean		Std. Dev.	Mean		Std. Dev.	Mean		Std. Dev.	Mean		Std. Dev.	Mean		Std. Dev.	Mean		Std. Dev.	Mean		Std. Dev.	Mean		Std. Dev.	Mean		Std. Dev.	Mean		Std. Dev.	Mean		Std. Dev.
Alb	5.1	ab	0.5	0.13	g	0.03	8495	c	22.4	359	ghı	6.0	23.6	ab	0.33	119	c	3.46	67.0	a	4.29	0.56	ns	0.02	2.5	ef	0.28	2.4	ghı	0.15	10.3	de	1.91	15.4	e	4.24
Alt	5.1	ab	0.6	0.18	def	0.00	5682	g	37.4	571	cd	17.2	10.0	fg	0.36	78.3	g	3.79	42.3	d	5.16	0.54	ns	0.04	3.6	cde	0.22	3.2	c-f	0.3	12.2	cd	0.19	18	de	2.67
Bez	4.2	abc	0.6	0.20	c-f	0.02	7348	e	188.6	347	ghı	18.2	21.2	bc	0.57	97.3	e	5.51	51.3	cd	2.34	0.53	ns	0.05	4.7	bc	0.66	3.8	abc	0.35	18.2	ab	4.17	41.5	a	7.5
Cum	4.7	ab	0.3	0.20	c-f	0.00	6725	f	372.5	835	b	37.0	8.1	g	0.09	78	g	3.46	45.3	cd	3.27	0.58	ns	0.02	5.5	b	1.37	4.3	a	0.46	13.6	cd	1.4	15.8	e	1.48
Ein	3.1	c	0.5	0.17	fg	0.01	6653	f	610.8	437	e	35.5	15.2	de	0.16	94.3	ef	3.79	43.7	cd	3.9	0.46	ns	0.06	1.1	g	0.45	2.6	fgh	0.44	5	f	1.12	7.5	f	1.05
EmB	3.9	bc	0.6	0.21	a-e	0.00	6491	f	59.5	377	fgh	48.1	17.4	d	2.4	100.7	de	2.31	49.0	cd	3.4	0.49	ns	0.03	1.5	fg	0.2	2.1	hı	0.25	5.3	f	1.25	6.5	f	2.5
EmW	5.1	ab	1.0	0.25	a	0.03	7526	de	53.0	305	ı	36.7	24.9	a	2.85	106.3	d	3.79	54.0	bc	9.74	0.51	ns	0.08	1.8	fg	0.1	1.9	ı	0.06	6	f	0.74	15.7	e	2.04
Ger	4.1	abc	0.6	0.24	ab	0.01	11578	b	5.4	1068	a	14.6	10.8	f	0.15	96.7	e	3.06	54.7	bc	4.98	0.56	ns	0.04	4.2	bcd	0.2	3.2	c-f	0.26	12.3	cd	1.88	17.9	de	1.96
Gok	5.4	a	0.6	0.17	fg	0.01	6373	f	177.0	311	ı	18.3	20.5	c	0.64	138.3	a	8.5	65.3	a	5.68	0.47	ns	0.07	9.3	a	1.57	3.9	ab	0.25	21.7	a	2.1	30.1	b	1.73
Kay	4.4	abc	1.1	0.22	a-d	0.01	8031	cd	21.8	593	c	51.1	13.6	e	1.14	86.7	fg	2.31	50.3	cd	4.48	0.58	ns	0.04	3.2	de	0.94	3	def	0.21	7.7	ef	0.89	14.7	e	2.69
Koc	5.1	ab	0.7	0.21	a-e	0.04	13480	a	360.2	622	c	33.8	21.7	bc	0.6	83.3	g	2.31	45.7	cd	1.77	0.54	ns	0.01	4	cd	0.66	3.6	bcd	0.35	21.5	a	2.3	27.9	bc	3.11
Sah	4.6	ab	0.4	0.21	a-e	0.02	7399	e	567.1	335	hı	6.1	22.1	bc	2.09	78.7	g	4.16	42.3	d	1.29	0.54	ns	0.03	5.4	b	0.66	4.1	ab	0.55	14.7	bc	2.87	22.8	cd	2.1
Sar	5.5	a	1.3	0.24	ab	0.01	7279	e	385.9	341	hı	24.3	21.5	bc	2.66	128.3	b	7.64	66.3	a	11.37	0.52	ns	0.09	5.5	b	0.9	3.2	cde	0.32	19.2	a	3.17	31.1	b	4.21
Tir	3.9	bc	0.4	0.25	a	0.04	8367	c	444.2	401	efg	47.8	21.0	bc	1.4	95.7	e	7.09	48.3	cd	6.03	0.5	ns	0.03	3.6	cde	0.37	2.9	efg	0.06	13.4	cd	3.23	25.5	bc	4.61
Tos	4.9	ab	0.2	0.20	c-f	0.00	11747	b	116.9	537	d	5.8	21.9	bc	0.45	83.3	g	1.53	41.3	d	10.21	0.5	ns	0.12	3.4	cde	0.6	3	def	0.25	14.5	bc	0.24	28.8	b	2.28
Zer	5.5	a	0.9	0.22	a-d	0.02	8295	c	44.3	419	ef	29.8	19.9	c	1.52	117.7	c	3.06	64.0	ab	4.66	0.54	ns	0.03	2.4	efg	0.21	2.9	efg	0.21	7.4	ef	0.85	8.3	f	1.45
Mean	4.7			0.21			8217			491			18.3			98.9			51.9			0.5263	ns		3.9			3.1			12.7			20.5		

Table 5. Stepwise multiple regression analysis for the dependent variables PLM and ALM

		Model Variable	B	Std. Error	Beta	t	Sig.	Tolerance	VIF	R^2
PLM	All varieties	(Constant)	12.924	27.795		0.465	0.644			0.623
		PHM	0.885	0.168	0.510	5.261	0.000	0.893	1.120	
		DSIA	-24.425	5.166	-0.458	-4.728	0.000	0.893	1.120	
	Lodging varieties	(Constant)	186.182	16.942		10.989	0.000			0.74
		DSIA	-58.996	9.414	-1.518	-6.266	0.000	0.246	4.069	
		BFA	3.676	0.989	0.901	3.719	0.002	0.246	4.069	
ALM	All varieties	(Constant)	-45.640	34.206		-1.334	0.189			0.650
		PHM	1.999	0.414	1.176	4.833	0.000	0.137	7.276	
		DSIA	-16.573	5.158	-0.318	-3.213	0.002	0.833	1.200	
		CGM	-1.853	0.624	-0.698	-2.969	0.005	0.147	6.790	
		NM	239.596	95.979	0.231	2.496	0.016	0.955	1.048	
	Lodging varieties	(Constant)	310.703	70.974		4.378	0.000			0.483
		CGM	-1.605	0.391	-0.859	-4.102	0.001	0.655	1.527	
		KM	-0.015	0.006	-0.498	-2.378	0.029	0.655	1.527	

The Spearman correlation coefficients for PLM, ALM, and other variables in the lodged varieties are given in Table 6. The PLM showed a significant negative correlation with PHM, PWM, SWM, GWM, DSIM, BFM, BEM, PWA, DSIA, and BFA. The ALM showed a significant negative correlation with W2ItoDM, CGA, and DSIA. No significant positive relationships were found.

Table 6. Spearman correlation coefficients between PLM and ALM with other variables in the lodged wheat varieties

	PLM	PHM	CGM	CGMto PHM	PWM	SWM	GWM	HIM	DSIM	BFM	BEM	W2Ito DM
PLM	1.000	-.445*	-0.408	-0.246	-.749**	-.719**	-.663**	-0.094	-.669**	-.591**	-.537*	-0.192
ALM	.755**	-0.312	-0.426	-0.392	-0.403	-0.306	-0.279	0.085	-0.282	-0.307	-0.350	-.517*
	W3Ito DM	**NM**	**KM**	**CaM**	**KMto CaM**	**PHA**	**CGA**	**CGAto PHA**	**PWA**	**DSIA**	**BFA**	**BEA**
PLM	-0.306	0.134	-0.056	-0.235	0.300	-0.418	-0.299	0.030	-.670**	-.788**	-.578**	-0.354
ALM	-0.403	0.227	-0.062	0.007	0.002	-0.359	-.455*	-0.197	-0.423	-.480*	-0.343	-0.192

Principal component analysis (PCA) revealed 6 principal components with eigenvalues greater than 1. PC1 alone explained 37.2% of the variance and gave high loading values for almost all parameters. The first two components (PC1 and PC2) explained 63.3% of the total variance (Figure 2). Analysis of the biplot plot revealed a grouping of the traits of the cultivars that depended on whether they had lodged. The traits with high positive loading values (0.849-0.948) with PC1 were SWM, DSIM, GWM, PWM, DSIA, PWA, BFM, and BFA. In contrast, only PHM and KMtoCAM had low negative loading values. High positive loading values with PC2 (0.819-0.952) were observed for PHA, PHM, CGA, and CGM, whereas negative loading values (0.511-0.634) were observed for CaM, HIM, and the CGMtoPHM ratio.

SWM, PWM, GWM, and DSIM had the largest positive contributions in the nonlodged varieties. In the lodged varieties, SWM, DSIM, GWM, and PWM were contributors. The lodged varieties Gök and Sar were found to be completely different due to the parameters having positive loading values with both PC1 and PC2. Although these varieties had thick stems, they lodged due to their high plant height and center of gravity. The Alb, Zer, Emb, and Emw varieties lodged because of the parameters with negative loading values in PC1 and positive loading values in PC2. The local Tir wheat variety showed completely different behavior, with a tendency to lodge due to the effect of plant height, KMtoCaM, and W2ItoDM parameters, which had negative loading values in PC1. The Ein variety showed different lodging behaviors due to the negative loading values of both principal components. Evaluation of its position in Figure 3 revealed a more dominant lodging tendency despite its low negative loading value in PC1 (PHM [−0.137], KMtoCaM [−0.136]) due to its proximity to the X-axis.

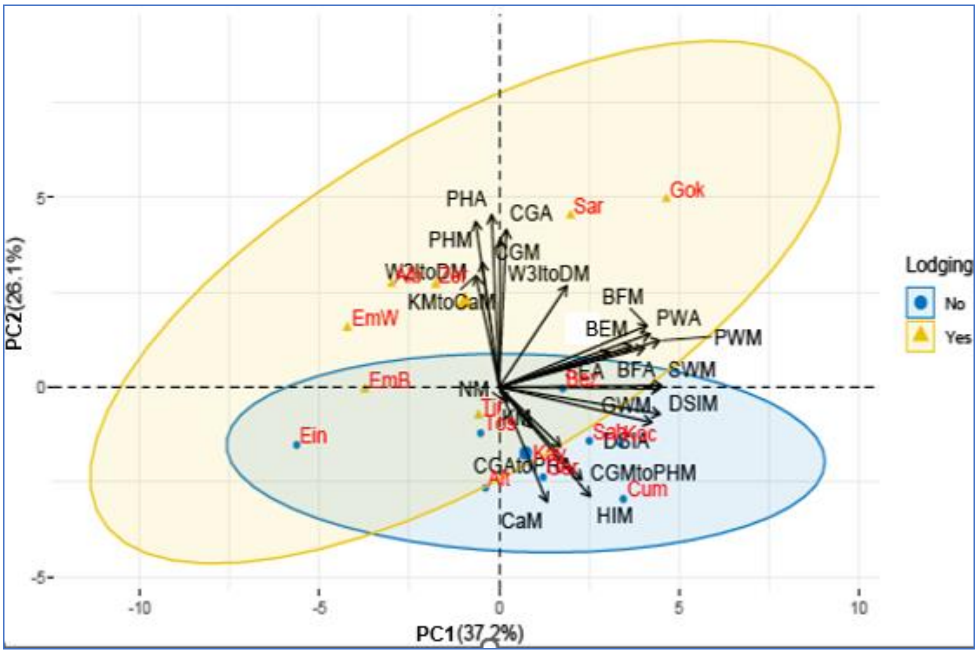

Figure 2. Principal component analysis (PCA) biplot of lodged and nonlodged wheat genotypes and the studied parameters

Stem lodging is associated with plant height and stem strength and typically occurs at the basal second internode (Zhang et al., 2016). In our study, logistic regression (Table 4), multiple regression (Table 5), correlation (−0.445*) (Table 6), and biplot analysis (Figure 3) clearly showed the relationship between plant height and lodging. Many studies have reported that plant height is the most effective factor in determining lodging in wheat (Kelbert et al., 2004; Navabi et al., 2006; Losert et al., 2017; Sher et al., 2018; Rabieyan et al., 2023). Genetic factors account for 66% of plant height (Zečević et al., 2008), but environmental factors also have an effect on plant height. Some plant growth regulators (PGRs) (e.g., ethephon, paclobutrazol, chlormequat chloride, mepiquat chloride, and trinexapac-ethyl) can shorten plant height and increase lodging resistance by reducing gibberellic acid synthesis, cell division, and cell elongation (Rademacher, 2000; Tripathi et al., 2003; Schluttenhofer et al., 2011; Peng et al., 2014). Increasing nitrogen availability and plant density can also lead to longer but thinner stems (Foulkes et al., 2011; Xiao et al., 2015).

In wheat breeding programs, plant height is still used as the most practical and easily selectable trait for lodging resistance (Kelbert et al., 2004). Foulkes et al. (2011) stated that the appropriate wheat height for yield and nonlodging should be 70 cm. However, other studies have indicated that in terms of the sustainability of yield increases, the height should be greater than 70 cm (Berry et al., 2015; Piñera-Chavez et al., 2016). Arinicheva et al. (2021) stated that the maximum plant height for lodging resistance should be 84-94 cm. In our study, the classification tree analysis yielded results only for the PHM value; however, when the PHM was above 104 cm, the probability of lodging was 95%. Considering the risk of lodging and the loss in grain and straw yields, the appropriate plant height appears to be

90 cm, which is just below the value found in our study.

Increasing the center of gravity, which is largely related to plant height (Okuno et al., 2014), decreases lodging resistance (Berry et al., 2003b; Khan et al., 2020). In our study, the Mann-Whitney U test established a critical value for CGM of approximately 80 cm. The lodging probability of varieties with higher CGM values seemed to be quite high. An increase in CGM, which is positively correlated with agronomic practices, such as nitrogen fertilization (Yang ShiMin et al., 2009) and planting density (Xiao et al., 2015), results in increased lodging.

Grain yield in wheat is related to the number of spikes per m^2 and the spike yield (Zheng et al., 2017). Lodging and yield are negatively correlated, as yield increases as spike weight increases (Navabi et al., 2006). On the contrary, decreases in the grain yield per plant (i.e., spike weight decreases) will lessen the risk of lodging (Tripathi et al., 2004). Our findings indicate a negative correlation between PL and PWM, SWM, and GWM (Table 6), and the biplot analysis confirmed a positive loading value for PL with PC1 (Figure 3). This result agrees with the findings of previous studies. A positive correlation is evident between lodging resistance and yield (i.e., the stronger the stem, the higher the yield) (Lubnin, 2006). However, simultaneously increasing wheat yield and lodging resistance is challenging (Li et al., 2023). Nevertheless, efforts should be made to understand and achieve a balance between the two (Kong et al., 2013).

The development of new varieties with fertile spikes, shorter plants that express the Rht gene, and agronomic advances naturally caused increases in the harvest index (Zheng et al., 2017). However, the increase in grain yield and harvest index has stopped in recent years (Shearman et al., 2005; Schauberger et al., 2018). In wheat plants 70 cm tall, the appropriate harvest index for maximum yield was reported as 0.42 (Berry et al., 2007). Since higher yield targets require varieties with higher stem resistance and greater plant height, the harvest index value will change. In our study, no significant relationship was found between Pl and either Al or HIM. Since HI is a proportional value, associating it with lodging alone is difficult. A meaningful result might be achieved by evaluating it together with other traits (e.g., yield, spike weight, internode diameter, and weight).

Stem diameter and stem physiological characteristics are important parameters in determining lodging resistance (Tripathi et al., 2003; Yizhen and Guohui, 2003). Stem diameter alone explains about 49% of the variance in lodging resistance (Zuber et al., 1999). A larger stem diameter increases lodging resistance, as a larger stem contains more lignin, cellulose, and water-soluble carbohydrates (Tripathi et al., 2004). Increases in stem diameter have been reported to significantly increase lodging resistance (Berry et al., 2003a; Zhang et al., 2020; Bisht et al., 2022; Wang et al., 2023). Similarly, our study findings confirmed a significant negative relationship between DSIM and PL rate in the logistic regression analysis (Table 4). In addition, as DSIM (OR: 0.263, 1/0.263=3.8) increases, the lodging resistance of plants increases approximately fourfold. The target size of the diameter of the second internode in terms of lodging resistance has been stated as 3.5 mm (Packa et al., 2015), 4 mm (Xiao et al., 2015), and 4.9 mm (Foulkes et al., 2011), whereas the risk of lodging seems to be quite high at values below 3.3 mm. In our study, a value above 3.3 mm was seen as a good reference value in terms of tilting resistance.

Lodging is mostly seen in the 2nd internode from the bottom because the lower 1st internode is short and has high resistance (Xiao et al., 2015). The resistance of the 3rd internode is weak; therefore, most of the load is borne by the 2st internode (Ageeva et al., 2020). Most often, 2nd internode data are used to determine stem resistance. In our study, ALM showed no significant correlation with BFM or BEM, whereas it showed a significant negative correlation with PLM (Table 6). In addition, logistic regression analysis showed that BFA had a negative effect on lodging (Table 4). As BFM decreased, the lodging rate increased.

Measurements made during the flowering period showed relatively low values compared to measurements made during the harvesting period. However, a point to consider is that the measurements of flowering period stem resistance were made after the stems were dried. Indeed, Feng et al. (2023) reported that stem resistance decreased after flowering, contrary to the results of our study.

The BFM values varied widely in the present study, with values ranging between 23.5 and 3.5 N among the varieties. This result is similar to the findings of previous studies (23.9 to 9.6 N) (Alizadeh et al., 2011; Chandio et al., 2013). The differences can be attributed to anatomical structure (Berry et al., 2003b; Tripathi et al., 2003), internode length (r=0.63) (Rabieyan et al., 2023), and test speed (Tabaracci et al., 2024).

K, Ca, and Si are the elements that have an effect on wheat stem anatomical structure (Liu et al., 2024). K increases the accumulation of structural carbohydrates, thereby increasing the thickness of the stem wall through the lignification of collenchyma and sclerenchyma cells (Zhang et al., 2010), while Ca and Si increase cellulose and lignin content in epidermal cells (de Bang et al., 2021). Therefore, these elements increase the stiffness, toughness, and elasticity of the stem to increase lodging resistance (Zhang et al., 2021; Liu et al., 2024). A low K content will reduce stem strength, as reflected in the negative relationship between ALM and KM in the lodged plants observed in the multiple regression analysis (Table 5).

Our study demonstrated a positive relationship between ALM and NM in multiple regression analysis using all varieties (Table 6). N fertilization is known to increase K and Ca concentrations, thereby increasing lodging resistance, but increases in pH and decreases in cellulose content decrease lodging resistance (Wang et al., 2023). The concentrations of cellulose, hemicellulose, and lignin in the cell walls of the middle and lower internodes did not change significantly in the presence of N, suggesting that structural resistance may be more related to the interaction and arrangement of carbohydrates and lignin in the cell walls (Knapp et al., 1987). The effects of mineral elements on the improvement of lodging resistance are apparently less than their effects on stem structure (Wang et al., 2023). In our study, more lodging occurred in varieties with high KMtoCaM values, suggesting that an increase in K content may cause a decrease in Ca uptake.

The need for the development of varieties resistant to disease and lodging is becoming greater for achieving sustainable nutritional supplies (Laidig et al., 2022). Although the relationship between various plant traits and lodging resistance has been extensively studied, traits that can be used in breeding programs have not yet been fully developed (Packa et al., 2015). This is because many traits of lodging and nonlodging varieties are similar, and large differences exist in yield potential and lodging resistance between varieties (Kong et al., 2013; Xiao et al., 2015). Although Kong et al. (2013) stated that lodging resistance is better reflected by morphological traits than by chemical characteristics, the evaluation of several traits together will give more accurate results in determining varieties with lodging resistance (Packa et al., 2015). Our study findings revealed a relationship between the lodging rate and several traits, including positive correlations with PHM, CGM, W2ItoDM, and KMtoCaM and negative correlations with DSIM, BFM, KM, CaM, CGAtoPHM, PWA, and BFA.

In our study, in general, the most resistant varieties in terms of lodging were modern varieties (Wang et al., 2023). This is because lodging resistance and stem diameter have increased with the use of shorter varieties in recent years (Packa et al., 2015; Zhang et al., 2016). The landrace varieties with spelt were the most prone to lodging. Bare-grained local varieties were in between these two groups. Although plant height seems to be the major contributor to lodging, some variation was also observed in taller wheats. This suggests that genetic gains in lodging tolerance can be obtained to some extent independently of plant height (Rht) (Navabi et al., 2006). Our study highlights varieties (Gök and Zer) with very high plant heights (143 and 135 cm) and very little lodging (PLM: 32%). Since increasing the lodging resistance of very tall plants will be difficult, concentrating on the development of medium-height varieties (91-99 cm) (Zuber et al., 1999) could be useful in terms of maintaining good grain and straw yields.

CONCLUSIONS

In recent years, increasing lodging resistance by shortening plant height (through the Rht gene) has been very successful in terms of yield and nitrogen efficiency. However, doubts have arisen regarding its sustainability, and breeding for lodging resistance may limit increases in yield.

The development of relatively tall, lodging-resistant, and productive varieties will mean an increase in straw production, which has many uses besides yield. The high lodging rate in some landrace wheat genotypes is related to plant height, and lodging seems inevitable under high-yield conditions. However, some genotypes (e.g., Gökala and Zerun) show the opposite characteristics: although they are quite high in height, they have very low lodging rates and angles. The effective factors here seem to be stem thickness and strength. These genotypes can be used as a genetic resource for obtaining high height and lodging resistance while still creating productive varieties.

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