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RESEARCH

Performance Assessment of Diverse Spelt Wheat (*Triticum spelta* L.) Genotypes Across Three Years Seasons in Central Europe

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Abstract

Spelt wheat (*Triticum spelta* L.), known as an ancient cereal, is gaining popularity again due to its exceptional dietary value, adaptability to climate change, and low resource inputs. However, limited information is available about the diverse spelt lines agronomic and nutritional performance under fluctuating environments in central Europe. To determine agronomic and grain nutritional characteristics of 46 spelt wheat genotypes from the Czech Republic, Germany, and Switzerland, a 3-year field study (2021–2023) was carried-out at the Crop Research Institute, Czech University of Life Sciences, Prague. Our results showed highest genotypic variability among measured traits. Agronomic traits such as plant height, spike length, 1000 grain weight and grain yield were highest in genotype 69Z6.205, followed by 69Z6.204. Nutritional quality traits such as crude protein and starch content were greatest in genotypes 69Z6.205 (20.7% and 63.3%). Moreover, Zeleny sedimentation values were noted higher in 69Z6.205 genotype, compared to genotypes under study. Regarding years comparison, 2023 significantly improved the agronomic and quality traits followed by 2021 and 2022. The correlation and principal component analysis demonstrated that the grain yield, harvest index and quality factors (starch and Zeleny sedimentation value) are strongly associated with each other, thus indicating integrated adaptability potential to promote productivity and quality. The principal findings of the mantel correlation test are that the interannual climatic variability was significant contributor, shows trade-offs in total biomass production and partitioning efficiency to grain components, thereby revealing insights into traits performance over temporal scale. Overall, certain genotypes (particularly, 69Z6.205, 69Z6.204, 69Z6.148 and 69Z6.153) produced high yield and had good nutritional value, these lines could be considered for future breeding projects because of the nutrient-enhanced and climate-resilient characteristics. These findings suggest that spelt wheat has agronomic and nutritional potential as a viable substitute for bread wheat in central European agroecosystems.

Keywords Spelt wheat · Agronomic traits · Grain quality · Genotype evaluation · Central europe

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Introduction

Spelt wheat (*Triticum spelta L.)* is the earliest grain that has ever grown, it is preceded by emmer and einkorn (Porto et al., 2025). According to archeological records, spelt was cultivated in Germany, Poland, and Denmark between 2500 and 1700 BC, and it is still grown in central Europe today (Şahin & Karakas, 2022). Until the late 19th century, the spelt was main cereal crop in German-speaking nations, including Austria, southern Germany, and Switzerland. Spelt fields decreased significantly after World War II, covering up to thousands of hectares (Gupta et al., 2019; Wang et al., 2024). Spelt is one of the first domesticated grains that was only preceded by Emmer (*T. dicoccum*) and Einkorn (*T. monococcum*). The increase in alternative agricultural

methods, initiatives to preserve biodiversity, and efforts to enhance nutritional needs have all contributed to the current increase in interest in spelt wheat production (Rakszegi et al., 2025). Additionally, the overproduction of basic cereals, eco-friendly farming practices, and consumer interest in novel foods that promote health have led to a rise in spelt crop areas. In countries such as Germany, Switzerland, Austria, Belgium, Italy, France, the Czech Republic, Hungary, and Slovakia, as well as in regions across other continents, the majority of spelt is grown organically (Şahin & Karakas, 2022). Spelt wheat played a very significant role in Europe already in the Bronze Age and during the Middle Ages. As Hexaploid, hulled, and non-threshable, spelt wheat has excellent nutritional, dietary, and flavor qualities (Andruszczak, 2017; Wang et al., 2024).

Spelt wheat is regarded as an ancient European grain, and its low input requirements and popularity in organic farming have increased interest in it recently. In addition to having a better-balanced amino acid profile than bread wheat, it has larger amounts of proteins, minerals, lipids, fiber, and vitamins (Porto et al., 2025). A breeding effort aims to improve spelt's overall performance while reducing unfavorable features like low spike productivity or lodging susceptibility (Takač et al., 2022). Additionally, spelt wheat has a high lipid content, particularly unsaturated fatty acids, which are good for the heart and circulatory system (Escarnot et al., 2012; Valsalan et al., 2025). In this way, it reduces the cardiovascular risk, like coronary heart disease, atherosclerosis, atherothrombotic endpoints, allergies, or multiple cancer types (Rediger et al., 2009). Additionally, spelt contains more vitamins: B1, B2, PP, A, E, and D (Żuk-Gołaszewska et al., 2022; Şahin & Karakas, 2022). There are two types of dietary fiber: crude fiber and soluble non-starch polysaccharides. Dietary fiber is recommended for preventing gastrointestinal disorders as it probably prevents the development of diabetes type II, obesity, cholelithiasis, and colon cancer (Sztupecki et al., 2023). Besides pectin, hemicellulose can absorb heavy metals, which makes it an important component of dietary fiber in cereals and improves food quality (Koenig et al., 2015). Due to their high hemicellulose content, they can swell and absorb water in the human alimentary canal, resulting in positive physiological effects (Bach Knudsen et al., 2017; Singh et al., 2018). Similarly, another important indicator of protein quality and gluten strength is Zeleny sedimentation value (ZST), which represents the ability of gluten forming proteins to swell. ZST in spelt wheat is directly related to processing and end use performance, especially for baking and traditional food products (Yilmaz et al., 2024). Moreover, assessing ZST in conjunction with agronomic characteristics enables a more comprehensive evaluation of genotype performance and quality stability across growing seasons.

Modern wheat breeding programs have made tremendous progress in spelt breeding and genetic improvement, despite the growing market demand and agricultural area (Curzon et al., 2021). There is a lack of systematic assessment of genotypic performance across various environments and years, and the genetic variety present in current spelt germplasm collections is still underexplored. Growing conditions in central Europe pose special challenges for crop production because of the region's significant climatic fluctuation (Le Gouis et al., 2020), variety of soil types (Dolijanović et al., 2022), and the increasing occurrence of extreme weather events is linked with climate change (Le Gouis et al., 2020). Understanding how different spelt genotypes perform under these conditions over multiple growing seasons is essential for creating improved variety which is agronomically and nutritionally superior and providing farmers with evidence-based recommendations.

However, there is limited information available on spelt wheat genotypic adaptability, especially concerning their suitability for cultivation and utilization in central Europe conditions across multi-years evaluations. Additionally, most of the current research assesses qualitative or agronomic variables separately (Dolijanović et al., 2022; Takač et al., 2022), lacking the comprehensive evaluation for genotype characterization. Moreover, the muti-year relationships between growth patterns, yield, and quality attributes in spelt wheat are still lacking, limiting the potential to identify favorable traits performance. Therefore, this research aimed to investigate the genetic diversity among 46 spelt wheat genotypes concerning their agronomic traits and nutritional quality characterization in central European conditions. The specific objectives were: (1) to evaluate genotypic variations in spelt wheat growth and yield attributes under three consecutive growing seasons; (2) determine the superior nutritional quality traits of diverse spelt wheat genotypes during the three consecutive growing seasons; (3) identify relationships between growth, yield and quality attributes in spelt wheat genotypes; (4) explore relationships among climatic factors, growth, yield and quality.

Material and Method

Experimental Site and Climate

A three-year field study (from 2021 to 2023) was performed at the Crop Research Institute, Prague University of Life Sciences (50°11′N; 14°32′E) Czech Republic. The soil at the study site has a clay-loam texture. The pH of soil ranges from 7.0 to 8.05, soil P content is 93 mg kg^{-1}, soil K content is 226 mg kg^{-1}, soil TN and SOC content are 0.159% and 2.106% respectively. The region experiences a warm

temperate climate with semi-arid conditions. The annual average temperature is between 7 °C and 9 °C and average precipitation of about 526 mm. The detailed weather data (including mean monthly average temperatures precipitation) during the three years (2021–2023) are presented in Fig. 1.

Experimental Design

A two-factor experiment consisted of 46 spelt wheat genotypes and different growing seasons (years), and randomized complete block design with three replications was used. These lines originated from three countries (Czech Republic, Switzerland and Germany) and include landraces, breeding lines, and cultivars obtained from recognized gene banks with including European Collection Numbers (ECN), BCHAR codes, original genotype names, and country of origin (Table S1). Net plot size was 4.5 m^2 and seed rate of 180 kg per hectare was used.

Crop Management Practices

Spelt wheat lines were sown on October 3, 2020, September 23, 2021, and September 29, 2022 by using a super sowlite seed drill. The fertilizers application including nitrogen, phosphorus and potassium was applied each year at the rate of 120, 40, and 106 kg ha^{-1} respectively. Three equal dressings of nitrogen were applied: first dose applied in the autumn prior to sowing, second dose applied at stem elongation or jointing stage, and third dose applied at booting to early heading stage. In autumn before sowing, all amounts of phosphorus and potassium fertilizers were applied. No irrigation was applied during the growing seasons, as it was totally dependent on rainfall. For the control of weeds,

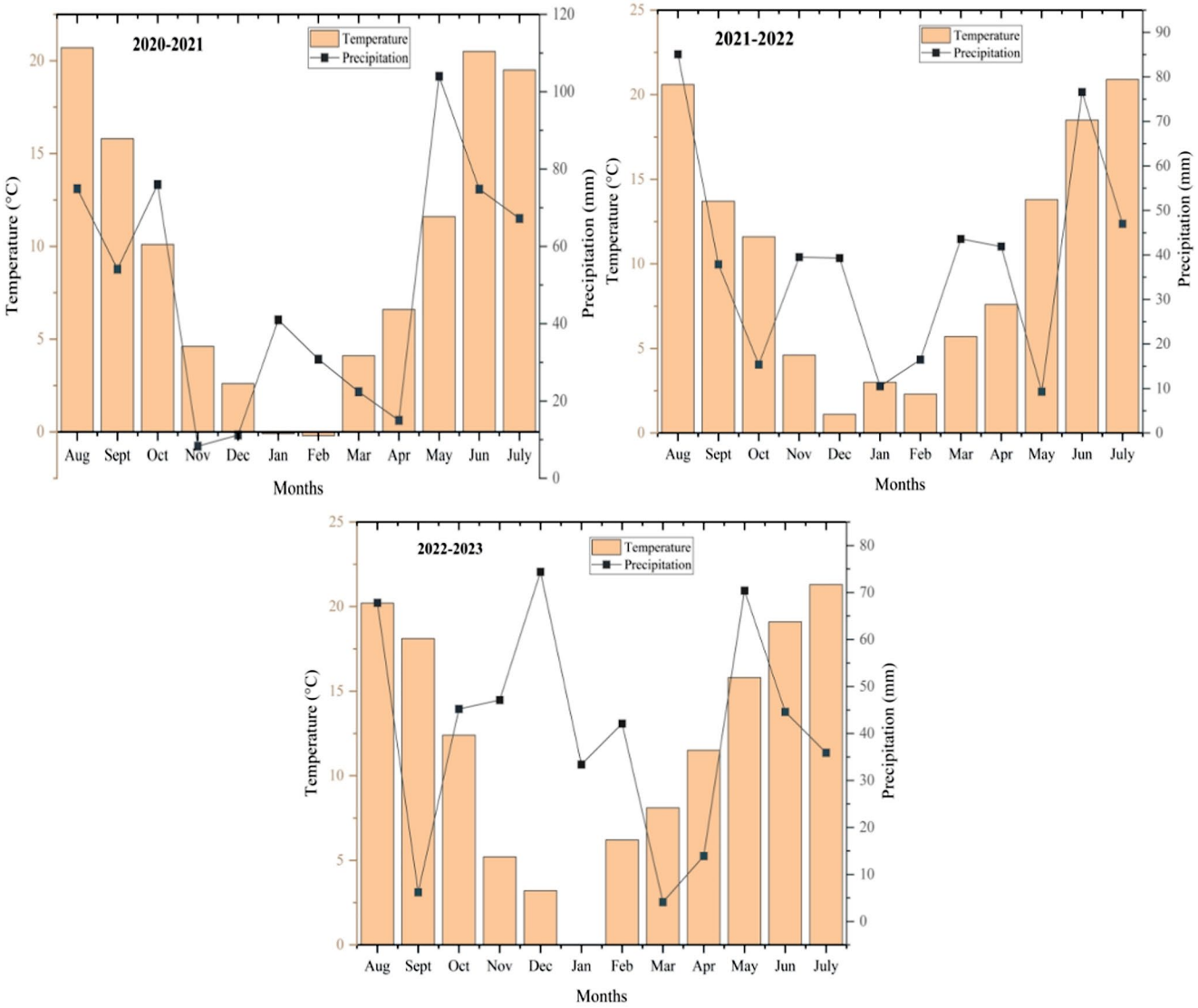


Fig. 1 Average monthly temperature and precipitation of the experimental area during 2021–2023

lodosulfuron-methyl- sodium applied at the rate of 30 g/ha. Insecticide, deltamethrin applied at the rate of 0.25 kg/ha for the control of sap sucking insects such as aphids. Fungicide, tebuconazole applied at the rate of 1 L/ha for the control of rusts.

Field Sampling and Analysis

Growth and Yield Traits

At maturity, plant height was manually determined using meter rod. Using a ruler, the length of each spike from the same plants was measured. The quantity of grains from each spike was counted after the spikes underwent threshing to separate the grains. To determine the biological yield, the plants were manually harvested and weighed in two central rows. Spelt wheat was threshed and separated into the grains and used electronic weighing balance to determine grain yield. To determine the 1000-grain weight, a subsample of 1000 grains was separated and weighed. Harvest index was computed based on the formula: grain yield/biological yield.

Grain Quality Attributes

Alina and Lazureanu (2011) procedure was used to quantify the grain starch contents. The Kjeldhal method was used to determine nitrogen content in the grain. Crude protein content was obtained by multiplying nitrogen fractions by 6.25 (AACC, 2000b). According to AACC's description, the volume of Zeleny sedimentation was estimated (AACC, 2000a).

Statistical Analysis

The experimental data statistically evaluated using two-way analysis of variance (ANOVA) designed for long-term experiments, and significant differences among treatments were determined using HSD at level of 0.05. This statistical package was performed under Statistics 8.1 software. Moreover, Pearson correlation and principal component analysis between measured indicators was drawn by using OriginPro 2021. Mantle correlation matrices were drawn by using R studio "ggcor" and "ggplot2" package.

Results

Spelt Wheat Genotypes Response to Growth Attributes

Analysis of variance showed that growth characteristics like plant height and spike length significantly ($p<0.05$) influenced by different spelt wheat genotypes and growing seasons (2021–2023). The interactive effects of genotypes and years were also significant. Interactive effects showed that greater plant height (135.6 cm) was obtained in genotype 69Z6.146 in 2023 closely followed by 69Z6.205 (135 cm). Whereas minimum plant height (107.6 cm) was noted in 69Z6.200 genotype in 2022 (Table 1). Regarding different years, 2023 resulted in highest plant height (130.9 cm), followed by 2021 (122.3 cm) and 2022 (121.8 cm). The result of spike length was noted as maximum for 69Z6.205 (15.8 cm) in 2023 followed by 69Z6.185 (15.7 cm), whereas the minimum spike length (9.3 cm) was measured in 2022 for genotype 69Z6.143 (Table 1). Regarding years comparison, the maximum spike length was attained in 2023 (14.0 cm), compared to 2022 (11.7 cm) and 2021 (11.6 cm). Maximum 1000 grain weight (54.3 g) were noted in 2023 for genotype 69Z6.205, closely followed by genotype 69Z6.205 (53 g) in 2022, compared to other spelt wheat genotypes. Minimum 1000 grain weight (38.6 g) were noted in 2022 for genotype 69Z6.198 (Table 2). The year 2023 resulted in highest 1000 grain weight (45.9 g), followed by 2021 (44.2 g) and 2022 (43.0 g).

Grain Yield Potential of Spelt Wheat Genotypes

Interactive results of the genotype and years showed that the maximum grain yield was noticed for genotype 69Z6.205 (7.5 t ha^{-1}), followed by genotype 69Z6.204 (7.3 t ha^{-1}) in 2023, whereas the minimum grain yield (4.24 t ha^{-1}) was determined for genotype 69Z6.163 in 2021, closely followed by 69Z6.190 (4.56 t ha^{-1}) in 2022 (Table 2). Regarding different years, 2023 resulted in highest grain yield (6.5 t ha^{-1}), followed by 2021 (5.8 t ha^{-1}) and 2022 (5.3 t ha^{-1}). The maximum biological yield was noticed for genotype 69Z6.205 (14.4 t ha^{-1}), followed by genotype 69Z6.204 (14.0 t ha^{-1}) were noted in 2023, whereas the minimum biological yield was obtained under genotype 69Z6.149 (10.2 t ha^{-1}), followed by genotype 69Z6.206 (10.1 t ha^{-1}) in 2022. In 2023, highest biological yield (12.1 t ha^{-1}) was recorded compared to 2021 and 2022. The highest harvest index (0.63) was noted in 2023 for genotype 69Z6.195 closely followed by genotype 69Z6.143 (0.61), while lowest harvest index (0.36) was observed in 2021 for genotype 69Z6.163 followed by 69Z6.163 (0.35) in 2022. In 2023,

Table 1 Performance assesment of diverse spelt wheat genotypes regarding growth performance such as plant height and spike length in central Europe under three consecutive growing seasons (2021 to 2023)

Treatments	Plant height (cm)				Spike length (cm)			
	2021	2022	2023	Mean	2021	2022	2023	Mean
69Z6.142	115.6 f-m	119.6 Z-i	132 A-I	122.4 N-R	11.2 e-w	9.9 t-y	12.2 V-O	11.1 P-Q
69Z6.143	117.3 e-m	119.3 Z-k	124.3 N-b	120.3 RS	12.5 S-m	9.3 y	14.1 B-S	11.9 K-O
69Z6.144	115 h-m	113.6 k-m	134.3 A-C	121 Q-S	12.3 U-n	10.9 i-y	13.2 J-a	12.1 I-N
69Z6.145	118 c-l	115 h-m	131.6 A-J	121.5 P-S	13 K-a	11 h-x	14.4 A-N	12.8 E-K
69Z6.146	121.3 U-f	117.6 d-m	135.6 A	124.8 G-O	12.1 V-p	10.9 j-y	13.5 F-W	12.2 I-N
69Z6.147	120.6 W-h	114 j-m	134.3 A-C	123 L-R	10.6 n-y	10.9 j-y	14.1 B-T	11.9 L-P
69Z6.148	129.3 B-P	129.6B-O	132 A-I	130.3 A-C	14.3 A-P	13.7 F-E	15.6 A-C	14.5 A-B
69Z6.149	124.6 M-a	114.6 i-m	131.3 A-K	123.5 K-Q	11.2 e-w	11.6 Y-r	12.9 L-c	11.9 L-P
69Z6.153	128.3 D-R	128.3D-R	131.6 A-J	129.4 B-T	13.9 C-U	13.5 G-W	15.5 A-D	14.3 A-C
69Z6.155	124.6 M-a	123.6 P-c	132.6 A-G	127 D-I	11.5 Z-t	10.8 L-y	14 P-T	12.1 I-N
69Z6.158	123.6 P-c	121 V-g	133.3 A-E	126 E-L	11.8 X-r	12.3 U-n	13 K-a	12.4 F-M
69Z6.159	126.3 I-W	124.6 M-a	132.3 A-H	127.7 C-G	11.6 Z-s	11.1 e-w	13.4 G-X	12 J-N
69Z6.160	124.3 N-b	120.3 X-i	128 D-R	124.2 H-P	12.2 V-o	11.8 X-r	14.6 A-L	12.8 E-J
69Z6.161	117.6 d-m	123.3 Q-d	130.3 A-M	123.7 J-Q	11 g-x	12.1 V-p	14.7 A-J	12.6 F-L
69Z6.163	115.3 g-m	122 S-e	129.6 B-O	122.3 O-R	11.2 e-w	12.2 V-o	13.6 F-W	12.3 G-M
69Z6.164	122.6 R-e	126.3 I-W	130 A-N	126.3 E-K	11.5 a-t	10.9 i-y	12.8 N-f	11.7 M-P
69Z6.166	123.6 P-c	120 Y-I	130.6 A-l	124.7 G-O	11.2 c-v	12.7 O-g	15.4 A-E	13.1 D-H
69Z6.167	123.3 Q-d	122 S-e	130 A-N	125.1 F-O	10.2 r-y	11.2 e-w	12.9 M-d	11.4 N-Q
69Z6.168	121.3 U-f	118.6 b-k	128.3 D-R	122.7 M-R	11.7 Y-r	10.8 L-y	13.9 D-U	12.1 I-N
69Z6.170	119 a-k	115.6 f-m	132 A-I	122.2 O-R	12.5 S-l	11.6 Y-r	14.4 A-N	12.8 E-J
69Z6.171	125 L-Z	119.6 Z-j	131 A-K	125.2 F-O	19.5 w-y	11.6 Y-r	14.1 V-T	11.7 M-P
69Z6.174	127.3 F-T	126 J-K	131.6 A-J	128.3 C-E	13.6 F-W	13.1 J-a	15 A-G	13.9 B-D
69Z6.175	124 O-b	118 c-l	130 K-N	124 I-Q	12.1 V-p	12.5 S-m	14.9 A-I	13.1 D-G
69Z6.178	120 W-h	118.6 b-k	127.6 E-S	122.3 O-R	11.1 g-w	9.8 u-y	12.4 T-m	11.1 O-Q
69Z6.179	126.3 I-W	124.3 N-b	131 A-K	127.2 D-G	13.3 H-Y	12.6 Q-i	13.8 E-V	13.2 D-F
69Z6.180	121.6 T-e	123.6 P-c	129.3 B-P	124.8 G-O	11.2 d-w	12.6 R-j	13 K-a	12.3 H-N
69Z6.181	119.6 Z-j	126 J-X	132 A-J	125.8 E-L	10.9 k-y	11.7 Y-r	12.2 V-o	11.6 M-Q
69Z6.182	124.6 M-a	129 C-Q	130.6 A-L	128.1 C-F	10.6 o-y	11.7 Y-r	13.2 I-Z	11.8 L-P
69Z6.183	117.6 d-m	124 O-b	132.6 A-G	124.7 G-O	10.1 r-y	12.5 R-k	14.1 B-S	12.2 H-N
69Z6.185	118.6 b-k	127.6 E-S	131 A-K	125.7 E-M	12 W-q	12.9 K-b	15.7 A-B	13.5 C-E
69Z6.187	130.6 k-m	125.6 K-Y	130.6 A-L	120.3 K-R	10.5 p-y	11.5 Z-t	13.5 F-W	11.8 L-P
69Z6.188	122.6 R-e	127 G-U	132 A-I	127.2 D-H	11.6 Y-r	12.6 P-h	14.2 A-R	12.8 E-K
69Z6.190	117 e-m	112.3 L-n	128 D-R	119.1 S	10.6 o-y	9.8 U-y	12.8 N-e	11 P-Q
69Z6.193	117.3 e-m	123.6 P-c	128.6 C-Q	123.2 L-R	9.7 u-y	10.3 r-y	12.5 R-k	10.8 Q
69Z6.194	112 m-n	118 c-l	126 J-X	118.6 S	10.6 o-y	11.7 X-r	13.1 J-a	11.8 L-P
69Z6.195	119.6 Z-j	125.6 K-Y	131 A-K	125.4 E-N	11.1 e-w	12.7 O-g	15.6 AB	13.1 D-G
69Z6.198	126 J-X	121.6 T-e	133.6 A-D	127.1 D-H	12 W-Q	11.1 f-w	15.2 A-F	12.8 E-K
69Z6.199	126.3 I-W	121.3 U-f	133.3 A-E	127 D-I	11.6 Y-r	10.4 q-y	14.5 A-M	12.2 I-N
69Z6.200	119.6 Z-j	107.6 n	129 C-Q	118.7 S	11 g-x	9.9 s-y	14.0 B-T	11.6 M-Q
69Z6.202	126.3 I-W	121.6 D-e	133 A-F	127 D-I	10.8 m-y	9.4 x-y	15.5 A-D	11.9 L-P
69Z6.203	127.6 E-S	118.6 b-k	130.6 A-L	125.6 E-M	12.2 V-o	9.9 t-y	14.3 A-O	12.1 I-N
69Z6.204	129.6 B-O	130.3 A-M	134.3 A-C	131.4 A-B	14.6 A-K	14 B-T	15.6 A-C	14.7 AB
69Z6.205	133.3 A-E	131.3 A-K	135 A-B	133.2 A	14.8 A-J	14.3 A-Q	15.8 A	14.9 A
69Z6.206	127.3 F-T	124.6 M-a	127 G-U	126.3 E-K	12.5 S-m	11.2 d-w	14.9 A-H	12.9 E-J
69Z6.207	126.3 I-W	123.6 P-c	130 A-N	126.6 D-J	11.3 b-u	11.6 v-y	14.0 B-T	11.6 M-Q
Rubiota	124.3 N-b	126.6 H-V	129 C-Q	126.6 D-J	11.6 Y-r	13.2 J-a	14.0 B-T	12.9 E-H
Mean	122.3 B	121.8 B	130.9 A		11.7 B	11.5 C	14.0 A	

Note: significant differences among 46 spelt wheat genotypes were determined using HSD level of 0.05. Lower case letters denote lower mean values, and upper-case letters denote higher mean values ($n = 3$)

Table 2 Performance assessment of diverse spelt wheat genotypes regarding yield performance such as thousand grain weight and grain yield in central Europe under three consecutive growing seasons (2021 to 2023)

Treatments	1000 grain weight (g)				Grain yield (t ha^{-1})			
	2021	2022	2023	Mean	2021	2022	2023	Mean
69Z6.142	48 E-S	45.1 Q-k	49.3 C-M	47.5 C-E	6.5 C-N	5.4 a-q	6.8 A-I	6.2 D-F
69Z6.143	42.3 g-w	46 M-c	44.1 V-o	44.1 H-K	6.2 J-V	5.2 d-t	6.4 E-P	5.9 F-J
69Z6.144	45.9 M-d	42.5 e-u	41.9 j-y	43.5 KL	6.5 C-N	5.1 g-u	6.1 K-Y	5.9 F-K
69Z6.145	42.5 f-u	40.9 o-y	49.9 B-I	44.5 H-K	5.3 b-t	5 k-u	7 A-E	5.7 I-O
69Z6.146	44.1 V-o	39.1 v-y	45.3 P-j	42.8 K-M	6.7 B-K	4.8 n-v	6.5 C-N	6 E-I
69Z6.147	46.4 K-c	39.3 u-y	46.3 K-c	44 I-K	6.3 F-S	4.8 O-V	6.6 C-M	5.9 G-K
69Z6.148	49.4 C-L	48.2 E-R	52 A-D	49.9 B	7 A-F	6.7 B-K	7.2 A-C	6.9 AB
69Z6.149	52.6 d-u	45.3 P-h	48.7 D-P	45.5 F-I	6.2 H-T	5.2 e-u	6.9 A-G	6.1 E-H
69Z6.153	48.1 E-S	47.4 F-V	50.2 B-H	48.6 B-C	6.9 A-H	6.5 C-N	7 A-E	6.8 B-C
69Z6.155	46.4 J-b	45.1 Q-k	49.5 C-L	47 C-G	5.4 Z-p	5.1 g-u	7 A-G	5.8 G-M
69Z6.158	46.1 L-c	45.9 M-e	47 G-Y	46.3 D-G	6.4 D-O	5.3 b-t	6.7 B-L	6.1 E-G
69Z6.159	45.5 O-g	44.9 R-k	45.7 N-g	45.4 G-J	6.3 G-S	5.2 d-t	6.4 D-O	6 E-I
69Z6.160	46.3 L-c	41.9 k-y	49.2 C-M	45.8 E-H	5.9 M-b	4.9 L-u	6.9 A-G	5.9 F-J
69Z6.161	44.5 T-m	42.4 g-w	43.5 Z-p	43.5 K-L	5.3 b-s	5.1 g-u	6.9 E-R	5.6 K-P
69Z6.163	40.9 o-y	40 r-y	42 h-x	41 N-Q	4.2 v	4.7 p-v	6.1 K-W	5.0 S
69Z6.164	48.5 E-Q	43.9 X-o	50.6 B-F	47.7 C-D	6 K-Z	5.4 b-q	7 A-E	6.1 E-G
69Z6.166	46.8 I-m	45.5 N-g	49.2 D-M	47.2 C-F	5.4 Z-p	5.5 W-m	6.9 A-G	5.9 F-J
69Z6.167	43.7 Y-o	41.9 k-y	46.3 L-c	43.9 I-K	6.5 C-n	5 k-u	6.3 E-R	5.9 F-J
69Z6.168	47.5 F-U	39.4 u-y	42.4 f-w	43.1 K-M	5.7 Q-h	4.7 q-v	6.1 K-X	5.5 L-P
69Z6.170	47.7 F-T	43.4 p-s	48 E-S	46.3 D-G	5.6 U-k	5.3 c-t	6.6 C-L	5.8 G-M
69Z6.171	45.7 N-f	43.8 X-o	46.9 H-Z	45.5 F-J	5.4 Y-o	5.6 U-L	6.6 C-N	5.8 G-L
69Z6.174	47.4 F-V	46.3 K-c	49.7 P-K	47.8 C-D	6.8 A-I	6.5 D-O	6.9 A-G	6.7 B-C
69Z6.175	43.6 Z-o	45.3 Q-j	42.4 f-w	43.8 J-L	5.2 d-t	5.8 O-d	6.2 I-U	5.7 I-O
69Z6.178	42.5 f-v	44.8 S-l	48.8 D-N	45.4 G-J	5.1 g-u	5.7 S-j	6.9 A-H	5.9 G-K
69Z6.179	46.4 K-c	45.3 P-i	49.3 C-M	47 C-G	6.7 B-K	6 L-a	6.9 A-H	6.5 C-D
69Z6.180	39.8 t-y	38.8 xy	39.5 u-y	39.3 Q	5.3 b-s	4.8 o-v	5.8 O-e	5.3 P-S
69Z6.181	43.6 Z-o	41.2 m-y	40.1 q-y	41.6 M-O	5.2 d-u	5.1 h-u	5.9 M-b	5.4 P-R
69Z6.182	39.5 u-y	41.3 m-y	41.2 m-y	40.7 N-Q	5.1 f-u	5.1 g-u	6.1 K-X	5.4 N-R
69Z6.183	40 s-y	40.1 r-y	44.1 U-o	41.4 M-P	5 k-u	5 k-u	6.3 E-R	5.4 O-R
69Z6.185	48.7 D-O	43.4 b-r	49.8 B-J	47.3 C-E	6.7 B-L	5.3 c-t	7 A-G	6.3 D-E
69Z6.187	39.6 u-y	39.6 u-y	42.1 h-x	40.4 N-Q	5.1 h-u	4.6 t-v	5.8 O-f	5.2 Q-S
69Z6.188	40 r-y	43.4 b-s	45.2 Q-k	42.9 K-M	5.1 g-u	4.9 k-u	6.4 E-q	5.5 M-Q
69Z6.190	43.5 a-q	39.7 t-y	45.9 M-d	43 K-M	5.3 c-t	4.5 uv	6.6 C-N	5.4 N-R
69Z6.193	42 i-y	43.3 T-n	41.9 i-y	42.7 K-M	5.2 d-u	5.4 b-q	6.2 I-V	5.6 K-P
69Z6.194	41.3 m-y	38.8 xy	43.3 T-n	41.5 M-P	5 j-u	4.8 o-v	6.4 E-P	5.4 P-R
69Z6.195	41.3 m-y	42.5 f-u	48.9 D-N	44.2 H-K	5.1 G-U	5.3 c-t	7 A-E	5.8 H-N
69Z6.198	43.1 c-t	38.6 y	44.5 T-m	42 L-N	5.5 X-n	4.8 o-v	6.3 E-R	5.5 L-P
69Z6.199	39.1 v-y	39.6 u-y	41.1 m-y	39.9 O-Q	4.8 m-v	4.7 r-v	5.8 O-d	5.1 RS
69Z6.200	41.2 m-y	39.5 u-y	40.9 o-y	40.6 N-Q	5 i-u	4.6 s-v	5.7 R-i	5.1 RS
69Z6.202	39.3 u-y	38.7 xy	44 W-o	40.7 N-Q	5.3 c-t	4.8 o-v	6.3 F-S	5.4 O-R
69Z6.203	41 n-y	44.9 R-k	47.3 F-W	44.4 H-K	5.9 N-c	5.5 W-m	6.6 C-L	6 E-I
69Z6.204	50.4 B-G	52 A-D	52.6 A-C	51.6 A	7.1 A-D	6.8 A-J	7.3 A-B	7.1 A-B
69Z6.205	51.2 A-E	53 A-B	54.3 A	52.8 A	7.1 A-C	7.1 A-D	7.5 A	7.2 A
69Z6.206	39.4 u-y	41.5 L-y	41.2 m-y	40.7 N-Q	5.3 b-r	5.1 g-u	5.7 P-g	5.4 P-R
69Z6.207	40.2 p-y	39.1 w-y	40 r-y	39.8 P-Q	5.7 R-g	5.5 V-l	5.6 T-k	5.6 J-P
Rubiota	47 G-X	44.3 T-n	46.1 L-c	45.8 E-H	6.2 J-V	5.6 U-l	6.4 D-O	6 E-I
Mean	44.1 B	43 C	45.9 A		5.8 B	5.3 C	6.5 A	

Note: significant differences among 46 spelt wheat genotypes were determined using HSD level of 0.05. Lower case letters denote lower mean values, and upper-case letters denote higher mean values ($n = 3$)

greater harvest index (0.54) was recorded compared to 2021 (0.5) and 2022 (0.46) (Table 3).

Response of Spelt Wheat Genotypes to Nutritional Composition

The results regarding crude protein showed considerable variability among tested wheat genotypes and years interaction ($p<0.05$; Table 4). The interactive effects of genotypes × years showed that highest levels of crude protein were recorded in 2023 for genotype 69Z6.147 (22.1%), closely followed by 69Z6.195 (21.8%), 69Z6.205 (21.6%) and 69Z6.204 (21.4%) whereas lowest crude protein concentration was recorded in 2021 for 69Z6.182 genotype (14.4%). In 2023, greater crude protein content (19.8%) was recorded compared to 2021 (17.6%) and 2022 (16.9%) (Table 4). Moreover, our results showed highest starch contents for genotype 69Z6.205 (65.7%) in 2023 followed by 69Z6.204 (65.4%), whereas lowest starch contents (46.4%) in 2022 were determined for 69Z6.168 genotype. Regarding years comparison, 2023 resulted in highest starch contents (61.2%), significantly followed by 2021 (53.8) and 2022 (52.5%) (Table 4). Maximum ZST contents were observed in genotype 69Z6.185 (45.6%), followed by 69Z6.205 (45.0%) and 69Z6.204 (43.6%) in 2023. Whereas lowest ZST content (19.6%) was determined in 2022 for 69Z6.178 genotype. In 2023, greater ZST content (36.4%) was recorded compared to 2022 (27.4%) and 2021 (26.8%) (Table 5).

Pearson correlation, Mantel Test and Principal Component Analysis Among Measured Variables

The three-year (2021 to 2023) correlation analysis showed significant positive correlations observed between most measured indicators (Fig. 2). GY showed strong positive correlations with many traits including HI, SC and ZST ($p<0.05$). Similarly, TGW and SL also showed positive correlation with SC and CP. BY showed some negative relationship with HI (Fig. 2).

The principal component analysis (PCA) biplot showed the relationship among different traits in consecutive three years 2021 to 2023 (Fig. 3). PC1 consists of 49.1%, 47.1% and 39.9% of the total variation, while PC2 explains 17.6%, 19.6% and 21.7% of the variation in three years respectively. In all years, the biplots showing GY, BY and HI are positively correlated with PC1, while SL and others parameter are also influenced under PC2. The overall distribution of datapoints fluctuated among different years, reflecting more unpredictability in 2022 and 2023 compared to 2021 due to environmental changes. Moreover, the study shows trade-offs in total biomass production and partitioning efficiency to grain, thereby revealing insights into traits performance as well as relationships over temporal scale (Fig. 3).

The muti year (2021 to 2023) network correlation plot or mantel analysis showed both the strength and significance of correlation among various traits (Fig. 4). The curved lines connect significantly correlated traits, with line thickness indicating correlation strength and various colors scheme represent Pearson correlation (red color denotes positive and blue color denotes negative correlation). The line thickness shows mantel's "r" values (≤0 = thin, 0-0.4 = medium, ≥ 0.4 = thick). The 2021 growing season showed positive correlations among most traits, with GY showing moderate network connectivity. A distinct shift occurred in 2022, characterized by increasingly negative correlations between BY and HI, and ZST, suggesting resource allocation trade-offs under potentially stressful growing conditions. The 2022 season also intensified negative associations with TGW, indicating yield component competition. By 2023, trait relationships stabilized with maintained yield-component clustering, though the negative BY associations persisted. Notably, in 2023, the PH and SL association significantly increased, which may have been caused by morphological response under multi-year selection pressure. These temporal relationship trends imply that the genetic architecture of trait relationships was impacted by environmental variation throughout time, with 2022 emerging as a critical year for the escalation of trade-offs (Fig. 4).

Impact of Climatic Attributes on Spelt Wheat Productivity and Nutritional Quality

The mantel correlation analysis showed that climate-trait relationships in spelt wheat differ during the three years (2021–2023) (Fig. 5). Vegetative parameters (PH, SL, TGW) were always positively correlated with temperature. Significant p-values ($p<0.01$) show these relationships are statistically meaningful. Both the temperature and precipitation are highly related to several traits, with temperature having positive effect on GY and BY, while precipitation positively correlate ZST and HI. The findings imply that agronomic and quality traits are greatly impacted by environmental conditions, with recurring patterns seen over years.

Discussion

Spelt wheat is usually grown in high-altitude areas with rich soil and frequent precipitation. A major determinant of yield and an indirect indicator of milling quality is the thousand-grain weight (TGW). In general, a higher TGW is associated with a greater flour extraction efficacy. In line with findings

Table 3 Performance assessment of diverse spelt wheat genotypes regarding yield components such as biological yield and harvest index in central Europe under three consecutive growing seasons (2021 to 2023)

Treatments	Biological yield (t ha^{-1})				Harvest index			
	2021	2022	2023	Mean	2021	2022	2023	Mean
69Z6.142	11.6 I-k	11.4 N-k	11.8 H-k	11.6 H-Q	0.5 A-N	0.4 O-i	0.5 A-G	0.5 A-C
69Z6.143	11.2 R-k	11.8 H-k	10.4 f-k	11.1 K-R	0.5 A-Q	0.4 Y-o	0.6 A-B	0.5 A-C
69Z6.144	10.8 Z-k	11.3 P-k	10.5 b-k	10.9 N-R	0.6 A-C	0.4 W-n	0.5 A-I	0.5 A-B
69Z6.145	10.6 b-k	11.9 G-i	12.4 B-a	11.6 H-P	0.5 F-f	0.4 e-p	0.5 A-L	0.4 C-J
69Z6.146	11.2 S-k	11 W-k	12.1 C-d	11.4 H-R	0.6 A-D	0.4 a-p	0.5 B-W	0.5 A-E
69Z6.147	10.9 X-k	12.6 B-W	11.6 I-k	11.7 F-N	0.5 A-H	0.3 m-p	0.5 A-L	0.5 B-H
69Z6.148	13.3 A-I	13.1 A-M	13.7 A-E	13.4 A-C	0.5 C-a	0.5 E-c	0.5 C-a	0.5 A-G
69Z6.149	11.2 R-k	10.2 k	11.7 I-k	11 M-R	0.5 A-O	0.5 F-d	0.5 C-Y	0.5 A
69Z6.153	13.1 A-M	12.7 B-V	13.4 A-H	13 B-D	0.5 C-Y	0.5 E-b	0.5 C-b	0.5 A-F
69Z6.155	11 U-k	10.4 g-k	12.1 D-f	11.1 J-R	0.4 J-g	0.4 H-f	0.5 A-I	0.5 A-F
69Z6.158	11.7 I-k	11.4 N-k	11.6 K-k	11.5 H-Q	0.5 A-Q	0.4 S-l	0.5 A-H	0.5 A-D
69Z6.159	11.5 L-k	11.1 S-k	11.9 G-j	11.5 H-Q	0.5 B-S	0.4 P-j	0.5 B-U	0.5 A-F
69Z6.160	10.3 h-k	10.5 c-k	12.4 B-a	11.1 L-R	0.5 A-I	0.4 Q-J	0.5 A-M	0.5 A-C
69Z6.161	10.6 b-k	10.4 e-k	11.5 L-k	10.8 O-R	0.5 F-e	0.4 J-g	0.5 A-Q	0.5 A-H
69Z6.163	11.7 I-k	13.3 A-J	13.1 A-M	12.7 C-E	0.3 o-p	0.3 p	0.4 Q-j	0.3 N
69Z6.164	12 F-h	11.1 U-k	13 A-P	12 E-J	0.5 F-d	0.4 K-g	0.5 B-W	0.5 B-H
69Z6.166	13.4 N-k	10.8 a-k	12.8 A-S	11.6 H-P	0.4 N-h	0.5 F-C	0.5 B-U	0.5 B-H
69Z6.167	12.1 C-d	11.4 N-k	11.8 H-k	11.7 F-M	0.5 B-W	0.4 b-p	0.5 B-U	0.5 B-I
69Z6.168	11.8 H-k	11.1 S-k	11.9 G-j	11.6 H-Q	0.4 K-g	0.4 d-p	0.5 D-b	0.4 G-L
69Z6.170	10.9 X-k	10.5 d-k	12 E-g	11.1 K-R	0.5 E-c	0.5 F-d	0.5 A-Q	0.5 A-F
69Z6.171	10.6 b-k	10.5 d-k	12.1 C-d	11.1 L-R	0.5 E-c	0.5 B-X	0.5 B-U	0.5 A-E
69Z6.174	12.9 A-R	12.5 B-Y	12.9 A-R	12.7 C-E	0.5 B-X	0.5 E-b	0.5 B-V	0.5 A-E
69Z6.175	12.2 C-c	10.9 Y-k	11 W-k	11.3 I-R	0.4 c-p	0.5 B-W	0.5 A-L	0.5 A-H
69Z6.178	11.6 J-k	11.6 U-k	12.4 B-a	11.7 G-O	0.4 Y-o	0.5 E-c	0.5 A-P	0.5 B-I
69Z6.179	12.8 A-T	12.1 C-d	12.7 A-U	12.5 C-G	0.5 C-Z	0.4 G-f	0.5 B-U	0.5 A-F
69Z6.180	11.1 S-k	11.5 L-k	10.2 j-k	10.9 M-R	0.4 M-G	0.4 f-p	0.5 A-K	0.4 E-K
69Z6.181	10.5 c-k	11 W-k	10.4 f-k	10.6 R	0.4 G-f	0.4 T-m	0.5 A-J	0.5 B-H
69Z6.182	10.6 b-k	11.7 I-k	11.3 P-k	11.2 J-R	0.4 K-g	0.4 b-p	0.5 B-U	0.4 D-K
69Z6.183	11.3 P-k	13 A-O	12.1 D-e	12.1 E-I	0.4 a-p	0.3 k-p	0.5 C-Z	0.4 K-M
69Z6.185	11.7 H-k	10.4 f-k	12.9 a-q	11.7 G-P	0.5 A-K	0.5 F-d	0.5 B-P	0.5 AB
69Z6.187	11.4 N-k	10.5 b-k	10.6 b-k	10.8 P-R	0.4 X-n	0.4 Z-p	0.5 A-Q	0.4 F-L
69Z6.188	11.5 L-k	11.7 I-k	13.2 A-K	12.1 E-I	0.4 X-n	0.4 d-p	0.4 L-g	0.4 J-M
69Z6.190	11.1 U-k	11.9 J-i	11.3 Q-k	11.4 H-R	0.4 M-g	0.3 L-p	0.5 A-F	0.4 F-L
69Z6.193	11.8 H-k	11.9 G-j	13.1 A-L	12.3 D-H	0.4 a-p	0.4 X-n	0.4 P-j	0.4 J-L
69Z6.194	12.4 B-a	12.2 C-b	11.2 S-k	11.9 E-L	0.4 g-p	0.3 x-p	0.5 A-J	0.4 J-L
69Z6.195	11.1 U-k	11.9 G-j	11 V-k	11.3 I-R	0.4 R-k	0.4 Y-o	0.6 A	0.5 A-H
69Z6.198	11.1 T-k	12.4 B-a	12.4 B-a	12 E-K	0.4 I-f	0.3 j-p	0.5 E-c	0.4 I-L
69Z6.199	12.5 B-Z	12.6 B-X	12.7 A-U	12.6 C-F	0.3 i-p	0.3 n-p	0.4 U-n	0.4 MN
69Z6.200	11.3 Q-k	11.4 M-k	12.1 C-d	11.6 H-Q	0.4 X-n	0.4 g-p	0.4 P-j	0.4 LM
69Z6.202	11.6 J-k	11.5 L-k	11.6 I-k	11.6 H-Q	0.4 V-n	0.4 f-p	0.5 B-U	0.4 H-L
69Z6.203	11.7 I-k	11.7 I-k	11.4 N-k	11.6 H-Q	0.5 F-d	0.4 P-j	0.5 A-F	0.5 A-F
69Z6.204	13.7 A-D	13.5 A-G	14 A-B	13.7 A-B	0.5 E-b	0.5 F-d	0.5 C-b	0.5 A-H
69Z6.205	13.8 A-C	13.7 A-F	14.4 A	13.9 A	0.5D-b	0.5 D-b	0.5 C-b	0.5 A-G
69Z6.206	10.8 a-k	10.1 k	10.9 X-k	10.6 R	0.4 G-f	0.5 F-d	0.5 D-Y	0.5 B-H
69Z6.207	10.4 f-k	10.3 i-k	11.6 I-k	10.8 Q-R	0.5 A-R	0.5 B-W	0.4 L-g	0.5 A-F
Rubiota	11.3 O-k	11.4 N-k	13 A-N	11.9 E-L	0.5 B-T	0.4 J-g	0.4 G-f	0.5 B-H
Mean	11.5 B	11.5 B	12 A		0.50 B	0.46 C	0.54 A	

Note: significant differences among 46 spelt wheat genotypes were determined using HSD level of 0.05. Lower case letters denote lower mean values, and upper-case letters denote higher mean values ($n = 3$)

Table 4 Performance assessment of diverse spelt wheat genotypes regarding nutritional composition such as starch and crude protein content in central Europe under three consecutive growing seasons (2021 to 2023)

Treatments	Starch content (%)				Crude protein (%)			
	2021	2022	2023	Mean	2021	2022	2023	Mean
69Z6.142	54.7 Z-m	48 u-A	64.4 A-C	55.7 G-N	19.5 E-T	17.3 Y-r	20.4 A-I	19.1 C-F
69Z6.143	48.5 r-A	46.4 z-A	58.1 K-a	51 ST	19.2 G-W	16.8 b-u	20.4 A-J	18.8 C-H
69Z6.144	54.1 a-p	49 q-A	64.3 A-C	55.8 G-M	19.6 E-R	17.1 Z-t	20.1 B-M	18.9 C-G
69Z6.145	50.6 L-A	47.2 w-A	62.1 A-L	53.3 O-R	20.3 A-J	17.6 V-O	20.1 A-F	19.7 B-C
69Z6.146	51 i-x	49.5 q-a	61.6 B-O	53.9 M-R	18.5 K-c	17.7 T-m	20.6 A-i	18.9 C-G
69Z6.147	50.9 i-y	49.6 q-A	62.7 A-J	54.4 J-Q	19.1 G-X	17.7 T-m	22 A	19.6 B-C
69Z6.148	60.5 C-S	59.5 E-X	64.1 A-D	61.4 A-C	19.6 D-X	17.6 U-n	21.3 A-e	19.5 B-D
69Z6.149	54.8 Y-l	49.8 p-A	61.4 A-n	55.3 G-O	17.3 Y-r	15.9 n-y	19.2 G-W	17.4 J-N
69Z6.153	59.7 D-W	58.3 J-a	62.9 A-I	60.3 B-D	19.3 F-V	17.4 X-q	21.1 A-F	19.2 C-E
69Z6.155	52.6 d-t	53.4 b-q	62.7 A-J	56.2 G-L	18.1 N-g	15.8 o-y	19.6 E-R	17.8 I-M
69Z6.158	55.6 V-h	50.1 o-A	62.5 A-K	56.1 G-M	18.1 N-i	15.9 m-y	19.1 H-Y	17.7 I-M
69Z6.159	54.6 Z-n	49.4 Q-a	60.1 C-U	54.7 I-Q	18.1 N-h	16.9 a-u	20.8 A-H	18.6 D-I
69Z6.160	50.3 m-A	47.1 w-A	59.8 D-v	52.4 Q-T	18.1 N-f	16.1 K-y	19.1 H-Y	17.8 I-M
69Z6.161	50.3 m-A	54.8 Y-l	63 A-G	56 G-M	16.3 i-x	17.1 Z-t	19.7 D-P	17.7 I-M
69Z6.163	46.5 y-A	50.2 n-A	55.2 X-j	50.6 T	14.7 v-y	18 P-j	20.6 A-i	17.8 I-M
69Z6.164	51.4 h-x	50.6 L-A	60.4 C-S	54.1 K-Q	16.4 e-w	41.7 v-y	17.2 Z-r	16.1 P-Q
69Z6.166	52.9 c-r	48.6 r-A	61.6 A-N	54.3 J-Q	18 O-i	17.5 W-p	20.8 A-H	18.8 C-H
69Z6.167	54.6 Z-m	49.2 q-A	61.2 A-N	55 H-P	17.2 Z-s	16.7 c-u	20.3 A-J	18.1 G-L
69Z6.168	49.6 q-A	46.4 zA	59.2 E-Y	51.7 R-T	17.7 U-n	16 L-y	18.2 N-e	17.3 K-N
69Z6.170	54.8 Y-l	50 o-A	61.4 A-n	55.4 G-O	18.8 I-Z	17.7 S-m	20.4 A-J	19.0 C-G
69Z6.171	50.5 I-A	48.2 t-A	60.3 C-T	53 P-S	18.2 N-e	17 Z-u	20.2 B-L	18.5 E-I
69Z6.174	58.7 G-Z	57.6 M-b	63.3 A-F	59.8 C-D	18.6 J-a	16.8 a-u	20.9 A-G	18.8 C-H
69Z6.175	54.8 Y-l	52.3 d-u	60.3 C-T	55.8 J-M	17.4 X-q	17.1 Z-s	19.8 C-P	18.1 G-L
69Z6.178	52.7 c-s	48.4 s-A	60.8 C-P	54 L-R	18.3 M-d	16.5 d-w	19.4 F-v	18.1 G-L
69Z6.179	58.6 G-Z	56.5 P-d	62.7 A-J	59.2 C-E	18.1 N-i	16.4 f-w	20.7 A-H	18.4 E-J
69Z6.180	50.4 L-A	56.7 O-d	61.8 A-M	56.3 F-K	15.2 u-y	17.0 Z-u	19.5 E-S	17.2 L-N
69Z6.181	49.4 q-A	53.4 b-q	62.5 A-K	55.1 H-P	18.2 N-e	17.7 U-n	19.2 C-N	18.6 D-I
69Z6.182	55.9 T-g	55.3 W-i	61.2 B-O	57.5 E-G	14.4 Y	16.3 g-x	18.1 N-g	16.3 O-Q
69Z6.183	51.4 h-w	56.2 R-d	61.1 B-O	56.2 F-L	15.3 t-y	16.2 j-y	18.4 L-c	16.6 N-P
69Z6.185	54.5 Z-o	55.8 U-h	60.8 C-P	57 E-H	16.2 k-y	17 a-u	20.8 A-H	18 H-M
69Z6.187	47.5 v-A	55.9 T-g	60.7 C-Q	54.7 I-P	17.1 Z-t	16 L-y	18.1 N-h	18.1 M-O
69Z6.188	51.6 f-w	58 L-a	58.4 J-a	56 G-M	14.8 v-y	15.4 s-y	16.4 f-x	15.5 Q
69Z6.190	51.5 g-w	46.5 y-A	62.2 A-L	53.4 N-R	15.6 q-y	17.8 R-l	19.3 F-v	17.5 J-N
69Z6.193	50.9 i-y	57.1 N-c	62.2 A-L	56.7 F-I	18.5 K-c	17.6 U-n	19.4 F-U	18.5 E-I
69Z6.194	50.7 k-A	55.8 U-h	63 A-H	56.5 F-J	15.6 p-y	17.4 X-q	18.6 J-b	17.2 L-O
69Z6.195	55.5 V-h	55.1 X-k	60.7 C-Q	57.1 E-H	15.5 r-y	17.6 V-o	21.8 A-B	18.3 F-J
69Z6.198	56 T-f	56.1 S-e	63.5 A-E	58.5 D-F	18.1 N-h	16.4 e-w	20.1 B-m	18.2 F-K
69Z6.199	55.1 X-J	58.3 J-a	56 T-f	56.5 F-J	16.4 f-x	15.4 r-y	18.0 O-i	16.6 N-P
69Z6.200	55.2 X-j	47 x-A	60.3 C-T	54.1 K-Q	17.2 Z-s	14.6 x-y	18.5 K-c	16.7 N-P
69Z6.202	58.5 H-Z	52.3 d-u	61.6 A-M	57.5 E-G	18.1 N-h	16.5 d-v	20.4 A-I	18.4 E-J
69Z6.203	58.5 I-a	49 q-A	58.9 F-Z	55.4 G-O	18.3 N-g	16.1 L-y	19.8 C-O	18.0 G-L
69Z6.204	61.3 A-N	60.6 C-R	65.4 A-B	62.4 A-B	19.8 C-P	20.1 B-L	21.4 A-D	20.4 A-B
69Z6.205	62.5 A-J	61.7 A-M	65.7 A	63.3 A	20.2 A-K	20.4 A-J	21.6 A-C	20.7 A
69Z6.206	56.4 P-d	50.9 j-z	58.5 I-a	54.3 G-P	17.2 Z-r	15.6 q-y	20.8 A-H	17.9 H-M
69Z6.207	57.3 M-b	49.6 q-A	58.8 U-h	54.2 G-Q	14.7 W-Y	15.9 n-y	16.3 h-x	15.6 Q
Rubiota	51.7 e-v	56.3 Q-d	59.3 E-X	55.8 G-M	17.7 U-n	17.9 Q-k	19.4 F-V	18.3 E-J
Mean	53.8 B	52.5 C	61.2 A		17.6 B	16.9 C	19.8 A	

Note: significant differences among 46 spelt wheat genotypes were determined using HSD level of 0.05. Lower case letters denote lower mean values, and upper-case letters denote higher mean values ($n = 3$)

Table 5 Performance assessment of diverse spelt wheat genotypes regarding nutritional performance such as Zeleny sedimentation test in central Europe under three consecutive growing seasons (2021 to 2023)

Treatments	ZST (%)			
	2021	2022	2023	Mean
69Z6.142	26.6 X-n	28.6 R-k	34.3 F-U	29.8 F-L
69Z6.143	24 f-o	20 n-o	28.6 R-k	24.2 P
69Z6.144	23.6 g-o	28.3 S-l	32.3 I-a	28.1 I-O
69Z6.145	27 W-m	19.6 o	29.3 P-i	25.3 N-P
69Z6.146	25.6 a-o	26.3 Y-o	34.3 F-U	28.7 G-N
69Z6.147	21.6 L-o	24.3 e-o	36.3 D-O	27.4 K-P
69Z6.148	32.3 I-a	32.3 I-a	42.3 A-D	35.6 B-C
69Z6.149	27.6 U-m	21.3 m-o	30 O-g	26.3 M-P
69Z6.153	31.6 K-c	26.3 Y-o	41.3 A-E	33.1 C-F
69Z6.155	28 T-m	27 W-m	34 F-V	29.6 F-M
69Z6.158	30.6 N-f	26 Z-o	37.3 C-N	31.3 D-I
69Z6.159	30.3 O-g	27 W-m	35 E-S	30.7 E-K
69Z6.160	24.6 d-o	20 n-o	30.6 N-f	25.1 O-P
69Z6.161	21.6 L-o	25.3 b-o	32.6 I-Z	26.5 L-P
69Z6.163	22.6 i-o	26.6 X-n	33 H-Y	27.4 K-P
69Z6.164	22 k-o	27.6 U-m	35 E-S	28.2 H-O
69Z6.166	23.6 g-o	31.3 L-d	38.3 B-K	31.1 D-J
69Z6.167	29 Q-j	27.6 U-m	36 D-P	30.8 E-K
69Z6.168	30 O-g	27.6 U-m	34.6 E-T	30.7 E-K
69Z6.170	29.6 O-h	24.3 e-o	38.6 B-J	30.8 E-K
69Z6.171	28.6 R-k	28.3 S-l	38 C-L	31.6 D-H
69Z6.174	29.3 P-i	27.6 U-m	40 A-G	32.3 C-F
69Z6.175	23.6 g-o	27.3 V-m	33.3 G-X	28.1 I-O
69Z6.178	24.6 d-o	19.6 o	35 E-S	26.4 L-P
69Z6.179	27.3 V-m	25.6 a-o	39.6 A-H	30.8 E-K
69Z6.180	26 Z-o	29.3 P-i	33.6 F-W	29.6 F-M
69Z6.181	25 c-o	31.6 K-c	38 C-L	31.5 D-I
69Z6.182	26 Z-o	28.6 R-k	38.6 B-J	31.1 D-J
69Z6.183	23 h-o	27.6 U-m	35.6 D-Q	28.7 G-N
69Z6.185	27 W-m	27.6 U-m	45.6 A	33.4 C-E
69Z6.187	24 f-o	28.6 R-k	36.3 D-o	29.6 F-M
69Z6.188	23 h-o	30 O-g	38.6 B-J	30.5 E-K
69Z6.190	22.3 j-o	28.3 S-l	35.3 E-R	28.6 G-N
69Z6.193	27 W-m	31 M-e	37.6 C-M	31.8 D-G
69Z6.194	22 k-o	25.6 a-o	32 J-b	26.5 L-P
69Z6.195	29 Q-j	28.6 R-k	40.3 A-F	32.6 C-F
69Z6.198	28.6 X-n	26.6 X-n	37.6 C-M	30.3 E-K
69Z6.199	22 k-o	27.6 U-m	33.6 F-W	27.7 J-O
69Z6.200	32 J-b	32.6 I-Z	39 A-I	34.5 C-D
69Z6.202	30 O-g	25.6 a-o	36.3 B-K	31.3 D-I
69Z6.203	29.6 O-h	30 O-g	36.3 B-K	32.6 C-F
69Z6.204	36.3 D-O	36 D-P	43.6 A-C	38.6 A-B
69Z6.205	38 C-L	36.3 B-K	45 A-B	40.4 A
69Z6.206	29.6 O-h	25.3 b-o	39.6 A-H	31.5 D-I
69Z6.207	27.6 U-m	24.6 d-o	30.6 N-f	27.6 J-P
Rubiota	24 f-o	31.6 K-c	36 D-P	30.5 E-K
Mean	26.8 C	27.4 B	36.3 A	

Note: significant differences among 46 spelt wheat genotypes were determined using HSD level of 0.05. Lower case letters denote lower mean values, and upper-case letters denote higher mean values ($n = 3$)

by Yilmaz et al. (2024) and Wang et al. (2024), who noted significant variation for this characteristic and proposed that genetic variety is crucial for wheat improvement. Our study found significant differences in TGW values among several spelt wheat genotypes. Similar findings were reported for wheat genotypes by previous researcher (Shivay et al., 2016; Rasool, 2021), who observed that wheat samples with healthier wheat kernels provide superior test weight. As a result of our study, we found that TGW is primarily dependent not only on genotype, but also on weather conditions during growth (Lacko-Bartošová et al., 2010; Andruszczak, 2017).

Wheat cultivars differ in their biomass accumulation, likely due to genetic variation influencing photo assimilates partitioning within plant structure, leading to distinct growth patterns and allocation to reproductive organs (Haque et al., 2016; Shivay et al., 2016). Differences in tillering capacity among wheat cultivars are likely influenced by traits such as plant height, spike size, and hormonal regulation (Ferrante et al., 2010; Yang et al., 2023).

Plant height significantly varies under diverse set of germplasm. Stem length plays a key role in resisting lodging; consequently, genotypes 69Z6.205 and 69Z6.204 showed the best performance in this trait across three years. Spelt wheat plant height is genetically controlled and has not been reported in scientific literature. Researchers have found that hybrid varieties produced by crossing different wheat types generally shows plant height that fall between those of the parent forms (Tverdohlib, 2010; Gupta et al., 2019). Some studies discovered that as spelt plants' height decreases, the morphology and anatomical structure of the plant change, affecting other agronomic aspects significantly (Lyfenko, 2014; Berry et al., 2015).

According to Wang et al. (2024), differences in grain yield (GY) among cultivars across various environments may result from either the activation of different sets of genes in each environment or the differing responses of the same genes to changing environmental conditions. Furthermore, the genetic configuration of cultivars may affect photo assimilation and grain filling, thus affecting yield and yield traits. Wheat grain yield and production are determined by multiple traits. According to Nadim et al. (2011), wheat yield is primarily determined by three factors: TGW, number of tillers, and grain number per spike. Parallel results were observed by Ali et al. (2008) who showed that spikelets per spike and spikes per plant influence the grain yield. Multiple field experiments also emphasized the role of spike length and discovered that there was considerable diversity across wheat germplasms (Ali et al., 2008; Longove et al., 2014; Rasool, 2021).

Spelt wheat is an alternative to common wheat, traditionally grown as a sustainable crop in marginal wheat

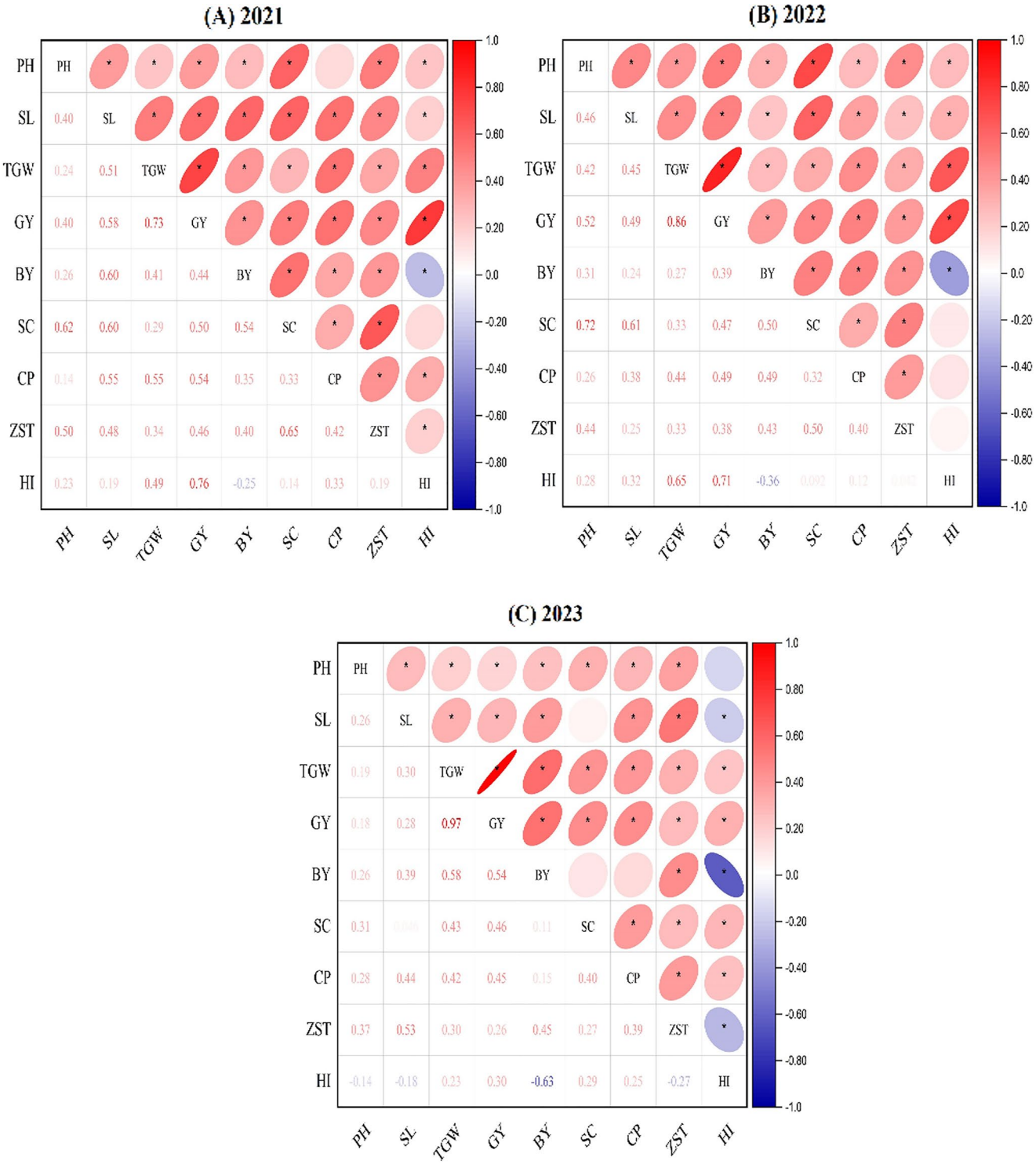


Fig. 2 The Pearson correlation analysis among growth, yield and nutritional quality attributes of spelt wheat lines under three consecutive growing seasons (2021 to 2023). PH; plant height, SL; spike length, TGW; thousand grain weight, GY; grain yield, BY; biological yield, SC; starch content, CP; crude protein, ZST; Zeleny sedimentation test, HI; harvest index

production areas that have low yield potential because of the limited resources (Sugár et al., 2019). Nevertheless, spelt yields significantly less than common wheat in the intensive farming practices. The spelt yield in Israel is 3.0 to 4.0 t ha^{-1} (Curzon et al., 2021), and the yield in Germany is 3.0 to 5.0 t ha^{-1} (Longin et al., 2012). Our research had high-growing spelt genotypes 69Z6.205 (7.27 t ha^{-1}), 69Z6.204 (7.1 t ha^{-1}), 69Z6.148 (6.98 t ha^{-1}), 69Z6.153 (6.83 t ha^{-1}) and

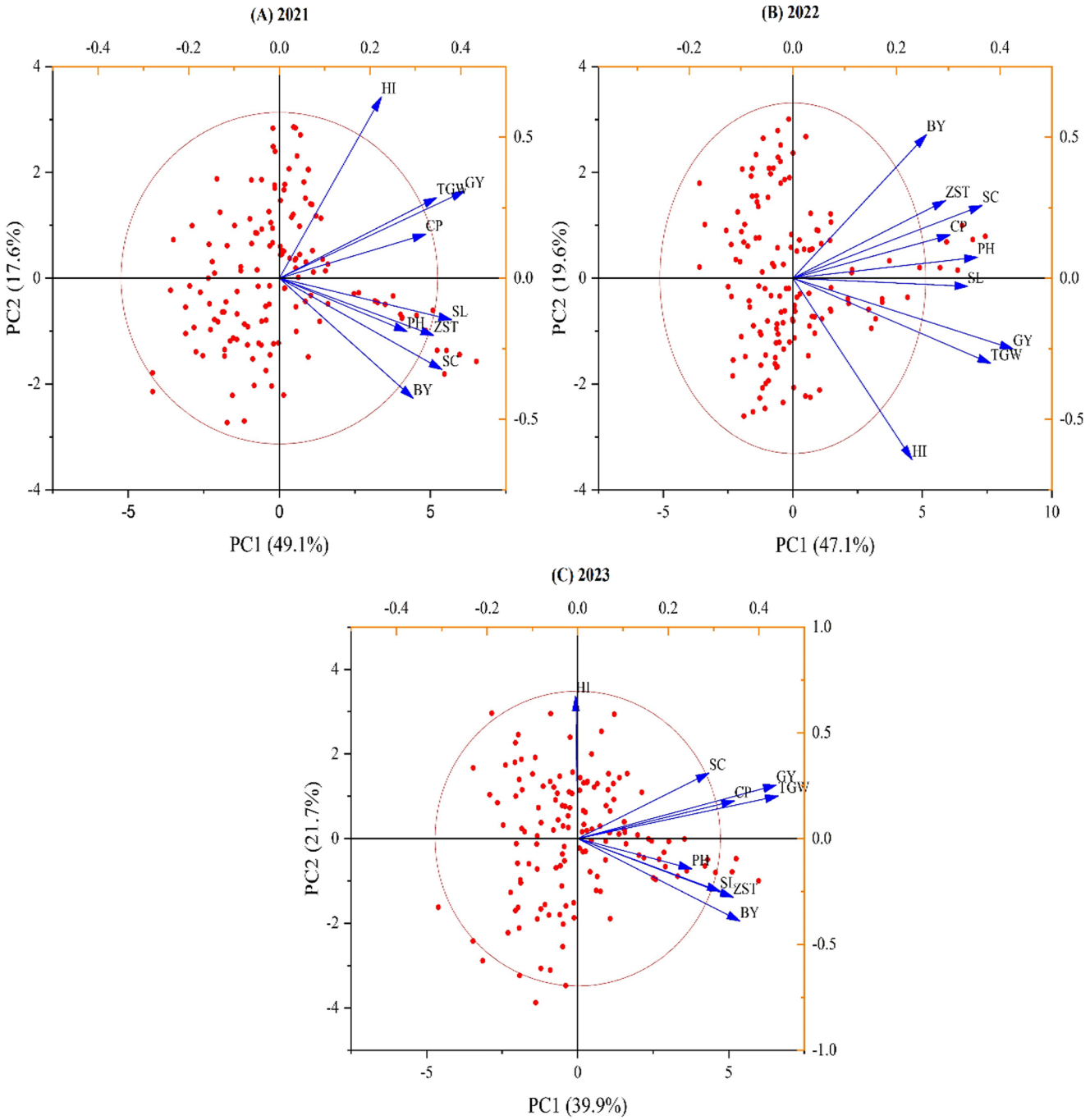


Fig. 3 The principal component analysis among growth, yield and nutritional quality attributes of spelt wheat lines under three consecutive growing seasons (2021 to 2023). PH; plant height, SL; spike length, TGW; thousand grain weight, GY; grain yield, BY; biological yield, SC; starch content, CP; crude protein, ZST; Zeleny sedimentation test, HI; harvest index

69Z6.174 (6.78 t ha^{-1}) that showed high productivity. These are useful samples on which breeding can be done later and spelt wheat improved genetically. The average spelt wheat yield of 5.84 t ha^{-1} was reported in western Slovakia, which has warm agro-climatic environment (Lacko-Bartošová et al., 2010).

Spelt wheat is recognized for its strong nutritional profile due to its rich protein content and quality, along with notable amounts of lipids, crude fiber, vitamins, and minerals (Tóth et al., 2022). The protein content of spelt wheat grains is generally higher than that of bread wheat; however, it varies considerably based on factors such as genotype, growing location, cultivation methods, and climatic conditions

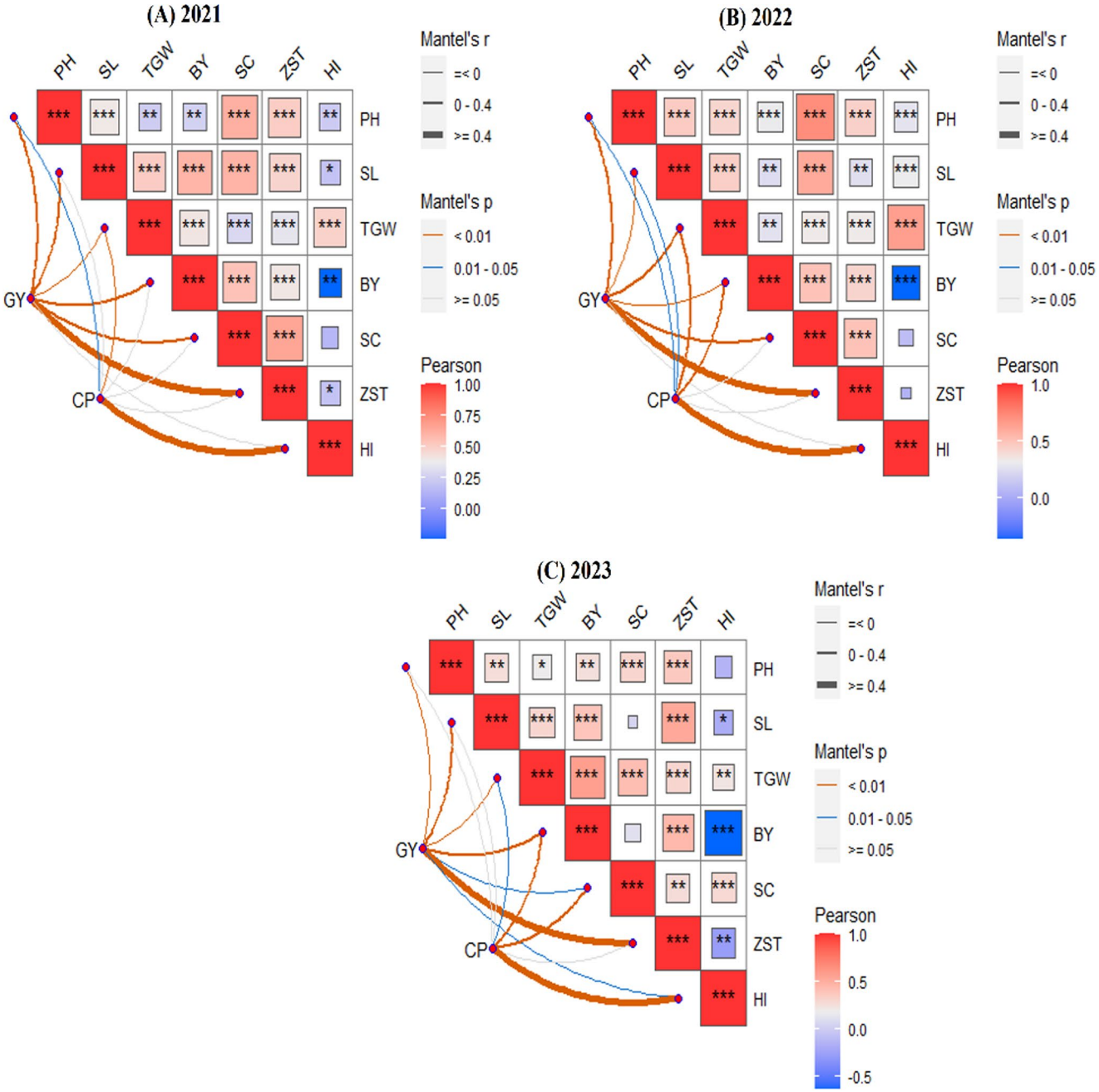


Fig. 4 Mantel correlation analysis among grain yield, crude protein and other growth, yield and nutritional quality attributes of spelt wheat lines under three consecutive growing seasons (2021 to 2023). PH; plant height, SL; spike length, TGW; thousand grain weight, GY; grain yield, BY; biological yield, SC; starch content, CP; crude protein, ZST; Zeleny sedimentation test, HI; harvest index

(Kohajdová & Polonorum, 2008; Wilson et al., 2008; Porto et al., 2025). It is also crucial to determine traits in which exceptional genotypes, exhibiting either breeders can select candidates with very high or very low values.

In present study, high crude protein was noted in genotypes 69Z6.205 and 69Z6.204 which make them most promising genotype cause high protein contents to increase its nutrition, improved bread-making quality, increased digestibility, and nutritional value (Rapp et al., 2017; Fatiukha et al., 2020). The crude protein content in this study varied across years, with 2023 resulting in higher crude protein content (19.8%), followed by 2021 (17.6%) and 2022 (16.9%). The average crude protein and starch contents of the 46 spelt genotypes and these values were much higher compared to wheat, a finding that has been reported by other researchers as well (Bodroza-Solarov et al., 2009; Rodriguez-Algaba et al., 2019; Wang et al., 2024).The present study highlights the genetic variability observed among

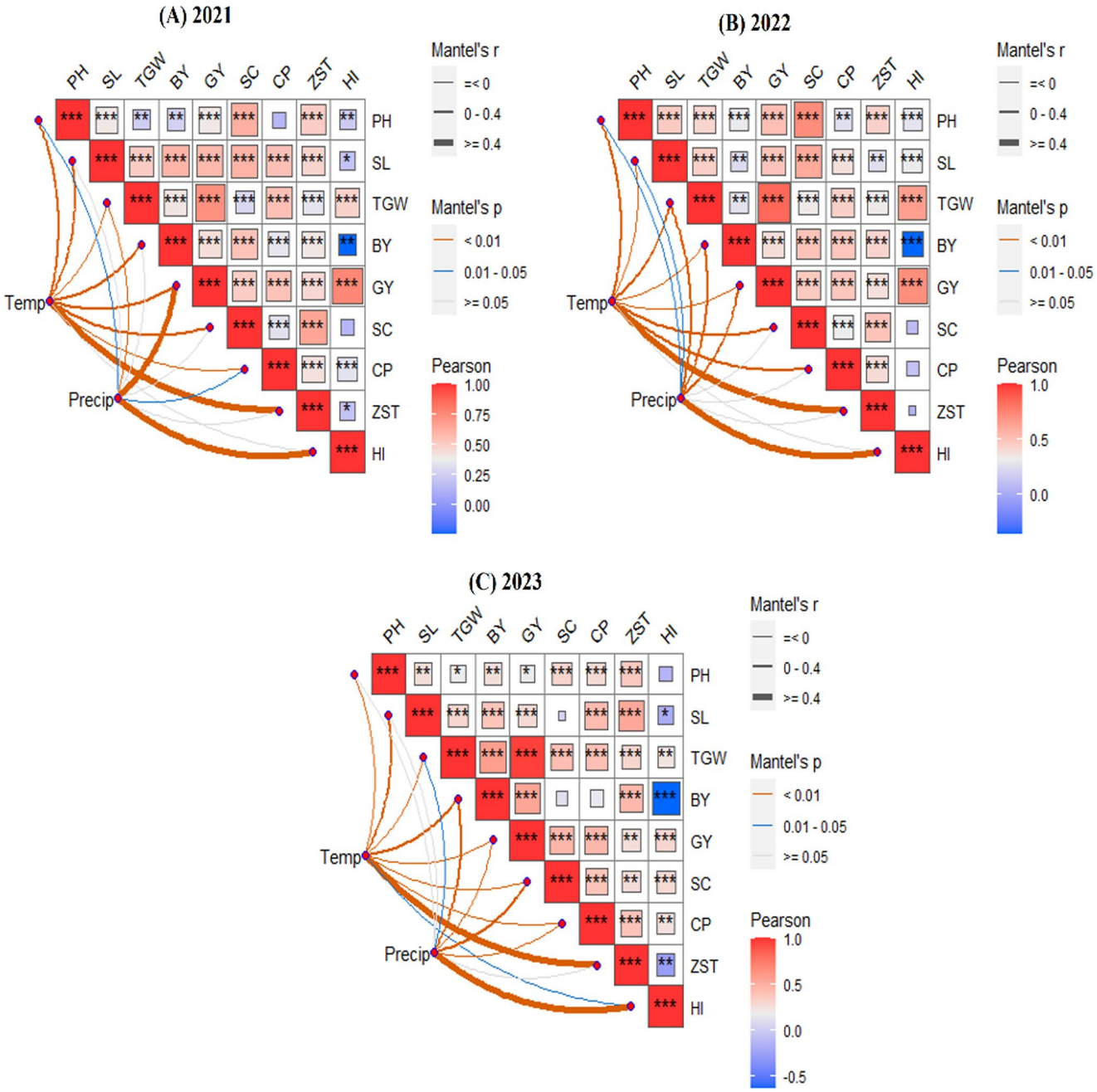


Fig. 5 Mantel correlation matrix climatic factors on spelt wheat productivity and quality attributes under three consecutive growing seasons (2021 to 2023). Temp; temperature, Precip; precipitation, PH; plant height, SL; spike length, TGW; thousand grain weight, GY; grain yield, BY; biological yield, SC; starch content, CP; crude protein, ZST; Zeleny sedimentation test, HI; harvest index

wheat genotypes. Crude protein content in wheat is primarily influenced by multiple factors, including genetic makeup as well as climatic conditions such as air temperature and heat stress during the growth period (Hafeez et al., 2024). As stated by Tahir et al. (2006) which found that the high temperature affects the protein contents of wheat genotypes. Grain protein content variations are often persuaded by both biotic and abiotic challenges, and they are directly linked to genotypes rapid responses to environmental fluctuations (Verma et al., 2015; Hafeez et al., 2024). Similarly, Pandey et al. (2016) indicated that the difference in protein content of different wheat lines. Several other studies reported similar results (Marcos-barbero et al., 2021; Wang et al., 2024).

Our research indicated that average starch content values were higher in 2023 followed by 2021 and then 2022 (Table 4). Although genotype has a substantial impact on crude protein (Takač et al., 2021) and starch content (Dai et al., 2016). Environmental conditions play an important

role in influencing both components (Nhan & Copeland, 2014). According to Labuschagne et al. (2007), environmental factors had the greatest impact on crude protein and starch levels. The ZST value is often regarded as an indicator largely determined by genetic factors (Yilmaz et al., 2024). However, our study also found that environmental influences played a significant role. In this study ZST content varied significantly across different years with 36.4% in 2023, 27.44% in 2022 and 26.8% in 2021 (Table 5). As a baking quality indicator, the ZST value suspended the sedimentation rate of flour particles in lactic acid solution (Häner et al., 2015). Furthermore, slower sedimentation and greater Zeleny values are typically linked to both a larger gluten concentration and improved gluten quality because the expansion of the gluten portion of flour in the lactic acid solution influences the sedimentation rate (Yilmaz et al., 2024).

It is worth noting that the correlation between BY (biological yield) and temperature changed in 2021 to a moderate positive correlation in 2022–2023, which indicated that the relationship became stronger with rising temperature (Fig. 5). The environment has a major impact on both protein and starch content (Nhan & Copeland, 2014), even while genotype has a considerable influence on these components (Dai et al., 2016; Takač et al., 2021). According to Labuschagne et al. (2007), the environment had considerable influence on the concentration of protein and starch. Therefore, the temporal variability in these relationships highlights the need for cultivars with consistent performance across a range of climatic circumstances and there is a need for multi-year trials for comprehending genotype × environment interactions in spelt wheat.

Conclusion

This multi-year evaluation of 46 spelt wheat (*Triticum spelta* L.) genotypes grown under the agro-climatic conditions of central Europe revealed substantial genotypic variability in growth, yield, and quality traits. The findings showed that some of the lines, including 69Z6.205, 69Z6.204 and 69Z6.148 had better agronomic performance with a grain yield exceeding 7.0 t ha^{-1} and positive indices of harvest, and thus, offered prospects of high-yield breeding programs. The genotypes 69Z6.205 and 69Z6.204 contain high starch content, crude protein and Zeleny sedimentation, which highlights the potential of the genotype in enhancing nutritional and end-use quality in spelt-based products. The correlation analysis and principal component results from the analysis indicated a significant positive relationship between productivity and quality, which showed that genetic gains in both the yield and nutritional quality could be made simultaneously. The mantel test also showed that the inter-annual climatic change significantly influenced the genotype's performance and the relationships between attributes. For this reason, environment-specific selection procedures are crucial. Overall, the study advances the understanding of spelt wheat adaptation and genetic diversity under central European conditions and provides a robust development in breeding programs targeting to high-yielding, nutritionally enriched, and climate-resilient spelt cultivars suited to sustainable and low input organic farming systems.

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Data Availability The data analysed for this paper can be requested from the corresponding author.

Declarations

Competing Interests The authors declare no competing interests.

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