

# Impact of genotype-environment interactions on wheat yield and quality: Evidence from multilocation trials

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Common wheat is a globally important cereal crop, with its winter form essential for milling and baking industries. This study explores the relationships between grain quality traits and yield in wheat, focusing on genetic and environmental influences. Field trials of 55 cultivars across 12 locations over five seasons evaluated grain yield (GY), grain protein content (GPC), thousand-grain weight (TGW), Zeleny sedimentation value (SV), and Hagberg falling number (FN) using linear mixed models and path analysis. Results revealed trade-offs between yield and quality: higher FN and SV correlated with increased GPC, while higher GY and TGW were linked to lower GPC. GY positively correlated with TGW but was negatively influenced by GPC. Path analysis confirmed these relationships, emphasizing genetic and environmental interactions. GGE biplot analysis identified cultivars with stable performance across environments. This study highlights strategies for balancing yield and quality in breeding programs, offering insights for developing resilient cultivars tailored to specific uses and environmental conditions, applicable beyond wheat breeding.

*Key words:* common wheat, grain quality, grain yield

## Introduction

The interdependence of quality variables necessitates a nuanced approach in cultivar selection, prioritizing traits most relevant to industry demands and consumer preferences (Doehlert et al. 2001). Across different regions, wheat classification systems vary based on end-use functionality, reflecting diverse market demands and breeding objectives (Malik et al. 2013). The influence of genotype and environment on grain quality variables underscores the need for tailored cultivar recommendations for specific growing conditions (Sanchez-Garcia et al. 2015, Johansson et al. 2020). The challenge lies in maximizing yield and optimizing grain quality parameters for producing high-quality dough and bread. Among these parameters, protein and gluten content, the Zeleny sedimentation value (Bustos-Korts et al. 2019), a falling number, holds significant sway over the suitability of wheat for diverse baking applications. However, the intricate inheritance patterns of these quality traits complicate breeding efforts, underscoring the need for a nuanced understanding of genotype-environment interactions. Enhancing baking quality is a main objective in wheat breeding, yet it poses considerable challenges due to the intricate inheritance patterns of quality traits (Goel et al. 2019, Plavšin et al. 2021). Understanding the interplay between genotype, environment, and G×E interaction is crucial for recommending stable cultivars with desired grain quality traits while maintaining high and stable yields (Williams et al. 2008, Derejko et al. 2020, 2021). By elucidating these relationships, we can enhance the effectiveness of wheat cultivar recommendations and contribute to sustainable agricultural practices.

This analysis can provide insights that inform cultivar selection and contribute to advancing wheat breeding practices. While genotype often influences grain quality traits, environmental factors such as location and climatic variations are crucial in impacting these characteristics. Understanding the dynamics of genotype-environment interactions is essential for recommending cultivars that excel in yield and quality across diverse agroecological settings. In this context, researchers have sought to unravel the complex relationships between grain quality variables and yield in common wheat. Studies by Sanchez-Garcia et al. (2015) and Liu et al. (2013) have underscored the significance of genotype in shaping grain quality variables, while studies by Johansson et al. (2020) and Williams et al. (2008) have highlighted the dominant influence of environmental factors on these traits. Studies from various locations worldwide have produced contrasting results in the context of genotype-environment (G×E) interactions (Williams et al. 2008, Welhalm et al. 2010).

Common wheat (*Triticum aestivum* ssp. *vulgare*) is the most widely cultivated cereal globally, with winter wheat varieties comprising a significant portion (source: <http://www.fao.org>, FAO 2024). The United States Department of Agriculture (USDA) estimates global wheat production for the 2023/24 marketing year at 785.7 million metric tons. The International Grains Council (IGC) in November 2023 estimated the global wheat harvested area in 2024/25 at 222.2 million hectares, a slight decrease from the previous year. This cereal's versatility extends from its fundamental role in providing staple food to its indispensable contribution to the milling and baking industry (El-Sayed 2024).

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Notably, in Poland, cultivars undergo meticulous classification into technological groups, emphasizing their suitability for bread baking among other end-users (Szfrańska and Stępniewska 2021). However, despite its importance, the pursuit of enhancing wheat quality, particularly for baking applications, remains a challenge for breeders.

Our study aims to investigate these interactions in hemiboreal climates but is not limited to analysing G×E alone; it fills a gap in the literature by focusing on the specific relationships between grain quality traits and their correlations with genotype and environmental conditions. To our knowledge, no previous study has thoroughly analyzed these.

Our study not only considers the effect of G×E on yield but also examines in detail how cultivar and environmental variables affect specific factors such as protein content, showing positive and negative correlations of these traits. GGE are essential tools in plant breeding to evaluate genotype performance and stability across environments, helping breeders make informed decisions in variety selection and testing strategies. GGE focus on two key sources of variation: G (Genotype effect) - how a genotype performs on average. GE (Genotype × Environment interactions) - how differently genotypes perform across environments. Through studies involving different genotypes and locations, this study provides valuable information on recommendations for variety selection, considering the impact of environmental conditions. In addition, the results contribute to the development of resistant wheat varieties that can meet the changing demands of the baking industry and consumers worldwide.

Against this backdrop, our study aims to evaluate the factors influencing wheat adaptation to diverse environmental conditions, focusing on key grain quality variables such as protein content (GPC), sedimentation index (SV), falling number (FN), thousand-grain weight (TGW), and yield (GY) through extensive field trials involving 55 cultivars across 12 locations over five growing seasons.

## Materials and methods

### Description of experiments

Data used in this study comes from COBORU (Polish Research Centre for Cultivar Testing) field experiments that were carried out in twelve rainfed locations across Poland during the period from 2015/2016 to 2019/2020 (sowing/harvesting) (Fig. 1).



Fig. 1. The 12 trial locations in Poland

Table 1 provides information on the 12 trial locations. In the COBORU trials, available phosphorus ( $P_2O_5$ ) was determined using the Olsen method, while potassium ( $K_2O$ ) and magnesium ( $MgO$ ) were extracted with 1 M ammonium acetate ( $NH_4OAc$ , pH 7). These are standard agrochemical soil analysis methods commonly used to assess the availability of nutrients to plants. Overall, the soils at the study locations were fertile, with  $P_2O_5$  content

ranging from 9.2 to 31.0 mg/100g, K<sub>2</sub>O content from 12.0 to 27.0 mg/100g, and MgO from 4.0 to 13.8 mg/100g. Soil pH was around 6. The weather data utilized in this research to describe the trial locations were sourced from COBORU meteorological stations. The average annual precipitation levels were from 550 to 750 mm. The average air temperature stood at around 9 °C. (Table 1). These temperatures and precipitation values are based on the 5 growing seasons, i.e., 2015/2016–2019/2020. In Poland the growing season of winter wheat begins in the autumn with sowing and initial growth, pauses during winter dormancy, and resumes in spring, ending with ripening and harvest in the summer of the following year.

Table 1. Characteristics of agroecological parameters in 12 locations

Locations	Longitude and latitude	Average annual temperatures (°C)	Yearly average rainfall (mm)	Mean yield (t ha <sup>-1</sup> )	Soil fertility, I - best VI - worst*	P <sub>2</sub> O <sub>5</sub> (mg/100g)	K <sub>2</sub> O (mg/100g)	MgO (mg/100g)	soil pH
Bezek	51°12'N 23°16'E	8 – 10	560 – 580	9.22	III-IV	15.0	13	4.0	5.6
Bialogard	54°00'N 15°59'E	6 – 8	600 – 750	8.05	III	15.0	12	3.0	5.8
Glubczyce	50°12'N 17°50'E	8.5 – 9	600 – 700	12.02	II-IV	30.3	21	13.8	6.5
Jelenia Gora	50°54'N 15°44'E	8 – 10	650 – 700	10.02	IV	26.7	27	4.0	6.1
Kaweczyn	52°10'N 20°20'E	8 – 9.5	600 – 700	9.74	III	20.0	15	9.0	6.5
Koscielna Wies	51°47'N 18°0'E	7 – 9	550 – 650	10.72	III	17.0	18	8.0	6.2
Krzyzewo	53°2'N 22°45'E	7 – 8	650 – 700	9.12	III	31.0	18	11.0	6.4
Pawlowice	50°45'N 22°75'E	6 – 8	550 – 750	12.64	III	9.2	19	7.6	6.0
Sulejow	51°21'N 19°53'E	8 – 10	550 – 650	9.38	II-IV	11.0	25	10.0	6.6
Wegrzce	50°7'N 19°58'E	7 – 9	550 – 700	8.72	III	14.0	20	4.0	5.8
Lisewo	53°17'N 18°41'E	8.5 – 9	600 – 700	8.57	II	19.0	21	7.0	6.6
Ruska Wies	53°47'N 22°12'E	6 – 8	550 – 650	11.13	III	20.0	12	4.0	6.8

\* Soil fertility was assessed according to the classification developed by the Polish Institute of Soil Science and Plant Cultivation (IUNG), which divides soils into six fertility classes based on the following criteria: including chemical tests (e.g., nutrient content, pH) and physical tests (e.g., soil structure, water holding capacity).

Experiments involved the evaluation of 55 common wheat cultivars. These cultivars encompass commercial relevance. The cultivars selected for the experiment were categorized into technological groups based on the Polish quality scheme ([www.coboru.pl](http://www.coboru.pl)): E (superior), A (good quality), and B (bread). According to the Polish quality scheme ([www.coboru.pl](http://www.coboru.pl)), out of the 55 tested cultivars of common wheat, 28 (49%) belonged to class A, 26 (49%) belonged to class B, and one (2%) belonged to class E (Table S1).

The experimental design consisted of a block design with two replications. Each plot occupied an area of 15 m<sup>2</sup>. The experiments were conducted under rain-fed conditions with conventional tillage. The nitrogen fertilization range is 120–180 kg N ha<sup>-1</sup> spread over 2–3 applications per season. Nitrogen fertilizer application was sufficient for the soil conditions in each trial location, plus 40 kg N ha<sup>-1</sup> at GS 59 (growth stage). Foliar fertilizers were applied at the following doses: MgO 250 g ha<sup>-1</sup>, Cu 50 g ha<sup>-1</sup>, Mn 150 g ha<sup>-1</sup> and Zn 80 g ha<sup>-1</sup>. Additionally, two fungicides were administered at growth stages 31–32 (carbendazim, dose 625g ha<sup>-1</sup>) and 49–60 (fenpropidin, dose 550 g ha<sup>-1</sup>), along with a growth regulator (trinexapac-ethyl, dose 125 g ha<sup>-1</sup>) at growth stage 31. Planting dates varied by location. Other agricultural activities such as tillage, fertilizer application, weed, and insect control were managed by local farmers following standard practices for each region.

The study assessed agronomical traits, including grain yield, thousand-grain weight in grams, grain protein content as a percentage, Zeleny sedimentation value in millilitres, and Hagberg falling number. Grain samples were ground using the Brabender Quadrumat Senior laboratory mill. Protein content (N × 5.7) was determined using the Kjeldahl method (Foss Tecator, Denmark) based on the ICC method 105/2 (ICC 1994). The sedimentation value was obtained using the Zeleny method ICC 116/1. The falling number was determined using the Falling Number Test Apparatus type 1400 (AACC Method 56-81B).

### Statistical analysis

The grain yield and quality variables were analysed using a single-stage approach for a linear mixed model (LMM). The LMM was represented by equation (1):

$$y_{ijklhn} = \mu + g_k + l_j + a_i + ga_{ki} + gl_{kj} + la_{ji} + gla_{kji} + r_{jih} + b_{jihn} + e_{ijklhn} \quad (1)$$

Where  $y_{ijklhn}$  represents the observed value of the dependent variable (grain yield or quality traits),  $\mu$  is the overall mean,  $g_k$  is the random effect of  $k^{th}$  cultivar,  $l_j$  is the fixed effect of  $j^{th}$  location,  $a_i$  is the random effect of the  $i^{th}$  growing season,  $ga_{ki}$  is the random interaction effect of  $k^{th}$  cultivar and  $i^{th}$  growing season,  $gl_{kj}$  is the random interaction effect of  $k^{th}$  cultivar and  $j^{th}$  location,  $la_{ji}$  is the random interaction effect of  $i^{th}$  growing season and  $j^{th}$  location,  $gla_{kji}$  is the random interaction effect of  $k^{th}$  cultivar,  $j^{th}$  location and  $i^{th}$  growing season,  $r_{jih}$  is the random effect of  $h^{th}$  replication nested in  $j^{th}$  location at  $i^{th}$  growing season,  $b_{jihn}$  is the random effect of  $n^{th}$  block nested in  $h^{th}$  replication at the  $j^{th}$  location and  $i^{th}$  growing season,  $e_{ijklhn}$  represents the random error associated with the traits observation ( $y_{ijklhn}$ ).

The models employed in the analysis were designed to account for various factors affecting grain yield and quality traits. We assumed heterogeneous variances across locations for location effects to accommodate the differing genetic variances in the trial locations. Conversely, we applied a diagonal homogeneous covariance matrix for cultivar effects. The restricted maximum likelihood (REML) method was used to estimate the parameters of the linear mixed model. The significance of fixed effects was assessed using Wald’s test, while the significance of random effects was determined by variance components along with their standard errors. Based on the linear mixed model, adjusting means for yield and grain quality traits were computed for main effects and relevant combinations of factors (e.g., cultivar × location × growing season). This calculation was conducted using the algorithm presented by Welham et al. 2010. According to this procedure, adjusted means are created by averaging the sum of the correct effects together with the intercept. Path and correlation analyses were also performed to explore the relationships between GPC, SV, FN, GY, and TGW for study locations and cultivars. These analyses were based on datasets comprising cultivar means and environmental means for each cultivar and location, respectively. To assess genotype-by-environment interaction, we used an approach based on the GGE (genotype main effect plus genotype by environment interaction) biplot, which is a method based on the principal components analysis (PCA) for the genotype x environment trait value matrix. The statistical analyses were carried out using the R 4.2.1 software package with MASS and GGEbiplot packages.

## Results

### Means for the studied variables across locations

The mean values of quality variables and grain yield of common wheat for 12 locations, five growing seasons, and 55 cultivars are presented in Table 2.

Table 2. Mean values of quality variables and grain yield of common wheat for five growing seasons and 55 cultivars in 12 locations

Location	GPC (%)	FN (s)	SV (ml)	GY (dt ha <sup>-1</sup> )	TGW (g)
Bezek	13.64	350.48	45.15	92.20	46.29
Białogard	12.65	318.98	32.96	80.48	51.18
Głubczyce	12.90	361.55	42.26	120.19	43.42
Jelenia Góra	11.28	351.00	39.20	100.17	41.91
Kawęczyn	13.46	377.68	43.94	97.43	46.66
Kościelna Wieś	13.73	386.23	43.07	107.17	41.55
Krzyżewo	13.04	342.13	42.19	91.22	43.18
Lisewo	12.19	347.24	43.17	126.40	49.79
Pawłowice	13.07	396.67	43.50	93.82	38.80
Ruska Wieś	12.91	337.22	44.10	87.18	45.50
Sulejów	13.86	405.71	40.30	85.67	38.91
Węgrzce	11.69	327.50	40.64	111.34	50.29

\* GPC = grain protein content, FN = Hagberg falling number, SV = Zeleny sedimentation value; GY = grain yield; TGW = thousand-grain weight

The mean protein content in the grain, expressed as a percentage (GPC), ranged from 11.29% (in Jelenia Góra) to 13.85% (in Sulejów). FN values ranged from 318.98 (in Białogard) to 405.71 (in Sulejów). In the Białogard location, the lowest values were observed for three common wheat grain variables: SV, FN, and GY. SV values in wheat grain

ranged from 32.96 to 45.15. Grain yields in the 12 locations ranged from 80.48 to 126.40 decitonnes per hectare (dt ha<sup>-1</sup>). The highest grain yields were recorded in Lisewo, while the lowest were found in Bialogard. TGW had the highest value in Bialogard, while the lowest value was in Sulejów.

Table 3 displays variance components and their contributions to explaining the variability in quality variables and grain yield of common wheat cultivars based on the LMM results.

Table 3. Variance components (VC) and their shares in explaining the variability of studied variables

Effects	GPC (%)		SV (ml)		FN (s)		GY (dt ha <sup>-1</sup> )		TGW (g)	
	VC	% Total of variance	VC	% Total of variance	VC	% Total of variance	VC	% Total of variance	VC	% Total of variance
cultivar (G)	0.08*	6.11	37.51**	59.67	1853.14**	39.26	2.20	0.59	3.68**	11.15
location (L)	0.21**	16.03	14.06**	22.37	322.24**	6.83	163.33**	44.00	14.47**	43.86
year (Y)	0.01	0.76	0.01	0.02	836.45**	17.72	38.79**	10.45	4.54**	13.76
G×L	0.30**	22.90	2.22*	3.53	427.07**	9.05	0.33	0.09	1.58*	4.79
G×Y	0.14*	10.69	0.73	1.16	408.76**	8.66	10.86*	2.93	0.34	1.03
L×Y	0.54**	41.22	8.30*	13.20	757.66**	16.05	154.37**	41.59	7.65**	23.19
G×L×Y	0.02	1.53	0.02	0.03	102.11*	2.16	1.12	0.30	0.56	1.70
Residual	0.01	0.76	0.01	0.02	12.71	0.27	0.21	0.06	0.17	0.52

GPC = grain protein content; FN = Hagberg falling number; SV = Zeleny sedimentation value; GY = grain yield; TGW = thousand-grain weight; \* significant at  $\alpha=0.05$ ; \*\* significant at  $\alpha=0.001$

The main effect of cultivars had the strongest impact on SV and the least impact on GY. The main effect of location had the strongest impact on TGW and the weakest on FN. The main effect of the year had the strongest impact on FN and the lowest on SV and GPC. The G×L interaction effect had the most substantial impact on GPC and no effect on GY. Additionally, the interaction G×Y had the strongest impact on GPC (10.69%). GY and GPC was strongly influenced by the L×Y interaction, accounting for almost 42% of the total variation.

A correlation analysis was conducted using the adjusted means for combination locations and years across cultivars to examine the relationships between wheat cultivar variables. The strongest negative correlation coefficient of  $-0.35\pm 0.07$  was observed between GPC and TGW, as well as between GPC and GY ( $r=-0.25\pm 0.09$ ). The highest positive correlation coefficient was obtained between FN and SV ( $r=0.38\pm 0.07$ ) and between SV and GPC ( $r=0.29\pm 0.08$ ). No correlation was observed between GY and SV or FN. Both correlation coefficients were below  $0.10\pm 0.09$ .

Table 4. Path analysis for grain yield (GY) and grain protein content (GPC) based on cultivar (a) or on location (b) effects

	GPC			GY			
	Path coefficient	Standard error	<i>p</i> -value	Path coefficient	Standard error	<i>p</i> -value	
a)							
FN	0.2298	0.0990	0.0244	GPC	-0.7941	0.0917	0.0000
SV	-0.0347	0.1011	0.7329	FN	0.1452	0.1048	0.1723
GY	-0.7552	0.0872	0.0000	SV	-0.0993	0.1029	0.3394
TGW	0.2233	0.0867	0.0130	TGW	0.2644	0.0869	0.0037
	R <sup>2</sup> = 0.6549			R <sup>2</sup> = 0.6371			
b)							
FN	0.1869	0.1694	0.2805	GPC	-0.5642	0.2284	0.0207
SV	0.3890	0.1502	0.0158	FN	0.3836	0.2072	0.0760
GY	-0.3478	0.1408	0.0207	SV	0.3845	0.2012	0.0675
TGW	-0.3087	0.1792	0.0973	TGW	0.1112	0.2404	0.6475
	R <sup>2</sup> = 0.5662			R <sup>2</sup> = 0.2964			

GY = Grain yield; GPC = grain protein content; TGW = thousand-grain weight (g); SV = Zeleny sedimentation value (ml); FN = Hagberg falling number

The analyses conducted at the cultivar and environmental levels provided insights into developing grain quality variables and yield, both for cultivars and environments. Path analysis for GY and GPC based on cultivar effect (Table 4a) revealed significant influences. GPC was significantly affected by FN (path coefficient 0.23), GY (−0.75), and TGW (0.22). An increase in FN and TGW led to higher protein content in grains, while an increase in GY decreased GPC. Conversely, GY was significantly influenced by GPC (−0.79) and TGW (0.26). This indicates that an increase in TGW leads to higher grain yield, but an increase in GPC leads to a decrease in yield.

Path analysis for grain yield based on location effects (Table 4b) demonstrated that SV and GPC had significant impacts (path coefficients 0.39 and −0.35, respectively). An increase in SV correlated with increased GPC, while an increase in GY correlated with increased GPC. However, grain yield based on location was only affected by GPC (−0.56). As GPC increases, GY decreases. Analysing the paths across environments (Table 4b), we can conclude that the variability of GPC in study locations was influenced by SV and GY, with similar contributions. However, they had opposite effects: an increase in GY led to a decrease in GPC, high GPC leads to high SV. There was no significant effect of FN and TGW on GY or GPC.

Figure 2 shows the relationship between genotypes (Gen) and environments (Env) under principal component analysis (PCA). The X-axis (PC1 - 51.61%) and Y-axis (PC2 - 19.4%) express the percentage of variation explained by the first two principal components. PC1 explains most of the variance, while PC2 additionally reflects specific interactions between genotypes and environments. Most varieties are located close to the center of the coordinate system, including Lokata, Titanica, Dubai, Moschus, and LG Keramik, which indicates that these varieties are stable and do not show strong interaction with specific environments. In contrast, varieties such as Kometa, Nordkap, Lindbergh, or Bonanza exhibit clearer interactions with particular environments.

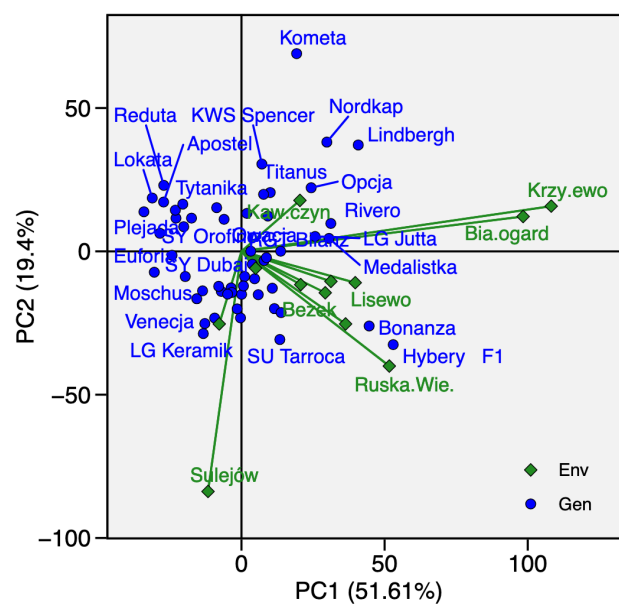


Fig. 2. GGE biplot for grain yield: the relationship between genotypes (Gen) and environments (Env) based on principal component analysis (PCA)

In Figure 3, PCA1 and PCA 2 together explain 63.26% of the variation in the data. Cultivars closer to the vectors of the environments are best suited to these conditions in terms of protein content. The cultivars Symetria, Kariatyda, SU Tarroca and SU Mangold are well suited to the Kawcyn environment, which clearly favors cultivars with high protein content in this region.

On the other hand, cultivars Admonit, Reduta are better suited to environmental conditions such as Jelenia Gora and Suleja. As stable cultivars, having average results in all environments can be considered among others Lokata, Apostel, Euphoria, or SY Yukon. These cultivars are suitable for crops where consistent grain quality (protein content) is a priority, regardless of environmental variability. In contrast, the Symetria cultivar has high performance in one environment (in Kawczyn), but may have poorer results in others.

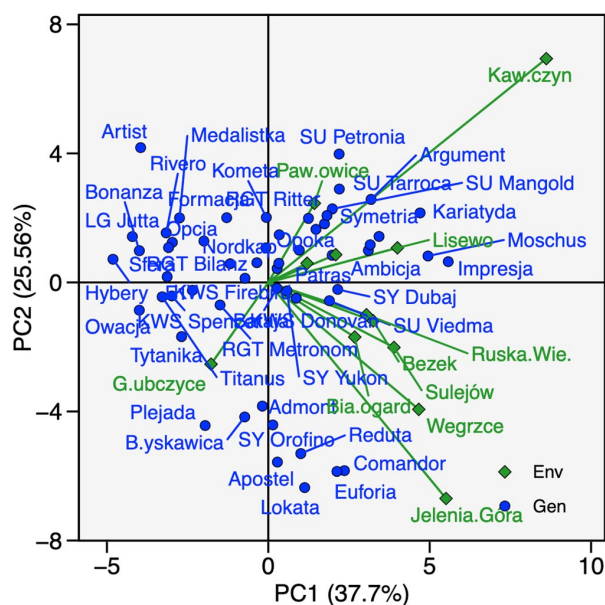


Fig. 3. GGE biplot for protein: the relationship between genotypes (Gen) and environments (Env) based on principal component analysis (PCA)

## Discussion

Grain quality and yield are important considerations in wheat breeding due to their direct implications on food production, processing and consumer satisfaction. However, traditional breeding methods face limitations in simultaneously optimizing these traits, often resulting in trade-offs between grain quality and yield. Despite advancements in breeding techniques, achieving optimal grain quality and yield remains challenging. Often, one trait is prioritized over the other, neglecting potential synergies between them (Kuchel et al. 2007, Hatfield et al. 2011).

The results reveal relationships between grain quality variables and yield in common wheat, emphasizing the influence of genetic and environmental factors. By incorporating field trials across 12 locations over five growing seasons, this study offers robust and contextually diverse data, supporting reliable analysis and practical applicability of the findings, in alignment with and contributing to existing research. The comprehensive nature of the study enables a well-founded analytical framework and enhances both the reliability and the practical applicability of the results, contributing valuable insights alongside previous work. Correlation analysis revealed significant associations between GPC and FN, SV, GY and TGW. Notably, higher FN and SV values were correlated with increased protein content, while elevated GY and TGW were associated with decreased GPC. This suggests a trade-off scenario where achieving high protein content and high productivity in a cultivar might be challenging. Furthermore, the influence of location on grain yield primarily operated through its impact on GPC. Achieving both high yield and high protein content is challenging due to the dilution of nitrogen at higher yield levels. Late nitrogen applications may improve protein content to some extent, but their effectiveness is limited and depends on environmental conditions and genotype characteristics.

Path analysis conducted across various environments further elucidated protein content has an impact on SV and GY. It is a biologically reasonable that FN and SV do not impact yield, rather GY might influence them indirectly (e.g. through its effect protein dilution or grain composition although Zeleny value did not directly affect grain yield, it may have indirectly reflected location-dependent changes in grain quality, particularly in relation to protein content). The findings also highlight the potential of low-yielding varieties with low SV to exhibit high protein content, suggesting the possibility of utilizing these varieties in breeding programs. By crossing such varieties with high-yielding counterparts, breeders can aim to develop new cultivars that balance both high yield and desirable protein content.

In addition, the results underscore the importance of conducting separate analyses that take into account the influence of location and varietal traits, allowing for more precise and targeted selection of genotypes. Moreover, the results underscore the importance of conducting separate tests based on location and variety effects, facilitating more targeted cultivar selection. While selecting cultivars with stable, high yields appears relatively straightforward

compared to those based on grain quality variables, aligning results from genetic and environmental analyses can enhance breeding efforts. These findings align with previous studies, including those in works (Williams et al. 2008, Malik et al. 2013, Rozbicki et al. 2015, Bustos-Korts et al. 2019, Studnicki et al. 2019), which also reported similar influences of genetics and the environment on grain quality characteristics or yield.

The dominance of environmental effects over other main and interaction effects is consistent with findings from work Plavšín et al. 2021. Considering variations in temperature and precipitation, as emphasized by Hatfield et al. 2011 and Hatfield and Walthall 2015, is crucial for ensuring food security amidst changing growing conditions. The influence of genotype-by-environment interactions on grain yield and quality in wheat has been widely recognized in agricultural research. Kuchel et al. 2007 highlighted the significant impact of environmental variables such as temperature extremes and stripe rust infection severity on grain yield, emphasizing the need to consider genotype-environment interactions in breeding programs. Similarly, Rozbicki et al. 2015 conducted a two-year study in Poland, concluding that environmental factors, particularly year and location, exert a stronger influence on grain quality traits such as baking score, loaf volume, and water absorption than genotype. Despite numerous studies discussing the overall impact of genotype-environment interactions on yield and protein content, this manuscript provides key data on specific varieties that stand out from the rest (Doehlert et al. 2001, Rozbicki et al. 2015, Nehe et al. 2019). This detailed information is important, especially for stakeholders who base their decisions on identifying the highest yielding varieties.

However, genotype is crucial in determining protein content and quality, which can be enhanced through effective crop management practices. Studies on various wheat cultivars across different regions have further emphasized the importance of considering genetic and environmental factors. For instance, Peterson et al. 1992 found significant contributions of genotype to variation in protein concentration and mixing characteristics in hard red winter wheat. In Latin American wheat, Vázquez et al. 2012 observed pronounced environmental effects on grain quality attributes, highlighting the critical role of the growing environment in shaping grain quality. Similar trends have been observed in other cereal crops, such as oats, where genotype significantly influences groat lipid content. At the same time, the environment has a stronger effect on grain yield and starch concentration than the influence of variety or year. Doehlert et al. (2001) and Nehe et al. (2019) reported genetic gains in grain yield and quality traits in Turkish spring wheat, which they attributed to changes in protein composition rather than to an increase in overall protein content.

Moreover, genome-wide association studies (GWAS) in Nebraska winter wheat revealed significant genotype-by-environment interactions for grain yield (Eltaher et al. 2021). In durum wheat, genotype-by-environment interactions were identified as important sources of variation in grain yield, with the AMMI model proving useful for selecting genotypes with high stability and yield (Mohammadi and Amri 2009). Brazilian wheat breeding programs have achieved genetic gains in grain yield, although these gains were partially offset by negative environmental effects, highlighting the regional variability in genetic gains (Mohammadi and Amri 2009). Overall, these studies underscore the diversity of environmental influences on grain yield and quality across different wheat cultivars and regions.

Understanding genotype-by-environment interactions is essential for developing resilient cultivars tailored to specific growing conditions, ultimately enhancing food security and sustainability in agriculture. It is worth noting that our research found that low-yielding varieties with low SV will likely exhibit high protein content, indicating the potential for using these varieties in breeding programs. Crossing these low-yielding varieties with high-yielding counter-parts makes it possible to develop new cultivars that combine high yield with desirable protein content. This finding validates the importance of conducting separate tests based on the effects of location and variety. Furthermore, the results highlight the relative ease of selecting cultivars with stable, high yields compared to cultivars based on grain quality variables, which are influenced by multiple factors. When the results from genetic and environmental analyses align, cultivar selection becomes more straightforward. However, interpreting divergent results from genetic and environmental analyses can be challenging. Nonetheless, such analyses facilitate the identification of cultivars with specific adaptability and enable focused efforts to enhance their fertility and grain quality variables within specific environments.

There is a broader purpose of breeding beyond cultivar recommendations, emphasizing growers' responsibility to enhance production capacity while preserving or improving quality under challenging conditions. Correlation and path analysis across diverse genotypes and environments provides valuable insights for breeders, assisting in parental selection for long-term breeding programs. The application of GGE analysis in our study enabled the identification varieties characterized by stability under varying environmental conditions, which is crucial in the face of ongoing climate change. By considering a broader range of genetic and environmental variables, accurate

recommendations and cultivar selections can be made to address specific grain utilization needs and navigate evolving agricultural landscapes.

## Conclusions

This research demonstrates that both cultivar and environmental factors and their interactions are crucial determinants of grain yield and quality in wheat. While genotype is a key in specific quality traits such as protein content, environmental factors often substantially impact grain quality and yield. Crop management practices and breeding programs can enhance certain quality traits, and genetic gains have been achieved over time. However, the variability of environmental conditions remains a significant challenge, emphasizing the need for adaptable and stable genotypes for different growing conditions.

Traditional breeding approaches often prioritize one trait over another; our analysis reveals significant correlations between grain quality variables and yield. While our study represents a step forward in understanding the complexities of grain quality and yield in wheat, it is not without limitations. The generalizability of our findings may be restricted to the specific conditions examined, highlighting the need for further research to explore additional genetic and environmental factors to ensure global food security and sustainability. Through the use of GGE plots and a measure of varietal stability in both yield and grain protein content, this provided key information on specific cultivars that outperformed others. This detailed information is essential, especially for stakeholders who rely on identifying outperforming cultivars.

Data Availability Statement: The data presented in this study are available upon request from the corresponding author (M.S).

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Supplementary Material

Table S1. Description of the wheat genotypes including their quality group based on the Polish quality scheme (E – superior cultivar, A – good quality cultivar, B – bread cultivar)

Cultivars	Quality group*	Cultivars	Quality group*
Ambicja	A	Medalistka	B
Apostel	A	MHR Promienna	B
Bataja	A	Opcja	B
Błyskawica	A	Owacja	B
Comandor	A	RGT Bilanz	B
Euforia	A	RGT Provision	B
Formacja	A	RGT Ritter	B
Impresja	A	RGT Specialist	B
Kariatyda	A	Rivero	B
Kometa	A	Sfera	B
KWS Firebird	A	SU Mangold	B
KWS Spencer	A	SU Petronia	B
KWS Universum	A	SU Tarroca	B
LG Keramik	A	SU Viedma	B
Lindbergh	A	SY Orofino	B
Lokata	A	Symetria	B
Nordkap	A	Titanus	B
Opoka	A	Tytanika	B
Patras	A	Moschus	E
Plejada	A	Venecja	A
Reduta	A	Admont	B
RGT Kilimanjaro	A	Argument	B
RGT Metronom	A	Artist	B
SY Cellist	A	Bonanza	B
SY Dubaj	A	Bosporus	B
SY Yukon	A	Hybery F1	B
KWS Donovan	B	KWS Talium	B
LG Jutta	B		