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GENOTYPE × ENVIRONMENT INTERACTION FOR GRAIN YIELD AND MORPHO-QUALITY TRAITS IN PROMISING SPRING WHEAT GENOTYPES

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Abstract. *The evaluation of spring wheat genotypes for grain yield and quality traits is essential for identifying promising breeding material adapted to specific growing conditions. This study assessed the agronomic performance and grain quality of 23 spring wheat genotypes, including registered cultivars and advanced breeding lines, at the Agricultural Research and Development Station (ARDS) Livada, northwestern Romania, during the 2026 agricultural year. The experiment was conducted using a balanced square lattice design with three replications. Grain yield, thousand-kernel weight, hectoliter weight, and grain protein content were evaluated, and principal component analysis (PCA) was used to investigate relationships among genotypes and measured traits. The mean grain yield was 4.337 t ha^{-1}, with the highest value recorded for the cultivar Lennox (5.32 t ha^{-1}), followed by the promising line T. 2601-22 (4.76 t ha^{-1}). The average TKW was 34.4 g, while T. 2601-22 and T. 4068-19 recorded values of 36.0 and 35.2 g, respectively. Mean grain protein content reached 14.5%, with T. 2601-22 and T. 4162-19 achieving 14.9%. The PCA differentiated genotypes according to their agronomic and quality profiles, indicating a positive association between grain yield and TKW. Hectoliter weight contributed to genotype differentiation along the second principal component, whereas protein content displayed a distinct multivariate pattern. Overall, Lennox demonstrated the highest grain yield, while T. 2601-22 combined favourable yield performance with high kernel weight and protein content. These results identify promising genotypes for further evaluation; however, multi-year and multi-location trials are needed to assess the stability of their performance and adaptation across environments.*

Keywords: *genotype, grain yield, protein content, spring wheat*

INTRODUCTION

Spring wheat is a form less widely used globally, both due to its lower production capacity compared to winter wheat and because of limitations regarding its adaptability to challenging conditions (MROZ et al., 2023). Although it exhibits some inferior characteristics compared to winter wheat, the possibility of expanding the area sown with spring wheat has become a realistic prospect given recent climatic condition- the primary obstacle previously associated with cultivating this variety having been its limited resistance to low temperatures (KOPPEL and INGVER, 2008). Furthermore, the drastic reduction in agricultural land area, combined with significant population growth, compels the agricultural research sector to find new solutions to ensure food security (MORA et al., 2020; RANJITHKUMAR A., 2025). One of the solutions for meeting global food requirements—particularly in regions that rely on wheat as a primary food source (ACEVEDO et al., 2018) and where natural soil and climatic conditions allow for optimal cultivation- is the development of high-performing genotypes (FRANTOVÁ et

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al., 2025). The development and identification of high-performing spring wheat genotypes for specific regions (AL-GHUMAIZ et al., 2019; SAQUEE et al., 2026) represent an important objective aimed at alleviating the pressure exerted by demographic and climatic factors on food security (REZK et al., 2025).

MATERIAL AND METHODS

The agronomic performance of 23 spring wheat genotypes was evaluated in experimental field at the Agricultural Research and Development Station Livada (ARDS LIVADA), Satu Mare County (lat. 47°51′, long. 23°08′; altitude 120–130 m) located in northwestern Romania- during the 2026 agricultural year.

The experimental plots at SCDA Livada were established on a typical luvic preluvosol (brown luvic soil). According to the soil analyses, the topsoil (Ap horizon, 0–18 cm) had a humus content of 2.82%, a total nitrogen content of 0.168%, and a pH of 5.19 measured in water, indicating acidic conditions. The clay content increased with depth, from 20.9% in the topsoil to 33.1% in the deeper horizons, reflecting the accumulation of clay in the subsoil. The soil also exhibited considerable variation in hydraulic conductivity across the profile, with values decreasing from 31.27 mm h^{-1} in the Ap horizon to 0.35 mm h^{-1} in the Bt1w horizon. These properties indicate a differentiated soil profile, with acidity and physical characteristics varying with depth (ANDRAȘ et al., 2026).

The experiment consisted of a comparative trial of spring wheat varieties and lines (table 1), with three replications, laid out according to a balanced square lattice design. The crop was established on March 9, with plant emergence occurring 14 days later. The earliest genotypes began heading on May 25, while the latest ones did so around June 2. The preceding crop was forage peas. In the autumn, complex NPK fertilizers (18:46:0) were applied in a rate of 150 kg ha^{-1}; and 300 kg ha^{-1} of calcium ammonium nitrate (27.5% N content) was applied in the spring. Weed control was carried out using the herbicide Sekator Progress at a rate of 0.15 l/ha. Plant harvest was made at full maturity (16 July) using experimental threshing machine (Wintersteiger, Ried im Innkreis, Austria).

Table 1

Origin of the genotype and year of registration

No.	Name of genotype	Year of release and breeding origin	No.	Name of genotype	Year of release and breeding origin
V 1.	Pădureni	1973- ARDS Turda, Romania	V 13.	T. 4194-19	Perspective spring wheat line
V 2.	Feeling	2015- Lemaire Deffontaines, France	V 14.	T. 2924-20	Perspective spring wheat line
V 3.	Ciprian	2003- ARDS Lovrin, Romania	V 15.	T. 2925-20	Perspective spring wheat line
V 4.	Lennox	2011- Strube Research GmbH & Co.KG, Germany	V 16.	T. 2929-20	Perspective spring wheat line
V 5.	Feleacu	2024 - ARDS Turda, Romania	V 17.	T. 2931-20	Perspective spring wheat line
V 6.	T. 4007-19	Perspective spring wheat line	V 18.	T. 2601-22	Perspective spring wheat line
V 7.	T. 4068-19	Perspective spring wheat line	V 19.	T. 4162-19	Perspective spring wheat line
V 8.	T. 4075-19	Perspective spring wheat line	V 20.	T. 2809-21	Perspective spring wheat line
V 9.	T. 4076-19	Perspective spring wheat line	V 21.	T. 2639-22	Perspective spring wheat line
V 10.	T. 4165-19	Perspective spring wheat line	V 22.	T. 2928-20	Perspective spring wheat line
V 11.	T. 4176-19	Perspective spring wheat line	V 23.	T. 2931-20	Perspective spring wheat line
V 12.	T. 4183-19	Perspective spring wheat line			

The experimental data were analyzed using Microsoft Excel Program alongside by Past program.

RESULTS AND DISCUSSIONS

Climatic conditions

The climatic conditions of the 2026 experimental year at ARDS Livada, during the growing season of spring wheat, show significant deviations in both recorded temperatures and precipitation (Table 2). Regarding temperatures, from the time the experimental spring wheat crop was established (the second decade of March), the plants experienced optimal conditions for growth and development. The most notable (positive) deviations during the growing season occurred in March (+3.9°C) and June (+3.0°C). Consequently, while these temperatures had a positive impact on plant phenology during the early phenophases of the spring wheat, the high temperatures in June negatively affected the optimal development of specific phenophases—an impact ultimately reflected in the plants' productive capacity. Thus, throughout the entire vegetation period of the plants, the temperature regime was nearly 2°C above the long-term average, accelerating the progression through generative phases- particularly during the grain formation and grain-filling stages.

Table 2

Climatic conditions of field experiments

Climatic conditions		March	April	May	June	Sum/ mean
Temperature (^{0}C)	**Decade I**	6,8	9,5	15,2	20,0	-
	Decade II	9,4	11,8	15,3	19,4	-
	Decade III	9,9	10,5	19,7	26,7	-
	Month mean	8,7	10,6	16,7	22,0	14.5
	Multiannual mean	4,8	10,5	15,8	19,0	12,53
	±	3,9	0,1	0,9	3,0	1,98
Rainfall (mm)	**Decade I**	0	0	15,2	35,2	-
	Decade II	0	2,2	16,5	57,0	-
	Decade III	21,7	4,4	4,6	0	-
	Sum	21,7	6,6	36,3	92,2	156,8
	Multiannual mean	46,3	50,3	74,7	90,6	261,9
	±	-24,6	-43,7	-38,4	1,6	-105,1

Analysing of the rainfall regime during the plant growing season reveals that precipitation levels were 105.1 mm below the long-term average for this period, which significantly impacted the plants' productive capacity. Correlating rainfall levels with the plants' growth and development stages (phenophases), it is observed that crop establishment took place under conditions of moisture deficit; consequently, emergence occurred 14 days after sowing, following rainfall recorded during the third ten-day period of March (21.7 mm). In the subsequent period—the month of April—precipitation was severely deficient (-43.7 mm compared to the long-term average for that month), which hindered plant growth and had direct, major consequences for the development of the primordia of the plants' yield-forming elements. During May, the rainfall recorded—particularly in the first two ten-day periods (31.7 mm)—had a positive effect on the plants' phenological development, while rainfall at the

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beginning of June helped ensure optimal conditions for the grain formation and grain-filling processes.

Grain yield

Regarding grain yield at ARDS Livada, the average yield of the evaluated genotypes was 4.337 t ha^{-1} (figure 1). The highest yields were recorded for the cultivar Lennox (5.32 t ha^{-1}) and the perspective line T. 2601-22 (4.76 t ha^{-1}) exceeding the average of the varieties by 400 and nearly 1000 kg ha^{-1}, respectively.

Although the vast majority of the analyzed genotypes recorded yields ranging between 4000 kg ha^{-1} and 4500 kg ha^{-1}, the genotypes T. 4176-19, T. 4183-19, and T. 4194-19, as well as the line T. 2931-20, can be also outstanding, with yields exceeding 4500 kg ha^{-1}.

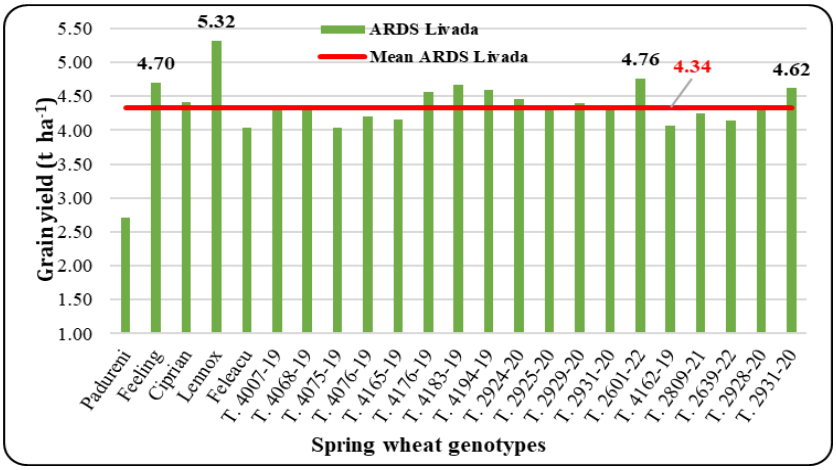


Figure 1. Grain yield of spring wheat genotypes under ARDS Livada conditions

The genetic progress achieved regarding grain yield capacity can be demonstrated by comparing the productive performance of the perspective lines with the 'Padureni' spring wheat variety. It can thus be observed that the yield level of the perspective lines exceeds that of the 'Padureni' variety by nearly 2,000 kg ha^{-1}.

Thousend kernel weight

The mean value for the trait thousand-kernel weight recorded for spring wheat genotypes under the conditions at ADRS Livada, was 34.4 g, suggesting the unfavorable conditions the plants encountered, particularly during the grain formation and grain-filling stages (An et al., 2025) (figure 2). Nevertheless, genotypes with a high value for this trait can be noted—in addition to the already registered varieties Ciprian and Lennox- namely the perspective lines T. 2601-22 (36,0 g) and T. 4068-19 (35,2 g).

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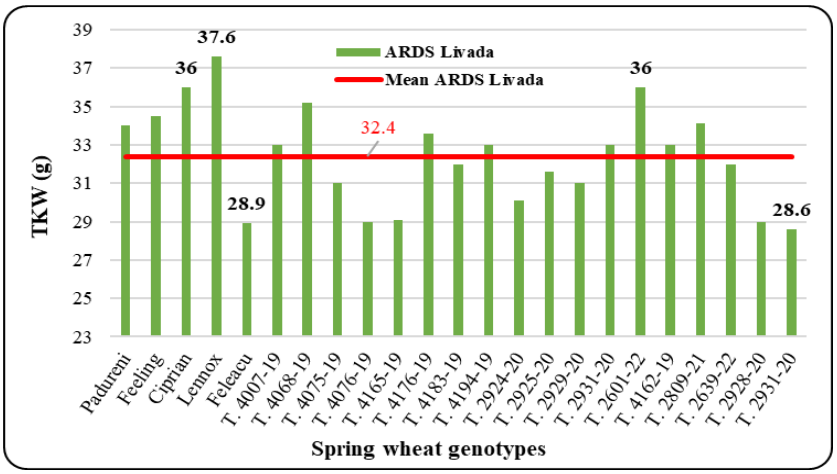


Figure 2. Thousand kernel weight of spring wheat genotypes under ARDS Livada conditions

Also, a low thousand-kernel weight (TKW) is observed for the Feleacu variety and the experimental line T. 2931-20, with values below 29 g; the experimental lines T. 4076-19, T. 4165-19, and T. 2928-20 also fall into this category, reaching the 29-gram threshold for TKW. Mitura et al. (2023) maintain that TKW (thousand-kernel weight) is one of the parameters that determine the suitability of wheat grains for milling. The higher the value of this parameter, the greater the potential yield of low-extraction flour (white flour), so in our experiment we ca identify that genotype T. 2601-22 can exhibite high milling indices.

Hectolitre weight

The hectoliter weight of the grains also shows significant variation within the group of genotypes analyzed (figure 3). Often, this trait is associated with the genotype's ability to tolerate drought conditions during the plants' generative phase (Ahmed et al., 2019). If we analyze this trait from this perspective, it is observed that the genotypes T. 4183-19, T. 2931-20, and T. 2931-20 possess greater adaptability to unfavorable environmental conditions compared to the other genotypes studied.

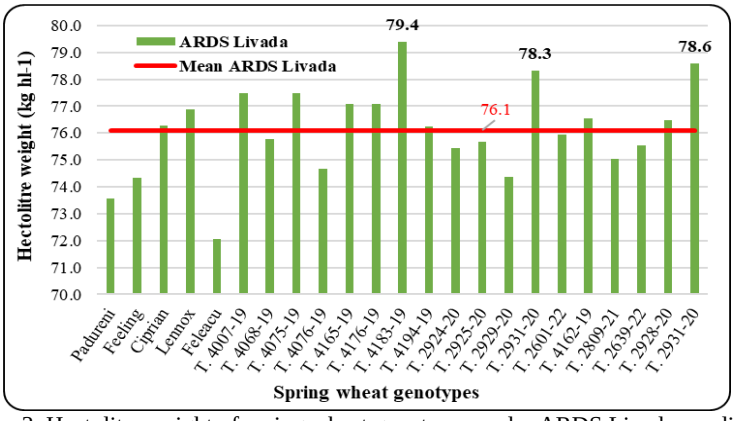


Figure 3. Hectoliter weight of spring wheat genotypes under ARDS Livada conditions

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On the other hand, the hectoliter weight of the grains is generally considered an indicator of grain quality (Cosma et al., 2026) thus, the previously noted genotypes may demonstrate superior baking qualities.

Grain protein content

Regarding the assessment of grain quality based on protein content, it can be observed that the mean value for this indicator was 14.5% (figure 4). Among the promising lines that achieve a higher protein content in the grain compared to the average of all genotypes, lines T. 2601-22 and T. 4162-19 stand out with 14.9%, as does line T. 2639-22 with 14.7%. Also, the promising lines T. 4194-19 and T. 2931-20 can be mentioned as genotypes that are above average for grain protein content.

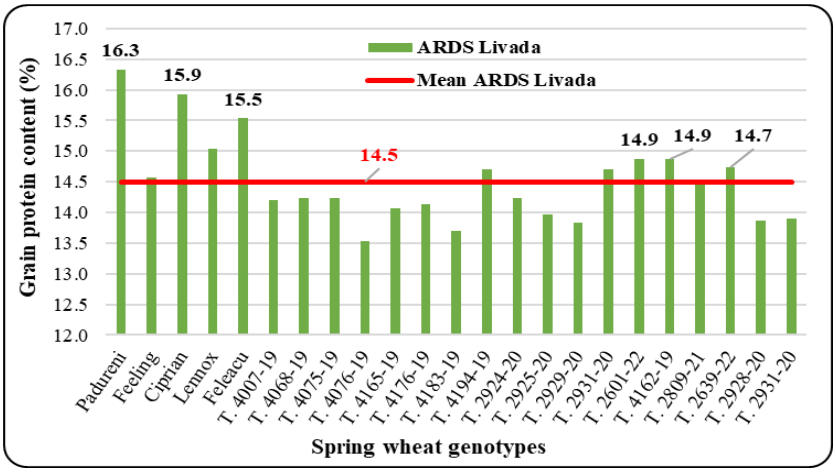


Figure 4. Grain protein content of spring wheat genotypes under ARDS Livada conditions

Although they record values below the group average (14.7%), the 12 promising lines exhibit an optimal protein content (13.5% – 14.5%), falling within the higher quality classes according to international regulations (International Food Regulations: Codex Alimentarius and ISO Standards).

The principal component analysis- PCA (figure 5) revealed differences among the experimental variants in terms of grain yield (A), thousand-kernel weight (B), hectoliter weight (C), and grain protein content (D).

Grain yield was mainly associated with the positive direction of PC1. Genotypes T. 4007-19, T. 4176-19, and particularly T. 2931-20 showed favourable associations with grain productivity, whereas T. 4076-19, T. 2924-20, and T. 2929-20 were positioned opposite to the GY vector, indicating less favourable associations with this trait.

Thousand-kernel weight also contributed substantially to genotype differentiation along PC1. T. 4068-19 and T. 2601-22 were closely associated with the TKW vector, while T. 2809-21 showed a favourable association with this trait and with hectoliter weight.

The similar orientation of the GY and TKW vectors suggests a positive relationship between grain yield and thousand-kernel weight among the evaluated genotypes. This indicates that kernel weight may have contributed to the observed differences in productivity.

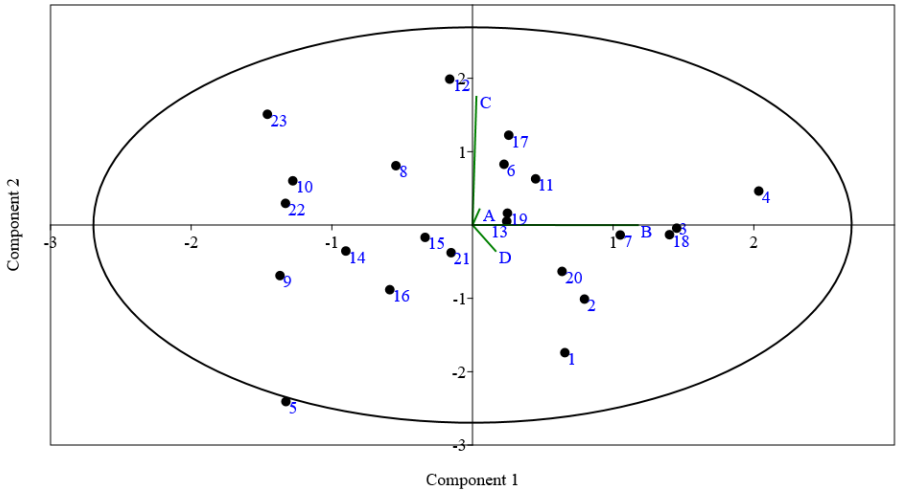


Figure 5. PCA for agromomic traits in ARDS Livada conditions

Hectoliter weight was an important factor in genotype differentiation along PC2. T. 4183-19 showed the strongest association with this trait, followed by T. 2931-20, T. 4007-19, and T. 4176-19. In contrast, Pădureni, Feeling, Feleacu, T. 4076-19, and T. 2929-20 exhibited weaker associations with the positive direction of the HW vector.

Grain protein content displayed a different distribution pattern from grain yield and kernel-related traits, suggesting that protein content contributed to genotype differentiation through a distinct multivariate pattern. Among the evaluated variants, T. 2809-21 showed a favourable association with grain protein content, alongside its association with kernel-related traits. Conversely, the distinct positioning of T. 4183-19 and T. 2931-20 was not primarily associated with higher grain protein content.

Overall, the PCA highlighted the diversity of the evaluated genotypes. T. 2931-20 appeared particularly promising for grain yield, T. 4068-19 and T. 2601-22 for thousand-kernel weight, T. 4183-19for hectoliter weight, and T. 2809-21 for its association with grain protein content and kernel-related traits. These results underline the importance of considering multiple agronomic and quality characteristics when selecting promising wheat genotypes.

CONCLUSSION

Grain yield varied among the 23 spring wheat genotypes, with an overall mean of 4.337 t ha^{-1}. The cultivar Lennox achieved the highest yield (5.32 t ha^{-1}), followed by the promising line T. 2601-22 (4.76 t ha^{-1}). Several promising lines, including T. 4176-19, T. 4183-19, T. 4194-19, and T. 2931-20, also recorded yields exceeding 4.5 t ha^{-1}, indicating their potential for further evaluation under the environmental conditions of Livada.

The mean thousand-kernel weight (TKW) was 34.4 g. The highest values among the promising lines were recorded for T. 2601-22 (36.0 g) and T. 4068-19 (35.2 g), highlighting their favourable kernel-weight characteristics. The lowest TKW values were observed for

Feleacu and T. 2931-20, at below 29 g. This variation emphasizes the importance of considering kernel weight alongside grain yield when selecting promising genotypes.

Hectoliter weight differed among the evaluated genotypes. The PCA indicated particularly favourable associations for T. 4183-19, followed by T. 2931-20, T. 4007-19, and T. 4176-19, suggesting that these genotypes merit further assessment for grain physical quality.

Mean grain protein content was 14.5%. Among the promising lines, T. 2601-22 and T. 4162-19 recorded 14.9%, while T. 2639-22 reached 14.7%, indicating favourable protein concentrations in these genotypes.

The PCA highlighted distinct multivariate profiles among the genotypes, suggesting that the traits contributing to productivity and grain quality do not always coincide. Overall, Lennox showed the highest observed grain yield, while T. 2601-22 combined high yield, high TKW, and favourable protein content. Further multi-year and multi-location trials are required to establish the stability of these performances.

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*** International Food Regulations: Codex Alimentarius and ISO Standards