Journal of Cereal Science 123 (2025) 104162

Contents lists available at ScienceDirect

Journal of Cereal Science

journal homepage: www.elsevier.com/locate/jcs

Inter- and intraspecific study on compositional quality traits of diverse sets of spelt and common wheat

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ARTICLE INFO

Keywords:
Breeding
Cereals
Diversity
Quality
Spelt

ABSTRACT

Genetically diverse fifty spelt and fifty bread wheat genotypes selected based on the results of a 25K SNP array analysis were compared for physical, compositional and breadmaking quality traits. Inter- and intraspecific diversity, the effect of the species, the genotypes and the year was evaluated. The variation found in the compositional and processing traits of spelt was narrower than that of bread wheat. Significant effect of the genotype was identified for both species for almost all the traits, and spelt genotypes were found to have longer kernels, higher protein content, and lower starch, fructan and β-glucan content than bread wheat in average. Processing of spelt was determined by the more extensible dough, lower starch damage and water absorption of the flour, the low starch viscosity values, high pasting-time and temperature. Although spelt comes with challenges in bread-making quality due to weaker gluten properties, its potential in functional food applications, specialized diets and organic cultivation is promising.

1. Introduction

Spelt (*Triticum aestivum* ssp. *spelta* L.), a hexaploid cereal in the Poaceae family, is genetically similar to bread wheat (*T. aestivum* L.) but often still treated as a separate species. It includes two main types: European spelt, which originated back to the Early Bronze Age in Europe, and Asian spelt, independently developed in regions like Iran (Gradmann, 1901).

Early spelt originated from a hybridization between *Triticum turgidum* subsp. *dicoccum* (Schübler, 1818 (Schrank)) Thell. (BBAuAu) and *Aegilops tauschii* (DD) Coss. The Au genome was derived from *Triticum urartu* Tumanian ex Gandilyan, while the B genome likely came from an extinct Aegilops species in the Sitopsis section, with *Ae. speltoides* (S genome) being its closest living relative (Alvarez, 2021; Gill et al., 2007; Sousa et al., 2021). Early cultivated Triticum species were hulled, and their domestication involved key genetic mutations: Brittle Rachis (Br) Gene (mutation to the non-brittle form (brbr) prevented ear fragmentation, aiding in harvestability), Glume Tenacity Gene (Tg) (determining how strongly the chaff sticks to the seed, mutation to a recessive form (tgtg) facilitated threshing), Spikelet Density (q Gene) (determining distant or tight position of the spikelets, mutation to a dominant form (QQ) increase spike density and thus free-threshing ability). Modern bread wheat carries the genetic combination brbrtgtgQQ, while spelt has a slightly different combination of these genes, brbrTgTgqq (Gill et al., 2007; Sormacheva et al., 2015; Zohary et al., 2012). Historically neglected spelt has regained popularity due to its suitability for organic farming, superior weed suppression, and presumed nutritional benefits. It has specific uses in food production, such as in baked goods like crackers, biscuits, and pretzels (Tóth et al., 2022).

Several studies have investigated the beneficial properties of spelt compared to the commonly used bread wheat. These studies primarily seek nutritional, functional or production benefits of spelt. Their results reveal several potential positive properties of spelt, however, these differences compared to bread wheat are small, were based on non-representative samples and/or their effects are not clinically proven. Thus, a high degree of genetic diversity has been found among Triticum species (spelt, bread wheat, einkorn: *T. monococcum* L. subsp. *monococcum*, 1753; Hammer et al., 2011) in protein, ash and starch content,

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https://doi.org/10.1016/j.jcs.2025.104162
Received 24 January 2025; Received in revised form 4 March 2025; Accepted 19 March 2025
Available online 20 March 2025

as well as in the degree of starch damage (Grela, 1996). Several studies have established a higher protein content in spelt compared to bread wheat (Chrenková et al., 2000; Escarnot et al., 2012; Bonafaccia et al., 2000), in addition to which an increased amount of non-essential amino acids, but a reduced lysine content, is found (Chrenková et al., 2000; Grela, 1996). However, as the reduced essential amino acid content is considered a primary limiting factor, this indicates a nutritionally unfavorable protein amino acid composition of spelt. In addition, lower levels of tannins and trypsin inhibitors were measured in spelt in one study, which improves protein digestibility for example in animal feeding (Grela, 1996). In addition, spelt contains more lipids (Escarnot et al., 2012), including more monounsaturated fatty acids (Grela, 1996), oleic and linoleic acids (Ruibal-Mendieta et al., 2004) in whole spelt flour. Thus, the fatty acid profile of spelt was considered more favourable than that of bread wheat. At the same time, spelt has found to have a lower carbohydrate (68 %) and fiber (12 %) content than bread wheat (75 % and 13.4 %, respectively) (Boukid et al., 2018; Escarnot et al., 2015; Rodríguez-Quijano et al., 2019). Less insoluble fiber (Escarnot et al., 2012), but more soluble fiber (Bonafaccia et al., 2000) was found in spelt. Among the fiber components, arabinoxylan content showed significant variability within species (Escarnot et al., 2012), while the arabinose/xylose ratio in the arabinoxylan molecule was found to be higher in spelt than in bread wheat (Schall et al., 2024). This has implications for the solubility of fibers and their effect on functional properties. Spelt starch was found to contain 2–21 % more amylose and thus resistant starch, than hard red winter bread wheat, so the gelatinization temperature was also measured to be higher in spelt (87–93 °C) than in bread wheat (84.6 °C) (Wilson et al., 2008). The starch content and composition of wholemeal bread was also examined (Bonafaccia et al., 2000) and spelt bread contained less starch, but had a higher proportion of resistant starch. Its consumption also contributes to a higher fibre intake. Since spelt bread contained non rapidly digested starch (RDS), its starch digestion index (SDI) was higher. Spelt also found to have different lutein, phytochemicals, antioxidant content and composition than modern bread wheat varieties (Arzani, 2011; Righetti et al., 2016). Thus, higher vitamin E content and lower alkylresorcinol content were measured in spelt (Grela, 1996). However, the amount of phytosterols was comparable in spelt and bread wheat (Ruibal-Mendieta et al., 2004). In addition, higher amounts of microelements have been measured in spelt (Grela, 1996). However, the amount of microelements taken up and incorporated by the plant depends largely on the composition of the soil and the amount of available, absorbable microelements. The health effects of the very small amount (ppm) of changes in their amount should clinically be approved.

Spelt wheat has demonstrated several unique technological properties like softer grains and greater gluten extensibility. It exhibits weaker dough stability, lower viscous properties, and generally lower bread-making quality. However, variations in spelt genotypes suggest potential for breeding, particularly for organic and low-input cultivation systems (Jaksics et al., 2024; Rakszegi et al., 2022, 2023; Schall et al., 2024).

Articles published so far on the topic of spelt quality includes contradictory information, generally do not take into account the genetic diversity of spelt genotypes and mostly draw conclusions from a narrow range of genotypes. Therefore, in our study, we set the goal of selecting 50-50 genotypes from the two species (bread wheat and spelt) grouping them beforehand based on the results of a 25K SNP array analysis of 255 genotypes. The selection for our study was carried out with a view to maintain as much genetic diversity as possible within the two species, while ensuring that each genotype belonged to a particular species. The physical, compositional and processing quality properties of the 50 selected spelt and 50 selected bread wheat genotypes were compared.

2. Materials and methods

2.1. Plant materials

169 spelt wheat, 73 bread wheat and 13 wild hexaploid genotypes (altogether 255) were analysed with 25K SNP array (Supplementary Table 1). These genotypes were originating from 28 different countries and having diverse morphological traits regarding spike -type (awn/awnless), -colour (white/red/grey/black) or -form (*T. aestivum* - QQ allele or T. spelta - qq allele type). 50 genetically diverse spelt and 50 bread wheat genotypes were selected and analysed from these for two years including 7 wild hexaploids that were genetically similar to bread wheat. The hexaploid wheat wild relatives were included as checks for hexaploid wheat genetic variation and indicator of genetic distances among heaxploid wheat species. These are free-treshing subspecies of bread wheat: *T. compactum* (Host) Mackey (10), *T. macha* Dekapr. & Menabde (2) and *T. sphaerococcum* (Percival) Mackey (1).

2.2. Field conditions

The field experiment was conducted in two replicated small plots (1.2m (6 rows) × 4m) at the Agricultural Institute of the Centre for Agricultural Research in Martonvásár, Hungary (latitude: 47° 3 ′N; longitude: 18° 8′ E; altitude: 115 m), during 2021 and 2022 and all sown during autumn. The soil was clayey chernozem (pH 7.25, 2.8 % humus). The annual average N intake as NPK combined fertilizer was 60 kg/ha active ingredient added during autumn. Further 60 kg/ha N was added to bread wheat during spring and 30 kg/ha to spelt. Herbicides and insecticides were applied, but no fungicides. The plots were treated with herbicide (4 l/ha U-46 D-fluid SL, 500 g/l 2-methyl-4-chlorophenoxy-acetic acid; 40 g/ha Granstar 50 SX, 50 % tribenuron methyl) and insecticide (0.2 l/ha Karate Zeon 5CS, contains 50 g/l λ-cyhalothrin) twice a year. Weather conditions (Supplementary Table 2.) were dry, with low precipitation and high temperatures (above 30 °C for 18 and 14 days respectively in the wheat growing season of 2021 and 2022). Post-harvest grain and flour quality traits were assessed after threshing and cleaning 2 kg of seeds per sample (using Wintersteiger LD350, Wintersteiger AB, Arnstadt, Germany and Haldrup DC-20, Haldrup GmbH, Ilshofen, Germany).

2.3. Analysis of the physical traits and milling

The test weight, the thousand grain weight (TGW) and kernel sizes (width and length) of the grains were measured using the FOSS Tecator 1241 and Marvin System instruments (MARViTECH GmbH, Wittenburg, Germany), respectively (MSZ 6367/4-86, 1986). Samples were conditioned to 15.5 % moisture and milled with a Chopin CD1 Laboratory Mill (CHOPIN Technologies, Ville-neuve-la-Garenne, France) for refined flour, while wholemeal samples were prepared using the Perten Laboratory Mill 3100 (PerkinElmer, Shelton, Connecticut, U.S.).

2.4. Analysis of the compositional traits

The crude protein content of wholemeal was measured using an Elementar Rapid N III Analyzer (Elementar Analysensysteme GmbH, Langenselbold, Germany) according to International Association for Cereal Science and Technology ICC 167 (1995) method. Wet gluten content was determined with a Perten Glutomatic 2200 (PerkinElmer, Shelton, Connecticut, U.S.) (International Association for Cereal Science and Technology ICC 137/1, 1995), and gluten spread was used to assess proteolytic activity. Starch content was estimated by NIR using FOSS Tecator 1241 (FOSS, Hilleroed, Denmark) (International Association for Cereal Science and Technology ICC 202, 1995). β-glucan was analysed enzymatically with spectrophotometry (Evolution 60S, Thermo Fisher Scientific, Waltman, USA) (American Association of Cereal Chemists, 1991b, AACC Methods 32-23.01). Pentosans, including arabinoxylan,

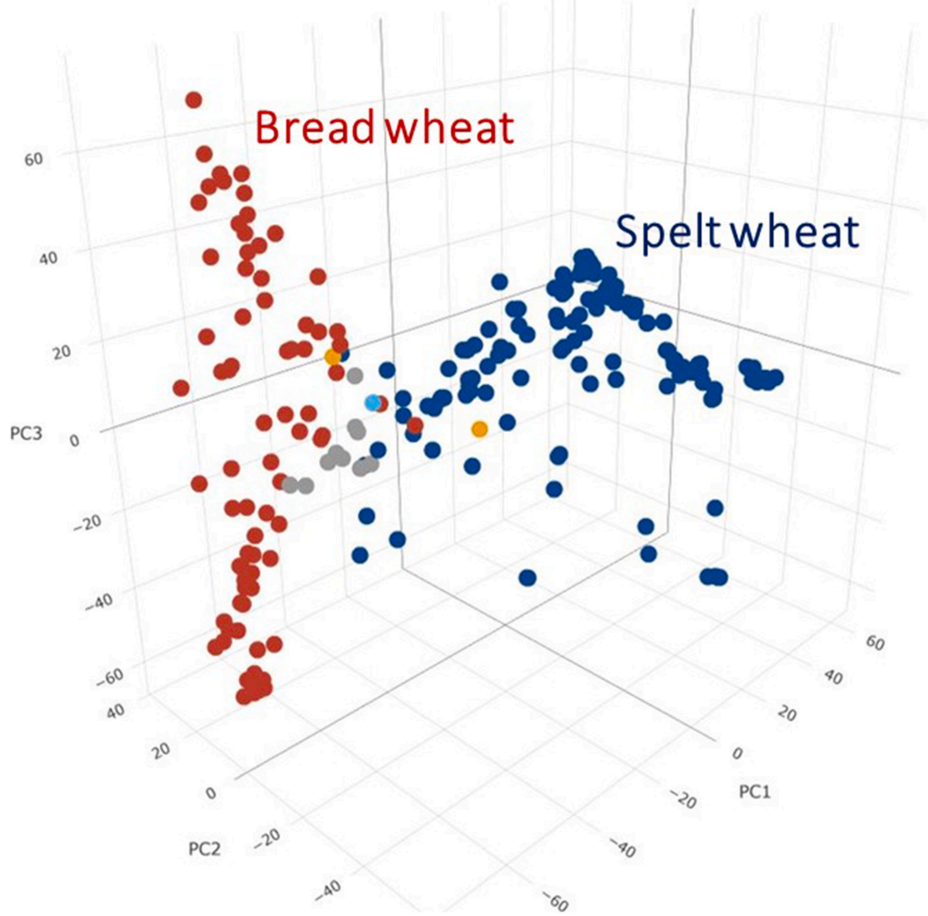


Fig. 1. Genetic structuring of wheat and spelt based on 25K SNP array analysis using principal component analysis method. Where wheat (81) is red, spelt (188) is blue and wild hexaploid genotypes are: *T. compactum* (10) - grey, *T. macha* (2) - yellow, *T. sphaerococcum* (1) - light blue, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

were measured colorimetrically (Douglas, 1981), while fructan content was determined using the Megazyme fructan HK assay kit (American Association of Cereal Chemists, 1995aAACC Methods 32.32.01). Measurements were done in two technical replicates.

2.5. Analysis of dough properties

The dough properties, including water absorption, dough development time, dough stability, dough softening, and quality number, were analysed using a Brabender Farinograph instrument (Brabender, Duisburg, North Rhine-Westphalia, Germany) (International Association for Cereal Science and Technology ICC 115/1, 1995). Gluten index (GI) was determined following the International Association for Cereal Science and Technology ICC 155 (1995) method, while Zeleny sedimentation was measured using the International Association for Cereal Science and Technology ICC 116/1 (1997) method with a SediCom System. Analyses were performed in one or two technical replicates depending on the method.

2.6. Starch properties

Pasting viscosities (peak-, through-, final- breakdown- and setback-viscosity, pasting time and temperature) were measured using a Rapid Visco Analyser (RVA-3D, Newport Scientific Pty. Ltd., Warriewood, NSW, Australia) with a 20-min pasting profile, including controlled heating and cooling phases. Silver nitrate (12 mM) was used to inhibit enzymatic activity (American Association of Cereal Chemists, 1991, AACC Methods 76-21; Batey et al., 1997). Starch damage was assessed using the Chopin SDmatic instrument (Chopin Technologies, Ville-neuve-la-Garenne, France) (International Association for Cereal Science and Technology ICC 172, 2007, standard method), reported at 14 % flour moisture and 12 % protein content, expressed in Chopin Units (UCD). These analyses were performed in one replicate.

2.7. Genotypic characterization

Genomic DNA extractions—according to the manufacturer's instructions—were conducted from fresh leaf samples (100 mg) using the DNeasy® Plant Mini Kit (Qiagen GmbH, Hilden, Germany). 25K Infinium analysis was performed by TraitGenetics (SGS INSTITUT FRESENIUS GmbH, Gatersleben, Germany), and the selected 25K SNPs represents a subset of markers from the 90K SNP array and the 35K Axiom Wheat Genotyping Breeders Array (Wang et al., 2014; Allen et al., 2017).

2.8. Analysis of population diversity

After filtering the various markers for missing values (<10 %) and minor allele frequency (>0.05), 20,075 SNP markers with known physical positions were retained for further marker analyses. The high-quality SNP calls for 169 spelt, 73 bread wheat and 13 wild hexaploid genotypes were combined to construct a matrix, and a neighbour-joining-based (Saitou and Nei, 1987) dendrogram was produced using the Genome Association and Prediction Integrated Tool (GAPIT 3.0) package in R (Wang and Zhang, 2021). Principal component analyses were conducted using GAPIT with default parameters. Principal

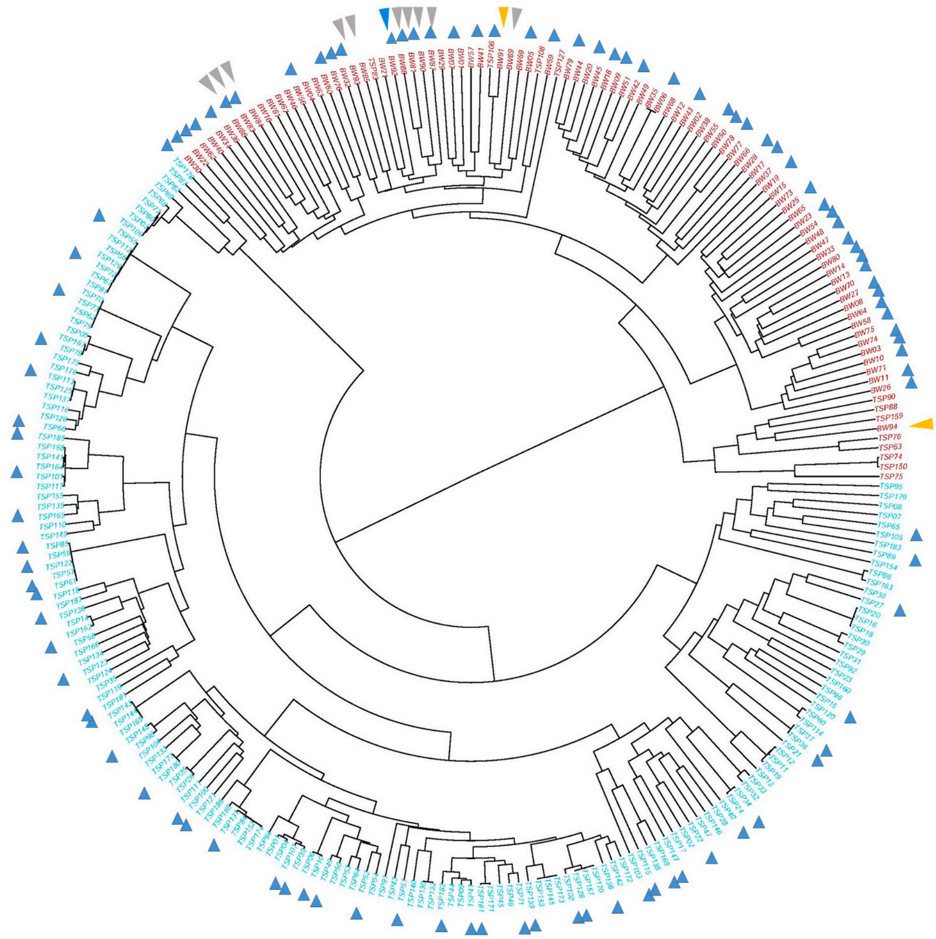


Fig. 2. The circular neighbour joining (NJ) tree of 268 Triticum genotypes. Spelt wheats were labeled as TSP (blue) and bread wheats as BW (red). The selected 50 spelt and 50 wheat genotypes are indicated by blue triangles and used later for detailed compositional analysis. Wild hexaploid genotypes *T. compactum* (10) - grey, *T. macha* (2) – yellow and *T. sphaerococcum* (1) - light blue are indicated by triangles. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

components applied to the genotypes provide information about population structure. The 3D PCA plot was created in Plotly (Sievert, 2020).

2.9. Statistical analysis

Construction of Principal Component Analysis (PCA) were carried out in Statistica 6.0 (TIBCO Soft-ware Inc., Palo Alto, California, USA). One and two-way ANOVA and Hierarchical Cluster Analysis (with Ward's Method and Euclidean distance) were performed using SPSS Statistics 27.0 software (SPSS Inc., Chicago, IL, USA). Datas were standardized by Statistica 6.0 before multivariate analysis. Level of significance were determined/rechecked by non-parametric Mann-Whitney probe in Statistica 6.0 when parameters distribution was not normal even after logaritmic transformation. Correlation analysis was calculated using the Microsoft Excel software (Microsoft Corporation, Redmond, WA, USA).

3. Results

3.1. Interspecific diversity

The SNP analysis of 282 spelt and bread wheat genotypes (188 and 94, respectively) was carried out on leaf DNA extract of plants grown in 2021. The sets of bread wheat genotypes (including 13 wild hexaploid genotypes of *T. compactum, T. macha* and *T. sphaerococcum*) and spelt were analysed as checks in order to better visualize the genetic distances among the Triticum subspecies.

After filtering the SNP markers for missing values (<10 %) and minor allele frequency (>0.05) 14 genotypes were excluded from the analysis. Based on the SNP data of 268 genotypes a principal component analysis was carried out, which showed considerable differences between the different spelt and bread wheat genotypes (Fig. 1.), indicating that wheat and spelt form two distinct gene pools. The wild hexaploid subspecies were located between spelt and bread wheat, but they were rather similar to bread wheat.

The circular neighbour joining (NJ) tree of the 268 Triticum genotypes (Fig. 2.) also demonstrated that spelt and bread wheat form two different groups, but it could also show the differences on the genotype-level. This analysis could identify some poorly clustered genotypes (12 spelt), which were excluded from further analysis as they were considered a species classification error. Furthermore one waxy genotype was also excluded as it shifted the statistical evaluation. Thus, 255 genotypes was analysed in 2021.

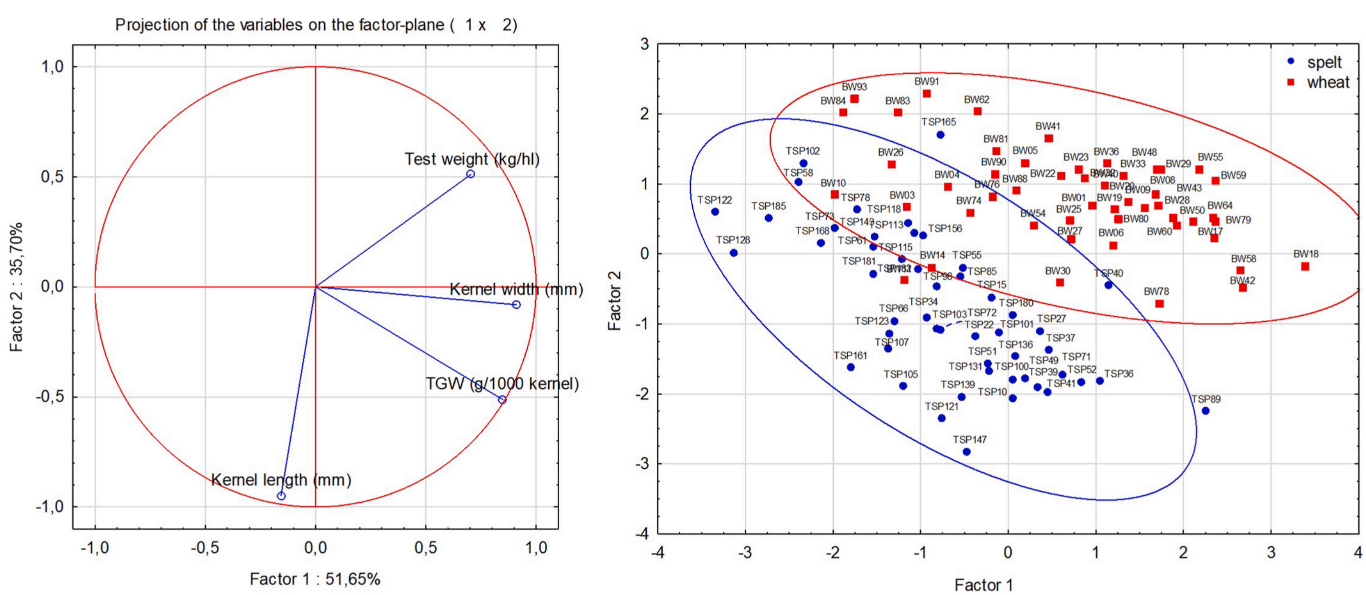
Based on NJ analysis, 50 spelt and 50 bread wheat genotypes (indicated by blue triangles on Fig. 2.) with diverse genetic traits were selected for a detailed compositional analysis in two harvest years (2021 and 2022) (Supplementary Table 1.).

Analysis of the physical, compositional and processing traits of the 255 genotypes was carried out in 2021, and the anova analysis showed that the two species (including the few wild hexaploids in the bread wheat group) significantly differred for almost all of the traits, except the total pentosan content and the pasting time (Table 1).

Table 1
Differences between the means of spelt (n = 169) and bread wheat (n = 86) physical, compositional and processing quality traits based on probability values of the analysis of variance.

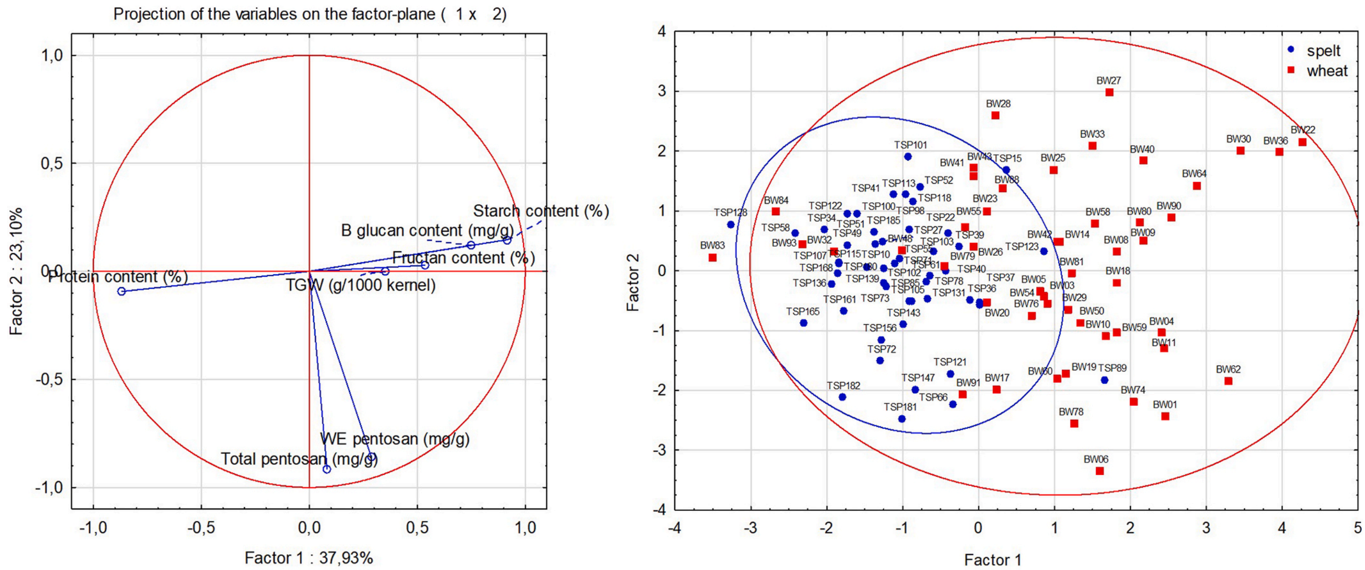
Descriptives	Spelt Wheat n = 169	Spelt Wheat n = 169	Bread Wheat n = 86	Bread Wheat n = 86	All genotypes n = 255	All genotypes n = 255	Sig (Specie)
	Mean	SD	Mean	SD	Mean	SD	
Test weight (kg/hl)	72.90	2.54	76.42	3.45	74.08	3.32	***
TGW (g/1000 kernel)	39.19	4.91	42.00	5.59	40.13	5.30	***
Kernel width (mm)	3.20	0.16	3.43	0.15	3.28	0.19	***
Protein content (%)	15.69	1.61	12.98	1.75	14.78	2.09	***
Starch content F (%)	54.71	2.01	58.19	2.12	55.87	2.62	***
Total pentosan (mg/g)	13.59	1.80	13.33	1.94	13.50	1.85	n.s.
WE pentosan (mg/g)	6.85	1.12	7.54	1.50	7.08	1.30	***
β glucan content (mg/g)	5.39	0.62	6.58	1.01	5.79	0.95	***
Fructan content (%)	0.93	0.20	0.98	0.25	0.95	0.22	*
Gluten content (%)	41.49	7.25	27.85	6.74	36.93	9.57	***
Gluten spread (mm)	7.31	2.96	3.68	3.41	6.10	3.55	***
Gluten Index	46.20	22.41	81.57	26.21	58.04	29.01	***
Zeleny sedimentation (ml)	29.37	6.42	37.60	11.02	32.13	9.10	***
Flour yield (%)	65.21	3.16	53.90	5.10	61.43	6.62	***
Peak viscosity (cP)	3380.70	175.16	3569.51	314.79	3443.89	247.47	***
Throug viscosity (cP)	1672.66	94.55	1926.73	130.48	1757.68	161.30	***
Viscosity breakdown (cP)	1708.05	168.02	1642.78	340.26	1686.20	241.12	*
Final viscosity (cP)	3406.91	151.17	3731.87	290.04	3515.66	258.28	***
Setback viscosity (cP)	1734.25	89.37	1805.14	189.76	1757.98	135.58	***
Pasting time (min)	9.32	0.13	9.28	0.19	9.30	0.15	n.s.
Pasting temperature (°C)	64.06	0.73	62.71	1.19	63.61	1.11	***
Starch damage (UCDc)	12.38	2.03	15.04	2.94	13.27	2.68	***
Water absorption (nir) (%)	57.37	7.04	51.48	5.71	55.40	7.18	***
Falling number (s)	357.33	72.43	382.89	61.18	365.88	69.80	**

SD—standard deviation.
***—$p < 0.001$, **—$p < 0.01$, *—$p < 0.05$, n.s.- not significant.



Variable	Factor 1	Factor 2
Test weight (kg/hl)	0,703771	0,510692
TGW (g/1000 kernel)	0,847600	-0,511449
Kernel width (mm)	0,909752	-0,081485
Kernel length (mm)	-0,156340	-0,948086

Fig. 3. Principal component analysis based on the physical traits of 50 spelt and 50 wheat genotypes (2021–2022 average). Table shows the two main factors/ principal components that together accounted for 87.35 % of the cumulative variance. Kernel width had the greatest contribution to Factor 1 and kernel length to Factor 2.



Variable	Factor 1	Factor 2
Starch content F (%)	0,917417	0,146641
TGW (g/1000 kernel)	0,352618	-0,001231
Protein content (%)	-0,868710	-0,093325
Total pentosan (mg/g)	0,081926	-0,914991
WE pentosan (mg/g)	0,286217	-0,856828
B-glucan (mg/g)	0,748317	0,120389
Fructan content (%)	0,534666	0,027945

Fig. 4. Principal component analysis based on the compositional traits of 50 spelt and 50 wheat genotypes (2021–2022 average). Table shows the two main factors/principal components that together accounted for 61.03 % of the cumulative variance. Starch- and protein content had the greatest contribution to Factor 1 and pentosan contents to Factor 2.

The effect of the species and the years are shown in frequency distribution diagrams of Supplementary Figs. 1A–E., made by using datas of the selected 50 spelt and 50 bread wheat genotypes from 2021 to 2022. Although variance analysis showed the significant effect of the species to almost all the parameters, except the thousand grain weight, the total pentosan content, the falling number and the viscosity breakdown values, the frequency diagrams show clear, most visible difference in kernel length (A), starch-, protein- and β-glucan content (B) of bread wheat and spelt with longer kernels and higher protein, but lower starch and β-glucan content of spelt. The gluten index and Zeleny sedimentation values of spelt are also representing lower values (C). The distribution of the quality number is different in spelt and wheat as bread wheat genotypes mostly have high breadmaking quality and thus shifted to higher values (D).

3.2. *Intraspecific diversity*

The high genetic variability found within species can be partly attributed to variability in the physical, compositional and baking quality of the grain.

Hierarchical Cluster Analysis Heatmaps were prepared to visualize differences between and within species based on 255 genotypes and one year (2021) datas (Supplementary Fig. 2.), while PCA analysis was used on the two-years average datasets of the selected 50 spelt and 50 bread wheat genotypes (Figs. 3–6.).

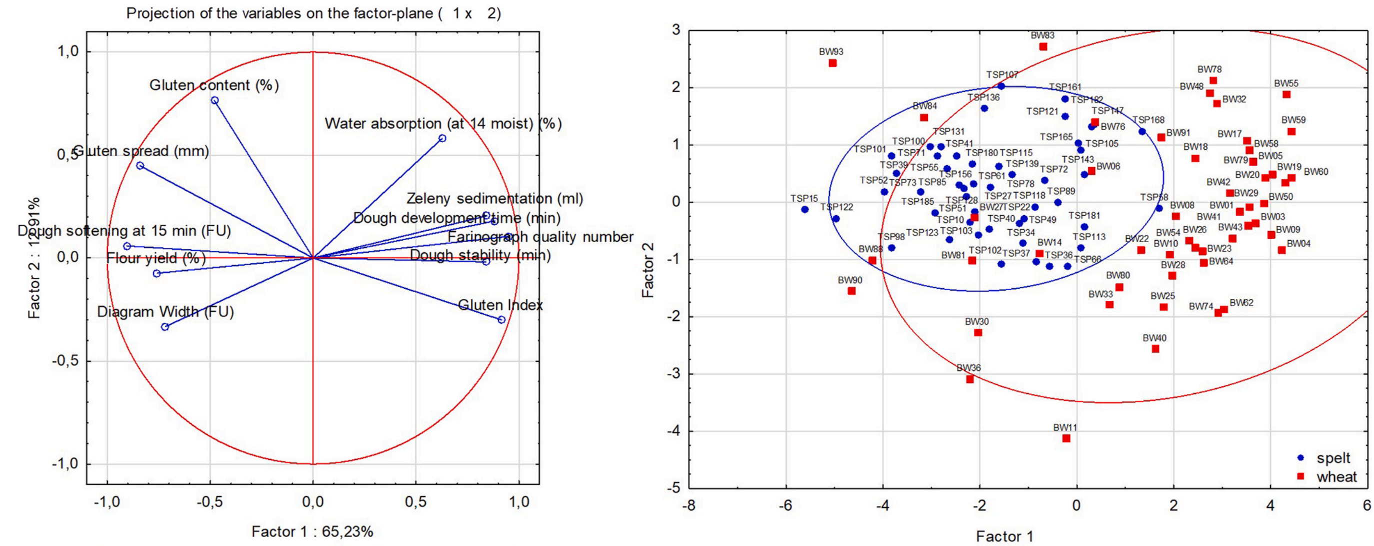
Both evaluations showed that although spelt and bread wheat traits were different in average, spelt represented narrower variation in multivariate analysis than bread wheat. An overlapping of the two groups was found, because some of the bread wheat genotypes located in the area of the spelt group (Figs. 3–6.).

The analysis of the physical properties of spelt (Fig. 3.) showed that spelt generally had longer and narrower grains with lower test weight. Four of the bread wheat genotypes (BW 3, 10, 11, 14, namely 'Solstice', 'Moulin', 'Valoris', 'Biscay') were similar to spelt based on these traits.

Based on the compostitonal traits, spelt had higher protein content in average, but had lower starch, fructan and β-glucan contents (Fig. 4.). Some of the bread wheat genotypes were similar to spelt (BW 17, 23, 26, 41, 48, 83, 84, 91, 93, namely 'Amadeus', 'Monopol', 'Hereward', 'Buck-Catriel', 'Arina', MvGB323, MvGB324, MvGB1071, MvGB657) in both analyses based on the composition (PCA and Hierarchical cluster, Fig. 4 and Supplementary F igure 2A).

The breadmaking quality traits of spelt was characterized by higher gluten content, but with higher gluten spread and dough softening and lower gluten index and Zeleny sedimentation than bread wheat (Fig. 5., Supplementary Fi gure 2B). At the same time its flour yield was higher with lower water absorption, referring to the soft kernel hardness of spelt. Some bread wheat genotypes were similar to spelt in their breadmaking characteristics in both of the analyses (BW 6, 14, 27, 76, 81, 84, 88, 90, 93, namely 'Mv-Marsall', 'Biscay', 'Alba', 'Atlas-66′, 'Big-Club43', MvGB324, MvGB322, 'Gluclub', MvGB657)

Spelt grain contained less starch than bread wheat, having higher pasting time and -temperature and lower viscosity traits. The damage of the starch during milling was lower in spelt referring again to the softer kernel hardness of spelt. The falling number was also lower in spelt than in bread wheat (Fig. 6., Supplementary F igure 2B). Some of the bread wheat genotypes had similar starch properties to that of spelt in both analyses (BW 23, 25, 32, 40, 43, 83, 84, 88, 90, 93, namely 'Monopol', 'Kanzler', 'Key', 'Isengrain', 'Alabasskaja', MvGB323, MvGB324, MvGB322, 'Gluclub', MvGB657).



Variable	Factor 1	Factor 2
Gluten content (%)	-0,480578	0,765826
Gluten spread (mm)	-0,841914	0,448372
Gluten index	0,915203	-0,300207
Zeleny sedimentation (ml)	0,843798	0,205194
Flour yield (%)	-0,757188	-0,073354
Dough development time (min)	0,882238	0,180138
Dough stability (min)	0,840669	-0,018473
Water absorption (at 14moist) (%)	0,626400	0,580546
Dough softening at 15 min (FU)	-0,905175	0,058888
Diagram Width (FU)	-0,717103	-0,332190
Farinograph quality number	0,949337	0,104954

Fig. 5. Principal component analysis based on the breadmaking quality traits of 50 spelt and 50 wheat genotypes (2021–2022 average). Table shows the two main factors/principal components that together accounted for 78.14 % of the cumulative variance. Farinograph quality number and gluten index had the greatest contribution to Factor 1 and gluten content to Factor 2.

3.3. *Effect of the genotype and the environment*

The effect of the genotype and the year (GxE) was analysed using the 50 selected spelt and 50 bread wheat genotypes (including 7 wild hexaploids in the bread wheat group). The trial was conducted in the same environment for two years, therefore the year was treated as the environmental factor in ANOVA.

Two-factor variance analysis (2-way ANOVA) of all the 100 genotypes (spelt + bread wheat) showed (Table 2.) that the genotype has more significant effect on the studied traits than the year, as the genotype influenced all the studied traits except the falling number, while the year did not affect the grain size, the total pentosan content, the Zeleny sedimentation, the setback viscosity, the dough stability and the Farinograph quality number. Thus, the genotype itself has stronger effect on bread wheat quality and composition.

Analysing the two species separately by anova (Table 3.), both bread wheat and spelt traits were affected significantly by the genotype, except falling number, which was more dependent on the environment (year) than the genotype in the case of spelt. The year also had effect on most traits, except on the total pentosan content of both spelt and bread wheat. However dough properties of the bread wheat (stability, softening), its kernel size, fructan content and starch damage were less affected by the year than those of spelt.

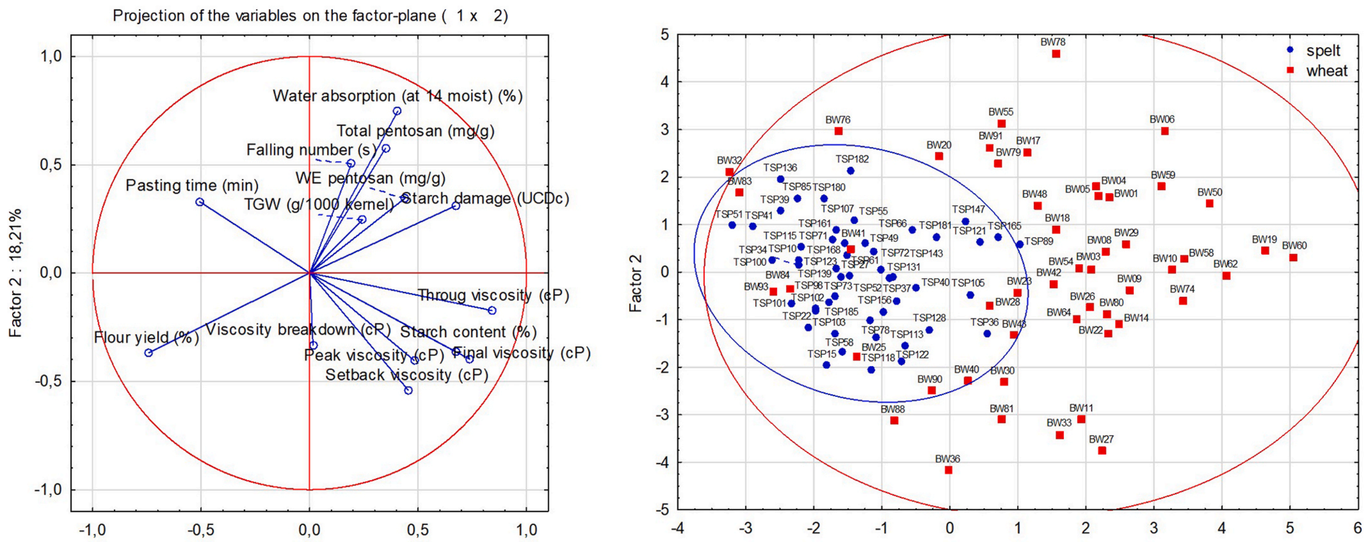
4. Discussion

In the recent study, we aimed to compare a genetically diverse population of spelt and bread wheat. For this purpose an SNP-based selection was carried out from a large genetic pool with diverse origin and morphological traits and genotypes with uncertain origin, genetic background, and/or analytical datas were excluded.

Several studies have assessed spelt's quality before, emphasizing its differences from bread wheat. Since we have already summarized these in our previous articles and in the introduction, we discuss our present results from the perspective of our own previous results.

A study of 90 spelt genotypes revealed significant diversity in physical, compositional, and breadmaking traits. Spelt showed higher protein and gluten contents but weaker dough stability and strength compared to two bread wheat controls (varieties 'Glenlea' and 'Ukrainka'). Thus the sample set is more balanced in our study. Thousand kernel weight varied widely (23.2–49.7 g), as did protein content (12.1–22.2 %) and gluten index (0.7–98.8) (Tóth et al., 2022). At the same time, spelt showed lower test weight, gluten index, farinograph quality number, water absorption, dough development time, dough stability and Zeleny sedimentation volume in an other study including five spelt genotypes (Takac et al., 2022). A study of 88 traditional Spanish spelt landraces, alongside nine bread wheat cultivars and a modern spelt variety, also showed that spelt had generally higher protein content (14.3 % vs. 11.9 %), softer grains, and lower gluten strength than bread wheat, yet exhibited similar baking performance (Huertas-García et al., 2023).

Our study also showed significant differences in spelt (50) and bread wheat (50) in protein content and related traits by two-way ANOVA analysis, frequency diagrams or multivariate analysis. Thus, spelt had generally higher protein and gluten content, but lower dough strength (GI, Zeleny, Farinograph quality number). At the same time narrower



Variable	Factor 1	Factor 2
Starch content F (%)	0,675035	-0,364409
TGW (g/1000 kernel)	0,243531	0,246176
Falling number (s)	0,192666	0,505425
Flour yield (%)	-0,741927	-0,367876
Starch damage (UCDc)	0,671758	0,310388
Peak viscosity (cP)	0,481267	-0,402951
Through viscosity (cP)	0,840166	-0,172730
Viscosity breakdown (cP)	0,015640	-0,332135
Final viscosity (cP)	0,736708	-0,396981
Setback viscosity (cP)	0,454430	-0,540492
Pasting time (min)	-0,506592	0,329199
Water absorption (at 14moist) (%)	0,405887	0,746767
Total pentosan (mg/g)	0,348735	0,574945
WE pentosan (mg/g)	0,440491	0,346654

Fig. 6. Principal component analysis based on the carbohydrate related traits of 50 spelt and 50 wheat genotypes (2021–2022 average). Table shows the two main factors/principal components that together accounted for 46.62 % of the cumulative variance. Starch damage, through and final viscosity had the greatest contribution to Factor 1 and water absorption and total pentosan content to Factor 2.

variation was found in the properties of the individual spelt genotypes, than in the group of bread wheat and some of the bread wheat genotypes overlapped with the spelt group area in the PCA figures. However almost all of the traits were affected by both the genotype and the environment (year), except the dough development time and the gluten content which were only affected by the genotype. The strong effect of the genotype on protein content and composition and thus on dough quality was examined before in a previous study, where the protein content and composition of five spelt and five bread wheat varieties grown under different production systems (conventional, organic) in Hungary and Serbia were compared (Takac et al., 2021). It found that spelt had significantly higher total protein content than bread wheat, and under conventional production than under organic. Greater kernel size (thousand grain weight), lower high to low molecular weight glutenin (HMW/LMW) ratio, lower alfa + beta gliadin content (A + B/Total), and higher gamma gliadin (G/Total) content were typical at the organic site compared to the conventional site, resulting in a generally better processing quality of seeds grown at the conventional sites. Some spelt varieties were identified being more tolerant to limited nitrogen applications and thus suitable for growing under low-input and organic systems. These results highlighted spelt's potential in organic and healthy food production (Takac et al., 2021).

Although spelt has a higher protein content than bread wheat, with a similar protein- and amino acid-composition, specific proteins in certain spelt genotypes can differentiate it from bread wheat. Spelt proteins should be considered to be similar to those of bread wheat regarding gluten sensitivity, as they can cause similar reactions. Despite being higher in sulfur-containing amino acids (like cysteine, methionine) and tryptophan, not like legumes, spelt has limited lysine content and has certain limitations as a protein source (Rakszegi et al., 2023).

As regards to starch viscosity traits, the viscous properties (such as peak viscosity, breakdown, final viscosity, trough viscosity and setback properties) were lower in spelt than in bread wheat, with higher variability, according to previous studies. Additionally, the type of cultivation (organic vs. conventional) impact on viscous properties varied based on harvest year and genotype (Jaksics et al., 2024; Takac et al., 2022). Spelt's lower starch damage and higher pasting temperature result in reduced water absorption. This diversity highlights spelt's potential for both genetic improvement and fulfilling specific processing demands. Specific accessions and varieties, such as those suitable for breadmaking, were identified, while others may meet niche local product requirements (Tóth et al., 2022).

Our results are in agreement with the previous findings except that the variation of starch properties were narrower than that of bread wheat, but the starch content of spelt itself was significantly lower. However, the near-infrared spectroscopy method used in this study can be considered a limiting factor in determining the starch content, as the measured results can be interpreted in relative rather than absolute values. The damage of the starch caused by milling was lower in spelt resulting lower water absorption and referring to the softer kernel hardness of spelt. Spelt had higher pasting time and -temperature and lower viscosity values. The falling number was also lower in spelt than in bread wheat. However the falling number of spelt was rather affected by the year than the genotye, while the viscosity breakdown was genetically detemined and not affected by the year in spelt.

Some health-related bioactive compounds (fibers, antioxidants) were

Table 2
Effect of the genotype and the year on the physical, compositional and processing traits of all spelt and bread wheat genotypes (100) in two years (2021, 2022) based on probability values of the two-factor variance analysis.

Properties	Mean all n = 200	Mean 2021 n = 100	Mean 2022 n = 100	Sig (G)	LSD5 % (G)	Sig (Y)	LSD5 % (Y)
Test weight (kg/hl)	76.10	74.54	77.66	***	0.50	***	7.64
TGW (g/1000 kernel)	40.41	40.37	40.46	***	0.76	n.s	11.74
Kernel width (mm)	3.32	3.32	3.33	***	0.02	n.s	0.33
Protein content (%)	14.56	14.25	14.87	***	0.27	***	4.19
Starch content F (%)	55.81	56.51	55.12	***	0.31	***	4.82
Total pentosan (mg/g)	15.17	15.05	15.29	***	0.45	n.s	6.86
WE pentosan (mg/g)	7.51	8.05	6.97	***	0.31	***	4.78
β glucan content (mg/g)	6.14	6.01	6.26	***	0.19	*	2.88
Fructan content (%)	0.94	0.97	0.91	***	0.04	***	0.55
Gluten content (%)	37.27	34.50	40.03	***	1.43	***	21.90
Gluten spread (mm)	6.77	5.51	8.04	***	0.58	***	8.89
Gluten Index	58.47	65.16	51.77	***	3.66	***	56.18
Zeleny sedimentation (ml)	33.84	33.33	34.36	***	1.45	n.s.	22.23
Flour yield (%)	52.86	59.52	46.20	***	1.10	***	16.93
Peak viscosity (cP)	3505.72	3462.33	3549.11	***	44.81	***	688.09
Throug viscosity (cP)	1762.75	1803.67	1721.84	***	31.67	***	486.35
Viscosity breakdown (cP)	1742.97	1658.67	1827.27	***	52.51	***	806.42
Final viscosity (cP)	3546.75	3588.04	3505.46	***	61.99	**	951.89
Setback viscosity (cP)	1784.00	1784.37	1783.62	***	39.06	n.s.	599.85
Pasting time (min)	9.11	9.30	8.93	***	0.03	***	0.52
Pasting temperature (°C)	62.58	63.46	61.69	***	0.19	***	2.99
Starch damage (UCDc)	14.44	13.67	15.21	***	0.52	***	7.95
Water absorption (at 14 moist) (%)	57.47	56.74	58.21	***	0.85	***	13.04
Falling number (s)	385.41	356.58	414.25	n.s.	18.73	***	287.59
Dough development time (min)	6.86	6.16	7.56	***	1.15	*	17.59
Dough softening at 15 min (FU)	62.50	52.78	72.21	***	8.24	***	126.61
Dough stability (min)	9.32	9.78	8.86	***	1.07	n.s.	16.48
Farinograph quality number	68.47	69.22	67.71	***	3.54	n.s.	54.38

SD−standard deviation, G-genotype, Sig-level of sifnificance: ***—$p < 0.001$, **—$p < 0.01$, *—$p < 0.05$, n.s.- not significant.

also studied in spelt and bread wheat. The carbohydrate composition of spelt compared to bread wheat were studied by Schall et al. (2024) focusing on β-glucan, arabinoxylan, arabinogalactan, and short-chain carbohydrates. While both species showed similar arabinoxylan and arabinogalactan contents, spelt had a higher arabinose/xylose ratio, which may have technological implications. Bread wheat had higher β-glucan levels, and both species contained similar amounts of FODMAPs (Fermentable Oligosaccharides, Disaccharides, Monosaccharides And Polyols), like fructose, raffinose, kestose, and nystose, with some differences in short-chain carbohydrate profiles. This suggests a degree of genetic variability within the species that could impact nutritional and technological uses.

The effect of the conventional and organic systems on some bioactive components was also studied in five spelt and five bread wheat genotypes. It found that spelt had higher alkylresorcinol, but lower fructan content. Organic spelt showed higher starch, fiber, and alkylresorcinol content compared to conventional spelt, but lower protein and β-glucan levels. The variety "Oberkulmer-Rotkorn" stood out with the highest values for most traits. Environmental conditions and farming systems contributed differently to the variations in bread wheat compositions (Takac et al., 2022).

We did not find significant difference in the total arabinoxylan content of spelt and bread wheat, while the β-glucan content of spelt was lower. At the same time, the fructan content was found to be low in spelt, which is beneficial for sensitive patients. The amount of either fiber type was not affected by the year.

Spelt generally had lower test weight, longer kernels and smaller kernel width than bread wheat. The differences in the physical properties of spelt compared to bread wheat might also contribute to the compositional differences found during this study. Based on the correlation analysis (Supplementary Table 3.), the starch content and the β-glucan content are affected the most by the kernel size (test weight, TGW, kernel width and length) when taking into consideration of the datas of both species.

Wild hexaploid genotypes were genetically closer to bread wheat than to spelt in our study, however this was not necessarily related to the compositional, breadmaking or carbohydrate-related properties, as the accessions MvGB324 and MvGB657 were more similar to spelt than to bread wheat based on all these traits. MvGB323 also had similar composition and carbohydrate-related traits than spelt, while MvGB322 and 'Gluclub' had similar breadmaking and carbohydrate-related traits to that of spelt. MvGB1071 was similar to spelt in its compositional traits, while the cultivar 'Big-Club43' in its breadmaking quality traits. Other traits not examined by us may be responsible for the fact that wild hexaploid genotypes resemble bread wheat more than spelt (Fig. 2., Supplementary Fig. 2.).

Among modern bread wheat varieties, 'Solstice', 'Valoris', 'Moulin' and 'Biscay' had similar physical traits than spelt. 'Amadeus', 'Monopol', 'Hereward', 'Buck-Catriel', 'Arina' had similar compositional traits, 'Mv-Marsall', 'Biscay', 'Alba', 'Atlas-66′' had similar breadmaking quality traits, while 'Monopol', 'Kanzler', 'Key', 'Isengrain', 'Alabasskaja' had similar carbohydrate-related traits than the 50 selected genotypes of spelt.

From this variety list, 'Solstice' is recognized for its strong breadmaking performance, making it a preferred choice for both conventional and organic wheat production systems. 'Hereward' wheat variety renowned for its superior bread-making quality. 'Monopol' is esteemed for its superior bread-making quality, making it a preferred choice for producing high-quality bread products. 'Mv Marsall' exhibits strong gluten characteristics, which are essential for dough elasticity and bread volume. Additionally, it has a favourable protein content, contributing to its suitability for bread production. 'Kanzler' is a wheat variety with strong bread-making quality, making it suitable for high-quality bread production.

'Valoris' and 'Atlas-66′' are soft wheat varieties. 'Valoris' is primarily cultivated for biscuit and pastry production due to its lower protein content and gluten strength. Therefore, it is not typically recommended for traditional bread-making processes that require stronger gluten networks to achieve the desired loaf volume and crumb structure. 'Atlas-66′' is a high-protein soft wheat variety which has been utilized in breeding programs to enhance the protein content of other wheat varieties.

Table 3
Effect of the genotype and the year on the physical, compositional and processing traits of spelt (50) and bread wheat genotypes (50) in two years (2021, 2022) based on probability values of the two-factor variance analysis.

Specie	Spelt Mean all n = 100	Spelt Mean 2021 n = 50	Spelt Mean 2022 n = 50	Spelt Sig (G)	Spelt LSD5 % (G)	Spelt Sig (Y)	Spelt LSD5 % (Y)	B.Wheat Mean all n = 100	B.Wheat Mean 2021 n = 50	B.Wheat Mean 2022 n = 50	B.Wheat p (G)	B.Wheat LSD5 % (G)	B.Wheat p (Y)	B.Wheat LSD5 % (Y)
Test weight (kg/hl)	74.41	72.83	75.99	***	0.53	***	5.67	77.79	76.24	79.33	***	0.87	***	9.26
TGW (g/1000 kernel)	39.87	38.86	40.89	***	0.95	***	10.21	40.95	41.89	40.02	***	0.95	***	10.11
Kernel width (mm)	3.22	3.20	3.25	***	0.03	**	0.30	3.42	3.43	3.41	***	0.03	n.s.	0.32
Protein content (%)	15.44	15.65	15.23	***	0.23	***	2.49	13.68	12.85	14.50	***	0.28	***	3.02
Starch content F (%)	54.40	54.71	54.09	***	0.36	**	3.85	57.23	58.31	56.15	***	0.43	***	4.56
Total pentosan (mg/g)	15.38	15.45	15.30	*	0.63	n.s.	6.69	14.96	14.65	15.28	***	0.64	n.s.	6.89
WE pentosan (mg/g)	7.10	7.75	6.44	***	0.42	***	4.48	7.92	8.35	7.49	***	0.47	***	5.02
β glucan content (mg/g)	5.48	5.42	5.54	**	0.22	n.s.	2.38	6.80	6.61	6.98	***	0.31	*	3.29
Fructan content (%)	0.90	0.96	0.84	***	0.05	***	0.54	0.98	0.99	0.98	***	0.05	n.s.	0.51
Gluten content (%)	42.00	41.21	42.79	*	1.91	n.s.	20.48	32.54	27.80	37.27	***	1.50	***	16.02
Gluten spread (mm)	8.83	7.10	10.55	***	0.88	***	9.42	4.72	3.91	5.52	***	0.69	***	7.42
Gluten Index	39.34	48.89	29.80	***	5.53	***	59.11	77.59	81.44	73.75	***	4.45	**	47.65
Zeleny sedimentation (ml)	28.51	29.53	27.48	***	1.56	*	16.72	39.18	37.12	41.24	***	2.17	***	23.23
Flour yield (%)	57.06	53.56	43.77	***	1.42	***	15.14	48.66	53.56	43.77	***	1.42	***	15.14
Peak viscosity (cP)	3417.73	64.11	61.85	**	0.23	***	2.41	3593.71	3524.22	3663.20	***	66.87	***	715.29
Throug viscosity (cP)	1669.97	1923.50	1787.58	**	45.46	***	486.25	1855.54	1923.50	1787.58	**	45.46	***	486.25
Viscosity breakdown (cP)	1747.77	1716.61	1778.92	**	73.59	n.s.	787.16	1738.17	1600.72	1875.62	***	64.85	***	693.62
Final viscosity (cP)	3450.48	3743.72	3542.32	***	78.57	***	840.43	3643.02	3743.72	3542.32	***	78.57	***	840.43
Setback viscosity (cP)	1780.51	1748.52	1812.50	*	52.63	*	562.96	1787.48	1820.22	1754.74	***	53.79	*	575.33
Pasting time (min)	9.17	9.27	8.85	***	0.05	***	0.56	9.06	9.27	8.85	***	0.05	***	0.56
Pasting temperature (°C)	62.98	64.11	61.85	**	0.23	***	2.41	62.17	62.81	61.53	***	0.26	***	2.78
Starch damage (UCDc)	13.60	12.46	14.74	***	0.49	***	5.23	15.28	14.88	15.68	***	0.89	n.s.	9.50
Water absorption (at 14 moist) (%)	56.39	57.31	55.47	*	0.82	***	8.77	58.56	56.16	60.95	***	0.72	***	7.72
Falling number (s)	375.44	329.54	421.34	n.s.	29.95	***	320.37	395.39	383.62	407.16	*	19.27	*	206.13
Dough development time (min)	3.61	3.87	3.36	*	1.28	n.s.	13.66	10.10	8.44	11.76	***	1.80	***	19.23
Dough softening at 15 min (FU)	81.24	63.24	99.24	***	11.88	***	127.10	43.75	42.32	45.18	***	9.83	n.s.	105.13
Dough stability (min)	6.97	8.02	5.93	***	1.49	**	15.93	11.66	11.53	11.79	***	1.53	n.s.	16.40
Farinograph quality number	58.76	62.75	54.78	***	5.08	**	54.36	78.17	75.70	80.64	***	4.42	*	47.27

SD−standard deviation, G-genotype, Y-year, Sig-level of sifnificance: ***—p < 0.001, **—p < 0.01, *—p < 0.05, n.s.- not significant.

'Biscay' has moderate bread-making quality, which suggests it may be more suitable for applications that do not demand outstanding baking performance. 'Moulin' has good bread-making quality, but due to its susceptibility to environmental stressors and its genetic instability made it less favourable for cultivation.

'Buck Catriel' has a specific starch molecular profile, with amylose and amylopectin ratios affecting dough properties and, consequently, bread quality.

No information was found on the processing traits of 'Amadeus', 'Arina', 'Alba', 'Key', 'Isengrain' and 'Alabasskaja' wheat cultivars. However it is visible that wheat varieties with diverse processing quality traits grouped together with spelt genotypes in multivariate analysis indicating the potential of spelt for different processing purposes.

5. Conclusions

The significant, but narrower variation found in spelt protein and starch content and related traits suggest that spelt is still a potential genetic resource to change the characteristics and processing traits of either spelt or bread wheat. The genetic characterisation of the cultivars, and breeding materials makes it possible to select genetically distant genotypes for the purpose of developing new lines with specific traits that could be utilized for different end-uses. We can take advantage of the properties of spelt wheat, such as: long kernels, high protein, low fructan-, starch- or β-glucan- content, extensible dough or low starch viscosity values, high pasting time and temperature for different applications.

In conclusion, while spelt wheat offers several advantages over bread wheat, it also comes with challenges in bread-making quality due to weaker gluten properties. However, several practical experiences have demonstrated its better usability in sourdough bakery production, where the drivers behind this quality-enhancing mechanism are still have to be investigated. Its potential in specialized diets and organic cultivation, along with its genetic diversity, makes it a promising crop for the future, especially when considering its potential health benefits and functional food applications.

CRediT authorship contribution statement

Marianna Rakszegi: Writing – original draft, Visualization, Supervision, Funding acquisition, Data curation, Conceptualization. **Viola Tóth:** Methodology, Investigation, Formal analysis. **Sándor Tömösközi:** Writing – review & editing, Supervision, Conceptualization. **Edina Jaksics:** Investigation, Formal analysis. **András Cseh:** Methodology, Investigation, Formal analysis. **Ildikó Karsai:** Writing – review & editing, Conceptualization. **Péter Mikó:** Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The research leading to these results received funding from the Hungarian National Research, Development, and Innovation Office under Grant Agreement No. K135211 and K135343, and TKP2021-NKTA-06 and from the EU Horizon Europe project COUSIN (Nr. 101135314). PM and AC were supported by Janos Bolyai Research Scholarship of the Hungarian Academy of Sciences (BO/00206/24/4 and BO/00416/23, respectively).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jcs.2025.104162.

Data availability

Data will be made available on request.

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