Bulgarian Journal of Agricultural Science, 31 (No 6) 2025, 1126–1136

Characteristics of triticale breeding lines and cultivars from IPGR Genebank in Sadovo

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Abstract

Bonchev, B., Chipilski, R., Uhr, Z. & Angelova, T. (2025). Characteristics of triticale breeding lines and cultivars from IPGR Genebank in Sadovo. *Bulg. J. Agric. Sci., 31*(6), 1126–1136

The study of breeding lines and cultivars of triticale was conducted between the 2019/2020 and 2022/2023 growing periods in an experimental field in Sadovo, Bulgaria. The most significant overall estimated positive indirect effect on yield is associated with the number of grains per spike, derived from the weight of grains per spike. The weight of grains per spike had the most significant positive correlation with grain yield. A negative correlation is confirmed between wet gluten content and crude protein with grain yield and spike-related traits. Wet gluten content and protein content had a positive correlation with thousand kernel weight. The standard cultivar Kolorit and breeding lines TC 295 and BGR 30816 had a high value of chlorophyll content index and grain yield. The investigated breeding lines and cultivars from the IPGR genebank have lower stems than the cultivar Rakita. An increase in harvest index in breeding line TC 295 and cultivar AD 7291 is associated with high grain yield. Breeding line BGR 26787 has a high chlorophyll content index, crude protein, and wet gluten content. However, this line occurs in the opposite interaction between technological characteristics and low grain yield, for breeding high-grain-yield triticale from investigated lines and cultivars in the IPGR genbank in Sadovo. A delicate balance between plant height, harvest index, and spike-related traits is necessary.

Keywords: triticale; crude protein; CCI index; elements of grain yield; correlation

Introduction

Triticale (×*Triticosecale Wittm*. ex A. Camus.) is a cultivated plant obtained artificially by methods of interspecific hybridization and experimental polyploidy from wheat (*Triticum* sp.) and rye (*Secale* sp.), with the main direction of use for fodder purposes (silage, hay, and concentrated cereal feed) (Wilson, 1876; Béres et al., 2018). Triticale is the product of crossbreeding of the tetraploid wheat *Triticum durum* L. or the hexaploid wheat *T. aestivum* L. with diploid rye *Secale cereale* L., with haploid doubling with colchicine to produce a stable amphidiploid. From these crosses, a hexaploid is obtained, in which there is no D genome, and an octaploid with the wheat and rye AABBDDRR genomes (Lorenz, 2003).

Triticale was given the status of an independent crop in the 1970s, when it was designated as hexaploid triticale by Larter et al. (1970). Further work by Simmonds (1976) provided a summary chart of the origins of different types of triticale, including their classification.

Being a derivative of rye, triticale has always been assumed to be relatively resistant to abiotic stress (Blum, 2014). The stages of plant development from germination to tillering include, and the stages of maturity depend mainly on the climatic conditions of the respective year and to a lesser extent on the cultivar (Georgieva and Kirchev, 2018; Kirchev and Muhova, 2018). Similar is the claim of Stefanova-Dobreva (2019) that differences in interphase Tillering-Terminal spikelet initiation periods, terminal spikelet initiation-heading, and Heading-Maturity are more apparent depending on the conditions of the year.

Desheva and Kachakova (2013) found low variation in the trait weight of thousand-kernel wheat. A strong positive correlation was found between grain weight and the number of grains of the main spike, and the number of spikelets with spike length (Dimitrov et al., 2020). Grain weight per spike, which is the main yield component, is highly dependent on environmental conditions (Zanke et al., 2015). Traits such as plant height, number of spikes/m2, and weight per 1,000 kernels have a direct effect and strong influence on yield expression (Markova-Ruzdik, 2015). The test weight of grain is a complex trait that varies depending on the genotype, the predecessor, fertilization, and agricultural practices (Lalević et al., 2022). Fertilization is a factor that changes agronomic and quality characteristics. The values found increased from 6.6 to 9.2% for the traits of plant height, ear length, number of grains per ear, grain weight, weight per 1000 grains, and quality traits (Jolankai and Nemeth, 2002) in triticale, as studied under organic and mineral fertilization (Muhova et al., 2021a).

A breakthrough in the cultivation, production, and use of triticale will be its importance as a human food (Salmon et al., 2004). The combination of several important agronomic traits: high grain yield, a significant amount of accumulated protein with a high content of essential amino acids, and above all, lysine, as well as a high degree of adaptability. It is a valuable source of protein for animal feed and human consumption (Burdujan et al., 2014). The results showed that the wet gluten content was generally low to medium (Tohver et al., 2005; Zecevic et al., 2010).

Further improvement of triticale end-use quality effectively requires breeding strategies that rely on rapid, simple, inexpensive, and accurate assays. Although significant improvements have been made in the physical characteristics of grain, many quality parameters still require special attention (Woś and Brzeziński, 2015; Randhawa et al., 2015).

Studies have found that spectral indices derived from light absorbance or reflectance in the visible and near-infrared (NIR) regions exhibit good correlations with LChl and can be used to develop non-destructive methods for LChl measurements (Gitelson et al., 2016; Sims and Gamon, 2002). Estimating plant traits using remote sensing data, such as leaf chlorophyll concentration (LChl), is important for mapping the spatiotemporal variability of crop and soil conditions (Padilla et al., 2018). Leaf chlorophyll content is a good indicator of photosynthesis activity, mutations, and stress conditions (Naumann et al., 2008), and chlorophyll content correlates with higher yields under diverse conditions (Monteoliva et al., 2021). Non-destructive methods offer a cost-efficient way to measure LChl frequently over a large area. One of the significant constraints to the productivity of cereal crops is drought stress, and under future climate change scenarios, water deficits are expected to increase in most arid and semi-arid regions (Wassmann et al., 2009; Ramazani et al., 2021).

It is assumed that there will be a positive correlation between the amount of chlorophyll and yield, and a negative correlation between the technological qualities of the grain and grain yield. This study aimed to characterize breeding lines and cultivars of triticale from the GenBank of IPGR-Sadovo in terms of yield elements, technological traits, crude protein content, CCI index, and grain yield.

Material and Methods

A single-factor field trial has been released at the 2019 – 2023, in Institute of Plant Genetics Resources experimental fields in Sadovo, to test productivity and to more fully assess and evaluate triticale lines and varieties in a competitive cultivar trial. The trial was conducted in three replications and a harvest plot of 10 m², with the cultivar Kolorit used by the Executive Agency of Variety Testing, Approval, and Seed Control as a standard. Pre-sowing fertilization was carried out with NPK 15:15:15+10 S at a rate of 20 kg/da. The agricultural practices of the experiment were carried out with the application of herbicides and insecticides, depending on visual findings of pests, without the spraying of fungicides. In spring, manual fertilization with 25 kg/da of ammonium nitrate was carried out. The total nitrogen applied over the years was 12 kg/da.

Relative leaf chlorophyll content, expressed as Chlorophyll content index (CCI), was measured with chlorophyll content meter-CCM 200 plus, manufactured by Opti-Sciences Inc, NH, USA. Data for the chlorophyll content index were presented as mean values ± SE. The physiological assessment was conducted in vivo on-site. The measurements were taken on two dates per vegetation period during the grain-filling phase from average leaf samples. The dates of the measurements were 01/06/2021 and 09/06/2021, for the first year, 20/05/2022 and 01.06/2022, for the second year, and 12/05/2023 and 07/06/2023 for the third year. From each genotype, measurements are made on 15 leaves (n = 15).

Wet gluten content was based on: (WGY, %), (BSS 13375:1990/Amendment 1:1993. „Grain. Methods for determining the quantity and quality of gluten“).

Crude protein (CP, %) was made according to the Kjeldahl method (BDS EN ISO 5983-1:2006).

Fit analysis was used to account for reliable differences between triticale cultivars and lines using least significant differences (LSD) and coefficient of variation, as determined by products JMP 5.0.1 (SAS Institute) and SPSS 19 (SPSS Inc., IBM Corp.). The strength and direction of the correlation were established by the scale of Genchev et al. (1975). Correlation analysis was used to determine the relationships between grain yield and its related traits. A grain yield linear model was established using multiple stepwise regression analysis (Vandev, 2003) and path analysis. ANOVA was performed to compare means at $p \leq 0.05$ using Microsoft Excel for Windows 10.

Results and Discussion

The first (14.2 mm) and last years (2 mm) are characterised by low rainfall during the sowing period. The second (6.3 mm) and third years (12 mm) are characterized by a lack of rainfall during the germination period in November. The exception is October 2021, when 168 mm fell. The highest rainfall in November occurred in 2019, with a total of 80.7 mm. In December 2021, significant rainfall was observed (96.1 mm). A drought is observed in January in the first year (2.1 mm). A winter rainfall maximum is observed in January 2022 (96.4 mm). Drought occurred in the last year in February (1.2 mm). Continuous rainfall was observed in March and April 2020, totaling 185.3 mm. In the third year, there is a spring drought in March (22.3 mm). In May, during anthesis, rainfall is below normal except in 2023 when 81 mm falls. In the third year, during the interphase period, a hailstorm is observed at the end of anthesis and the beginning of grain filling. The last two years have seen above normal rainfall at the end of grain set, with 159.7 mm in the third year. In three of the years, the total rainfall exceeded the norm, with the most significant increase occurring in the third year, at 215 mm. The last year was characterized by low rainfall totals, with droughts in October and February (Figure 1).

October 2020 is characterized by a high average temperature of 15.1°C, accompanied by above-normal precipitation. The same period in 2022 was colder (11°C) with significant rainfall. November 2019 is characterized by the highest temperature of the four years during the triticale emergence period (10.7°C), accompanied by increased precipitation. The month of December is typically warm, with temperatures around biological zero for cereals, although cooler temperatures were observed in December 2019 and 2021. In January of the third year, vegetation can be observed at a temperature of 5.7°C. The February monthly average temperature is above biological zero for triticale, at 3.33 °C (38°F), for germination (www.biotill.com). In March 2022, the temperature was colder (4.9°C), and insufficient rainfall was observed. In April 2022, the temperature exceeded 13.7°C, accompanied by deficient rainfall. May temperatures for the period are higher (around 18°C). The exception is the month of May of the last year (15.7°C), which has significant rainfall. High temperatures and below-normal rainfall are unfavourable for anthesis in the first three years. June is the warmest month in 2023 (23°C), when most rainfall also occurs. The overall average temperature for the period October to the end of

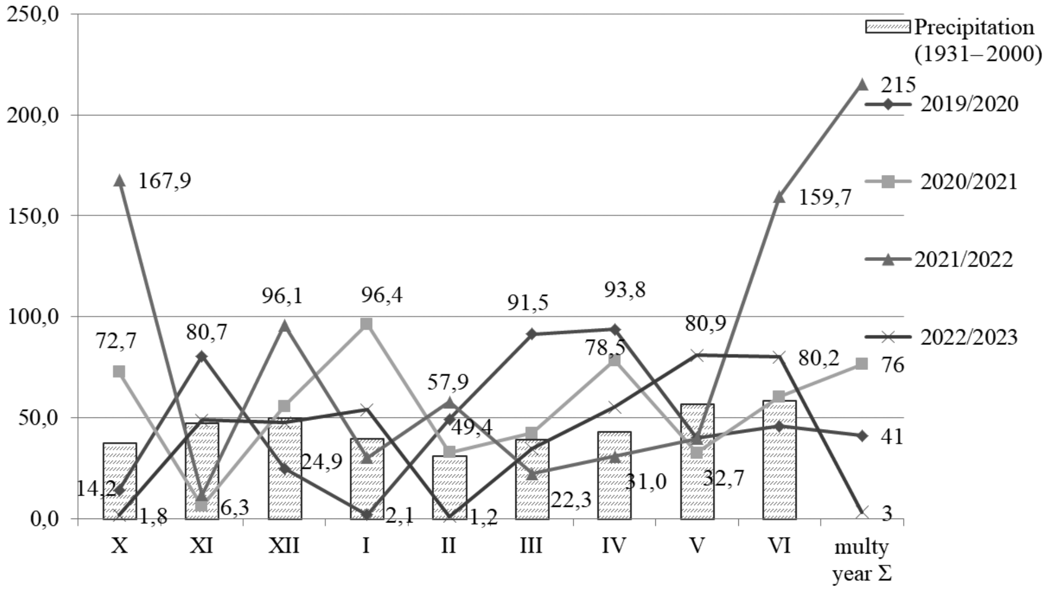

Fig. 1. Meteorological characteristic of precipitation amount during period 2019–2023
Source: Authors' own elaboration

June is highest in 2023 (11°C) and lowest in 2022 (10.1°C) (Figure 2).

The morphological characteristics of triticale varieties and lines during the period 2019 – 2023 are presented in Table 1.

Plant height exhibits a low variation of 6.69%, ranging from 93 cm to 135 cm. The cultivar Rakita is the tallest (135 cm), and actually belongs to the triticale varieties of rye type (Kirchev, 2019). The lowest values were observed for BGR 31374 (93cm) and differed significantly from the other lines and varieties, except lines TC 78 (98 cm) and TC 295 (102 cm), and BGR 30071 (104 cm). There is an intermediate group of lines, forming a height of 60 cm, including Trit 32/6, cultivars AD 7291, Kolorit, and lines BGR 30816, BGR 26787, and BGR 30814, with heights ranging from 110 to 118 cm. According to Kirchev (2019), as a result of reducing the height of plants, it is possible to increase the level of grain yield and to improve the quality of grain. Breeding lines and cultivars from the IPGR genebank included in this investigation are lower than cultivar Rakita.

The length of the spike exhibits low variation (6.91%), ranging from 8.20 cm to 11.88 cm. The spike of the Kolorit cultivar (11.88 cm) has proven to be the longest spike of the studied plant materials of triticale. Cultivar Rakita (11.45 cm) and BGR 30814 (11.18 cm) are close to the standard value. Triticale cultivar AD 7291 (10.8 cm) and line TC 295 (10.65 cm) are below the value of the standard cultivar Kolorit. The lines Trit 32/6 (8.2 cm), BGR 30816 (8.4 cm), TC 78 (8.53 cm), BGR 26787 (8.63 cm), BGR 31374 (8.8 cm), BGR 30071 (9.03 cm), and KS 60 (9.00 cm) have proved the shortest length of the spike.

The number of spikelets in the spike exhibits moderate variation (10.2%). The trait has maximum values in the Kolorit cultivar (30) and the Rakita cultivar. Close to the standard value of the number of spikelets are cultivar AD 7291 (29), line BGR 30814 (29), and TC 295 (26). Low is the number of spikelets of lines BGR 30816 (20), TC 78 (21), BGR 26787 (22), Trit 32/6 (22), BGR 31374 (22), KS 60 (23), and BGR 30071 (24). The mentioned lines and cultivars are below the standard Kolorit for the number of spikelets per spike.

The number of grains per spike exhibits medium variation (14.19%). Standard cultivar Kolorit (72) has the largest number of grains per spike. Close to the standard value but proven lower are lines BGR 30814 (57), TC 295 (53), and cultivars AD 7291 (54) and Rakita (50). Also, lines KS 60 (46) and BGR 31374 (45) are lower. A lower value for the number of grains per spike has lines of Trit. 32/6 and BGR 30071 (44), TC 78 (40). For the number of grains per spike, the lowest proven difference from cultivar Colorit is breeding line BGR 26787 (31).

The weight of the grains in the spike exhibits a medium variation (18.76%). The cultivar Kolorit has the highest value of the trait (2.78 g). Lines TC 295 (2.31 g) and AD 7291 (2.26 g) have lower values, but without a proven difference from the standard. The cultivar Rakita (2.01 g), lines BGR 30814

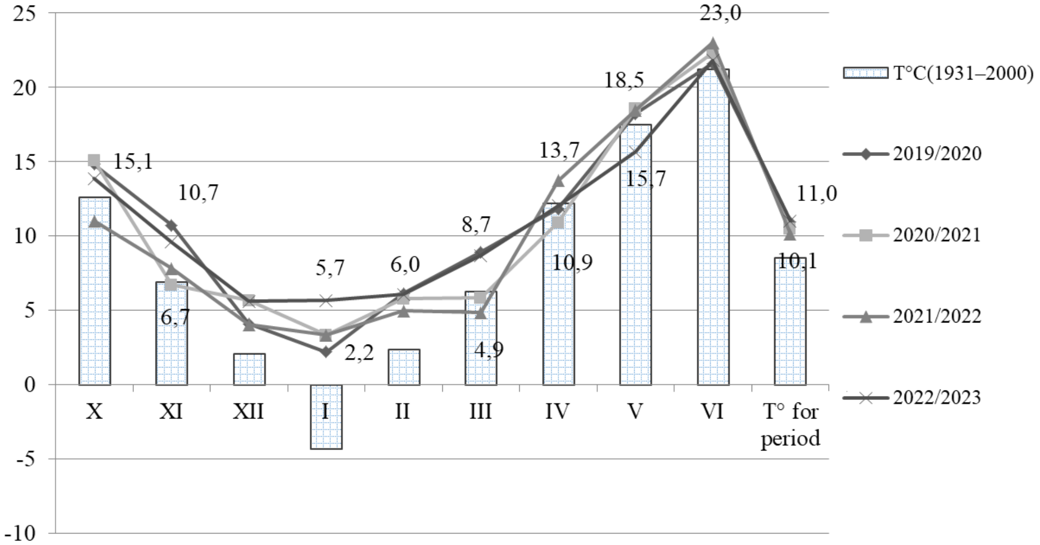

Fig. 2. Meteorological characteristic of monthly mean temperature during period 2019–2023
Source: Authors' own elaboration

(2.04 g), BGR 30071 (1.93 g), BGR 30816 (1.89 g), and BGR 31374 (1.71 g) are lower, with a proven difference from the standard. The lowest value of grain weight per spike has lines TC 78 (1.66 g), BGR 26787 (1.54 g), and Trit 32/6 (1.38 g), which are proven differences to the standard (Table 1).

The cultivar with the most favourable combination of plant height and traits associated with the spike is Kolorit. The Rakita cultivar is the tallest, with a large number of spikelets and a long spike. The line BGR 39039 has a significant weight of grains per spike. The cultivar AD 7291 has a large number of spikelets per spike. The line BGR 30814 has a favourable combination of plant height, spike length, and number of spikelets per spike (Table 1).

The number of productive tillers per m² varied widely (25.59%) (Table 2). This trait varies from 431 for the Kolorit cultivar to 663 for the KS 60 line, with a proven difference. The other studied breeding lines and cultivars have no proven difference from the standard cultivar Kolorit.

The weight per 1000 grains had a low variation (8.67%) from 35.49 to 48.47 g. The 1000-grain weight was the highest value for line BGR 26787 (48.47 g) and BGR 30071 (43.23 g), with a proven difference from the standard for BGR 26787. Line BGR 30816 (42.54 g) has a higher value of the weight of 1000 grains, but with no proven difference to the standard cultivar Kolorit (37.65 g). Standard Kolorit has no proven difference compared to line KS 60 (36.75 g), BGR 31374 (37.97 g), cultivar Rakita (37.93 g), line TC 78 (40.58 g), cultivar AD 7291 (38.06 g), and line BGR 39039 (40.60 g). Below the standard for weight of 1000 grains is line BGR 30814 (35.49 g) (Table 2).

The hectolitre weight is similar to the weight per 1000 kernels, with a low variation (5.88%). It exhibits the lowest variation in the studied traits. It varied from 67.4 kg/hl in the Kolorit cultivar to 73.2 kg/hl kg/hl kg/hl in the line BGR 30814. There were no proven differences between varieties and lines for this trait.

The biomass at the Heading-Anthesis interphase period varied significantly (24.45 %) from 1.218 kg/m² in line TC 295 (BGR 39039) to 1.669 kg/m² BGR 30071. No proven differences were found. Biomass in the complete maturity phase had less variation (20.45 %) than biomass in the Heading-Anthesis interphase period. It is close to the medium variation limit. The biomass at full maturity varies from 1.887 kg/m² in TC 78 to 2.228 kg/m² in line BGR 30814.

The harvest index has a medium variation (16.85%) of 0.245 to 0.439. The highest harvest index of 0.439 is TC 295 (BGR 39039). After TS 295, with close values of harvest index, are cultivar AD 7291 (0.405) and line BGR 30814 (0.400). Lines KS 60 (0.344), BGR 31374 (0.336), BGR 26787 (0.335), cultivar Rakita (0.336), TC 78 (0.319), and BGR 31816 (0.294) have harvest index values below that of cultivar Kolorit (0.381), but without a proven difference. The lower value of the harvest index is observed in line BGR 30071 (0.260) and line Tritcale 32/6 (0.245), which have the lowest value below the standard, with a proven difference.

The wet gluten content varies significantly from year to year. The values for the first year of the study were low, ranging from 3.32% for cultivar Rozhen to 20.6% for line BGR 26787. In the second year, a significant increase was observed, from 14.0% for line BGR 30812 to 27.36% for

Table 1. Morphological characteristic of triticale varieties and lines

№	Varieties and lines	Height (cm)		Spike length (cm)		Number of spikelets per spike		Number of grains per spike		Weight of grains per spike (g)	
St	Kolorit	117	b	11.88	a	30	a	72	a	2.78	a
2	BGR 26787	118	b	8.63	c	22	de	31	e	1.54	de
3	BGR 28729- Trit.32/6	114	b	8.20	c	22	c-e	44	cd	1.38	e
4	BGR 30071	104	c-e	9.03	c	24	cd	44	cd	1.93	b-d
5	BGR 30814	119	b	11.18	ab	29	ab	57	bc	2.04	b-d
6	BGR 30816	117	b	8.40	c	20	e	39	de	1.89	b-e
7	BGR 31357- KS 60	110	b-d	9.00	c	23	c-e	46	b-d	1.76	b-e
8	BGR 31373-TC 78	98	ef	8.53	c	21	de	40	de	1.66	c-e
9	BGR 31374	93	f	8.80	c	22	de	45	b-d	1.71	b-e
10	BGR 34824-Rakita	135	a	11.45	ab	30	a	50	b-d	2.01	b-d
11	BGR 39039-TC 295	102	d-f	10.65	b	26	bc	53	bc	2.31	ab
12	AD 7291	114	bc	10.80	b	29	ab	54	bc	2.26	a-c
x̄		112		9.71		24.7		48		1.94	
CV %		6.69		6.91		10.2		14.19		18.76	
LSD		10.7		0.96		3.6		11.46		0.61	

Source: Authors' own elaboration

Table 2. Agronomic, technological and biochemical traits of triticale lines and varieties

№	Varieties and lines	Number of productive tillers/m²		Weight thousand kernel (g)		Test weight (kg/hl)		Biomass in Heading-Anthesis kg/m²		Biomass in Full maturity kg/m²		Harvest index		WGC, %		CP, %	
St	Kolorit	431	b	37.65	b-d	67.4	a	1.332	a	2.052	a	0.381	a-c	16.97	ab	10.58	a
2	BGR 26787	522	ab	48.47	a	70.8	a	1.390	a	1.846	a	0.335	b-e	26.74	a	13.20	a
3	BGR 28729- Trit.32/6	572	ab	37.86	b-d	69.1	a	1.326	a	2.123	a	0.245	e				a
4	BGR 30071	517	ab	43.23	ab	70.4	a	1.669	a	2.228	a	0.260	de				a
5	BGR 30814	478	ab	35.49	d	73.2	a	1.396	a	1.826	a	0.400	ab				a
6	BGR 30816	530	ab	42.54	bc	72.4	a	1.523	a	1.973	a	0.294	c-e	21.24	ab	12.28	a
7	BGR 31357- KS 60	663	a	36.75	cd	67.8	a	1.371	a	1.887	a	0.344	a-d	18.05	ab	12.07	a
8	BGR 31373-TC 78	547	ab	40.58	b-d	68.2	a	1.254	a	1.743	a	0.319	b-e	19.41	ab	12.10	a
9	BGR 31374	592	ab	37.97	b-d	67.6	a	1.288	a	1.927	a	0.366	b-e	16.11	b	11.72	a
10	BGR 34824-Rakita	486	ab	37.93	b-d	72.3	a	1.269	a	2.100	a	0.336	b-e	18.65	ab	11.62	a
11	BGR 39039-TC 295	554	ab	40.60	b-d	70.4	a	1.218	a	2.146	a	0.439	a	18.65	ab	11.94	a
12	AD 7291	569	ab	38.06	b-d	71.8	a	1.382	a	2.220	a	0.405	ab	19.03	ab	11.40	a
$\bar{x}$		538		39.76		70.1		1.37		2.010		0.340		19.37		11.86	
CV %		25.59		8.67		5.88		24.12		20.45		16.85		31.04		14.23	
LSD		197		5.81		6.9		0.473		0.590		0.097		11.56		2.90	

WGC, %-Wet gluten content; CP, %-Crude protein

Source: Authors' own elaboration

line BGR 26787 (data by year are not presented). The variation (CV%) for the study period is high (31.04%), with average WGY values ranging from 16.11% to 26.74%. The highest average value was reported for line BGR 26787, and the lowest for line BGR 31374. The other investigated varieties and lines vary from the standard (16.97%) to 21.74 % (BGR 30816).

The trend of crude grain protein content persisted, with wet gluten (initially low and then higher in the second year of study). The variation of crude protein in the grain is medium for the years (CV = 14.23%), ranging from a value of 10.28% in the cultivar Colorit to 12.28% in the line BGR 30814. The LSD value for the protein content did not allow for the indication of proven differences between the investigated selection lines and cultivars (Table 2).

It was found that line BGR 39039 (692 kg/da) had a difference of -9%, cultivar AD 7291 (687.7 kg/da) had a difference of -1.9%, line BGR 30816 (638.3 kg/da) had a difference of -8.94%, KS 60 (613 kg/da) had a difference of -12.55% and line TS 78 (598 kg/da) had a difference of -14.65%. The differences with the standard are not proven. Below the standard in grain yield is the line Trit. 32/6 with a difference of -36.19 %, which is very well proven at GD 0.1 %. Below the standard with proven differences are the lines BGR 26787 (-17.97%), BGR 30814 (-21.02%), BGR 31374 (-21.49%), and BGR 30071 (-23.78%) (Table 3). Similar results for grain yield per 10 m² plot in three replications have been reported for 24 breeding lines and cultivars stored in the Sadovo IPGR genebank, as reported by Dimitrov et al. (2018).

The cultivar Kolorit, breeding lines BGR 39039 and BGR 30816, had a high value of chlorophyll content index and grain yield (Table 3 and Table 4). During 2021, the highest CCI values were reported for the lines with numbers BGR 39039, BGR 26787, BGR 30071, BGR 30816, and standard Kolorit (Table 4). The line BGR 39039 shows a statistically

Table 3. Grain yield of triticale lines and varieties

№	Varieties and lines	$\bar{x}$ (kg/da)	Difference	%	Prove
St.	Kolorit	701.0	0	0	IV
2	BGR 26787	575.0	-126.0	-17.97	V
3	BGR 28729- Trit.32/6	447.3	-253.7	-36.19	VII
4	BGR 30071	534.3	-166.7	-23.78	V
5	BGR 30814	553.7	-147.3	-21.02	V
6	BGR 30816	638.3	-62.7	-8.94	IV
7	BGR 31357- KS 60	613.0	-88.0	-12.55	IV
8	BGR 31373-TC 78	598.3	-102.7	-14.65	IV
9	BGR 31374	550.3	-150.7	-21.49	V
10	BGR 34824-Rakita	621.0	-80.0	-11.41	IV
11	BGR 39039-TC 295	692.0	-9.0	-1.28	IV
12	AD 7291	687.7	-13.3	-1.90	IV
LSD	5%	123.9			
	1%	168.8			
	0.1%	226.9			

Source: Authors' own elaboration

significant difference compared to a standard. At the same time, the early lines BGR 31373 and BGR 31374 expressed low CCI values.

In the second year, the lines BGR 31373, BGR 31374, BGR 30071, BGR 26787, BGR 30816, and the standard Kolorit showed the highest results. This year, lines BGR 31373 and BGR 31374 demonstrated their full potential in the early reading of the chlorophyll content index. During 2023, six lines showed high CCI values compared to the standard. The highest average values for the three vegetation years were estimated for lines BGR 26787, BGR 30071, BGR 30816, BGR 31374, BGR 39039, and the standard Kolorit, as the mean difference relative to the standard was not statistically significant (Table 4).

The meteorological conditions in May during the vegetation periods of 2021 and 2022 are similar to and typical of the last five years for the Sadovo area. The precipitation was below normal, while average temperatures were normal for the last forty years. These unfavorable ambient conditions affect the plant water exchange and induce water stress before and during the measurement of the CCI. Consequently, breeding lines with higher values are more tolerant to adverse climatic conditions. The climatic conditions during the period of active wheat vegetation in 2023 differed from those in previous years. The average temperatures were lower, while precipitation and relative humidity were higher; therefore, no plants with parameters characterizing drought availability were found.

Akbarian et al. (2011) suggest that triticale lines performed better than wheat cultivars in terms of drought tolerance, considering both grain yield and the majority of physiological traits. Grain yield positively and significantly correlated with the ratio of total chlorophyll (a+b) and RWC under drought stress conditions. Méndez-Espinoza et al. (2019) reported that the higher yield of triticale was linked to higher values of chlorophyll content, leaf net photosynthesis (An), the maximum rate of electron transport (ETRmax), the photochemical quantum yield of PSII [Y(II)], and leaf water-use efficiency.

The correlation analysis reveals a medium positive correlation between grain yield and spike length (r = +0.614*), a medium correlation with harvest index (r = 0.694*), and a strong correlation with grain weight per spike (r = 0.808*). According to Kirchev et al. (2007), the proportion of stems relative to leaves and spikes at the Chirpan and Sadovo sites is lower compared to the proportion of stems at General Toshevo, as confirmed by Muhova (2018) for Chirpan, which has a relationship with the harvest index.

Number of grains per spike (r = +0.501$^{n.s.)}$ and number of spikelets per spike (r = +0.483 $^{n.s..}$) positively correlated with grain yield. Spike length is strongly positively correlated (r = +0.971**) with the number of spikelets per spike. Also positive is the correlation between the number of spikelets per spike and grain weight per spike (r = +0.755**). It is confirmed that positive correlations exist between the number and weight of grains per spike, and between plant height and spike length (Muhova et al., 2021b). It is also confirmed that there is a positive correlation between the grain weight of the spike and the number of spikelets in the spike (Koshkin, 2016). Plant height (r=+0.156) is positively but weakly correlated with grain yield. This is due to the prevalence of lower forms and increased harvest index.

Table 4. Chlorophyll content index (CCI)

Varieties and lines	2021	2022	2023	Average 2021–2023
St-Kolorit	32.6±3.10	38.7±2.63	33.7±1.86	35.0
BGR 26787	37.7± 2.54	35.9± 2.00	37.5±2.00	37.1 n.s.
Trit 32/6	24.3 ±2.01	32.6±1.98	37.1±2.96	31.3 n.s.
BGR 30071	33.2 ±3.12	39.3±2.28	29.7±1.76	34.1 n.s.
BGR 30816	31.6±3.22	35.1±1.85	36.8±2.03	34.5 n.s.
BGR 31373 (TC 78)	22.8±2.20	40.6±2.56	34.50±1.61	32.6 n.s.
BGR 31374	21.8±2.25	41.3±2.54	39.9±1.65	34,3 n.s.
Rakita	22.0±1.90	26.5±1.47	40.6±1.78	29.7*
KS 60	29.1±2.95	33.6±2.13	31.2±2.35	31.3 n.s.
BGR 30814	27.3±2.70	30.5±2.25	25.2±1.72	27.7*
BGR 39039 (TC295)	39.5±3.75	29.6±1.81	33.8±2.31	34.3 n.s.
AD 7291	30.5±2.71	28.1±1.97	29.1±2.08	29.2*

LSD 5% = 5.46
LSD 1% = 7.78
LSD 0.1 % = 10.81
The data are presented as means±standard error; (n = 15)
Source: Authors' own elaboration

Table 5. Correlation of morphological, agronomic, economic, technological and biochemical traits of triticale varieties and lines

	NPT/m²	Plant height	Spike length	NSS	NGS	WGS	WTK	TW	Biomass H-A	Biomass FM	HI	GY	WGC %	Crude protein %
NPT/m²	1	-0.478	-0.580*	-0.538	-0.456	-0.530	-0.096	-0.341	-0.109	-0.089	-0.093	-0.201	-0.126	0.356
Plant height		1	0.466	0.518	0.186	0.178	-0.070	0.584 *	0.051	0.145	-0.046	0.156	0.305	-0.064
Spike length			1	0.971 **	0.848 **	0.843 **	-0.463	0.271	-0.267	0.297	0.679 *	0.614 *	-0.410	-0.757*
NSS				1	0.814**	0.755 **	-0.487	0.303	-0.191	0.385	0.576 *	0.483	-0.368	-0.720*
NGS					1	0.862 **	-0.662*	-0.098	-0.219	0.317	0.547	0.501	-0.672*	-0.940**
WGS						1	-0.294	0.062	-0.061	0.381	0.630 *	0.808 **	-0.461	-0.825**
WTK							1	0.136	0.361	-0.063	-0.305	-0.050	0.940 **	0.801 **
Test weight								1	0.304	0.181	0.100	0.090	0.474	0.296
Biomass H-A									1	0.249	-0.502	-0.202	0.427	0.259
Biomass FM										1	-0.049	0.193	-0.308	-0.540
Harvest index											1	0.694 *	-0.369	-0.433
GY												1	-0.242	-0.587
Wet gluten content %													1	0.807 **
Crude protein %														1

NPT/m²- Number of productive tillers/m², NSS- Number of spikelets, NGS- Number of grains/spikes, WGS- Weight of grains /spikes, WTK- Weight thousand kernels, TW- Test weight, Biomass H-A-Biomass Heading-Anthesis, Biomass PM-Biomass Full maturity, HI- Harvest index, GY- Yield of grain, WGC%- Wet gluten content %

Source: Authors' own elaboration

Grain protein content was negatively correlated with grain yield ($r = -0.587^{n.s.}$). Crude protein is in a medium to strong negative proven correlation with all yield elements originating from the spike: spike length (r = -0.757*), number of spikelets in the spike (r = -0.720*), number of grains in the spike (r = -0.940**), grain weight in the spike (r = -0.825**). The thousand-kernel weight correlates strongly and positively with crude protein (r = +0.801**) and with wet gluten content (r = +0.940**), and this correlation is well established. Yield could be increased by a compromise combination of the number of productive tillers and the number of kernels per spike, while maintaining the existing level of 1000 kernels per weight (Tsenov et al., 2013). Protein is strongly positively correlated with wet gluten yield (r = +0.807**), a fact that can be used for breeding purposes (Table 5).

The regression model with predictors spike length, number, and weight of grains per spike, and harvest index describes the yield dependence with R=0.928 and coefficient of determination R^2 = 0.862 (Table 6). The scatter plot visually shows that the regression model with a high R^2 yield is apparently linear (Figure 3). The R^2 value measures the strength of the relationship between the model under study and the dependent variable on a scale of 0–100% (Frost, 2020).

Table 6. Grain yield regression

R	R²	Adjst.R²	Std. Err.
0.928	0.862	0.783	35.035

Source: Authors' own elaboration

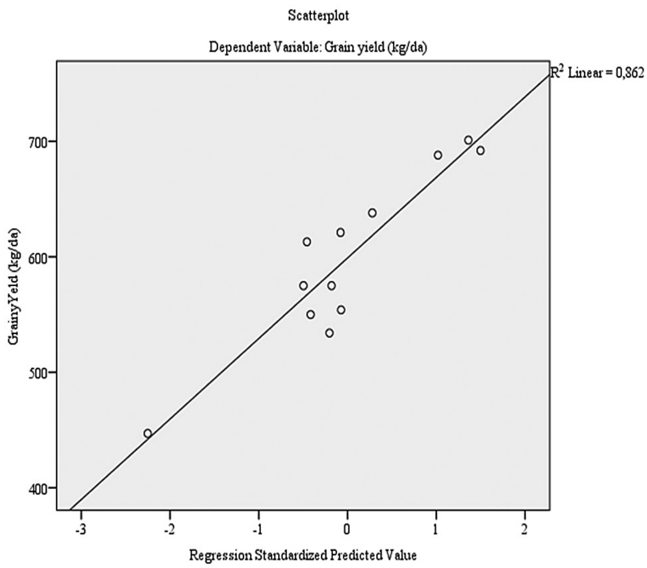

Fig. 3. Linear model of grain yield regression

Source: Authors' own elaboration

The variance of the yield regression model, with predictors of spike length, number and weight of grains per spike, and harvest index, was proven at sig.<0.01, confirming the regression model (Table 7).

The constant of the yield equation is positive and statistically significant at $p < 0.05$. Grain number per spike has a direct effect on grain yield, but is negative (β=-0.719), close to the sig=0.057 proved value. The adverse effect of the number of grains per spike is partially compensated by a positive correlation with grain yield ($r=0.501^{n.s.}$). Grain weight per spike has a positive direct effect (β=1.301**), which is overplayed on the positive correlation of yield with grain weight per spike (r=+0.808**) (Table 8).

The most significant overall positive indirect effect on yield is the number of grains per spike (1.220) derived from the weight of grains per spike. Next in importance is the indirect effect of spike length (+1.097). Grain weight per spike has an adverse indirect effect relative to grain number per spike on yield (-0.620) (Table 9). According to the researchers Slafer et al. (2014), the variation in yield is primarily due to changes in the number of grains per square meter, rather than the number of grains per spike (Tsenov et al., 2013).

Conclusions

The weight of grains per spike had the most significant positive correlation and direct effect on grain yield. Indirect effects of the number of grains per spike through the weight of grain per spike and spike length form the grain yield of the investigated triticale lines and cultivars. The adverse general path coefficient effect of grain weight per spike is low. Plant height is positively correlated with grain yield. This is a consequence of the prevalence of lower forms of life. Triticale cultivar AD 7291 and line TC 295 (BGR 39039) had increased harvest index connected to the grain yield.

It is confirmed that spike-related traits and grain yield have a negative correlation with wet gluten content and crude protein. However, wet gluten content and protein content had a positive correlation with thousand-kernel weight. Breeding line BGR 26787 exhibited high chlorophyll content index, crude protein, and wet gluten content, but had a low grain yield.

The standard cultivar Kolorit and breeding lines TC 295 (BGR 39039) and BGR 30816 had a high value of chlorophyll content index and grain yield. These accessions were more tolerant of drought conditions.

Table 7. Dispersion of the grain yield regression model

Source of variation	SS	df	MS	F	Significance
Regression	53489.98	4	13372.49	10.89	0.004
Residual	8592.02	7	1227.43		
Total	62082	11			

Source: Authors' own elaboration

Table 8. Unstandardized and standardized regression coefficients and grain yield correlation

Predictors	Unstand. Coeff.		Stand.Coeff.	t	Sig.	Zero-order
	B	Std. Err.	β			
(Constant)	256.101	82.84		3.092	0.018	
Spike length	-5.526	17.548	-0.100	-0.315	0.762	0.614*
Number grains per spike	-5.172	2.267	-0.719*	-2.282	0.057	0.501
Weight of grains per spike	256.276	61.583	1.301**	4.161	0.004	0.808**
Harvest index	429.022	252.099	0.335	1.702	0.133	0.694

Source: Authors' own elaboration

Table 9. Path coefficient analysis of grain yield

Predictors	Spike length	Number of grains/spikes	Weight of grains/spike	Harvest index	Gen.path coeff.	Correlation
Spike length	**β** = -0.100	-0.610	1.097	0.227	0.714	0.614*
Number of grains/spike	-0.085	**β** = -0.719*	1.121	0.183	1.220	0.501
Weight of grains/spike	-0.084	-0.620	**β** = +1.301**	0.211	-0.493	0.808**
Harvest index	-0.068	-0.393	0.820	**β** = +0.335	0.358	0.694

Source: Authors' own elaboration

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Received: **March 13, 2024**; *Approved*: **July, 05, 2024**; *Published*: **December, 2025**