An evaluation of spelt hybrids for breeding new varieties of spring spelt

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Abstract: This study evaluated F5 hybrids which were obtained by crossing 5 parental forms of spring spelt from different geographical regions characterized by various morphological and performance traits. A total of 11 quantitative traits were analyzed, including 6 traits relating to yield components, 4 traits relating to grain quality and 1 trait relating to plant height and susceptibility to lodging. The applied clustering method supported the identification of 4 groups of hybrids which were presented graphically in a heatmap with dendrogram. Group I contained 33.0% hybrids, and it was most distant from the remaining groups. It was composed of tall hybrid plants characterized by high values of yield components, high fat content and high susceptibility to lodging. Groups III (30.4%) and IV (17.0%) were most similar and were characterized by lower values of yield components, a high content of protein, ash and fiber, and lower susceptibility to lodging. Group II contained 19.6% hybrids, it was more similar to groups III and IV than group I. Hybrids with satisfactory performance traits can be selected from each group and used to breed new varieties with the desired traits.

Keywords: Triticum spelta; F5 generation; yield components; grain quality; lodging

1. Introduction

Spelt (Triticum spelta L. 1753, syn. Triticum aestivum ssp. spelta (L.) Thell. 1918, 2n=6x=42, AABBDD) is one of the oldest species/subspecies of wheat which was cultivated already 7,000-8,000 BCE in the Neolithic period. Spelt had probably originated in Southeast Asia, and it spread to northern and central Europe where it became a staple cereal. In Poland, spelt, emmer and einkorn were cultivated already 4,000 years ago. Spelt had probably originated from multiple crosses between club wheat and hulled tetraploid emmer in the Fertile Crescent region. Spelt spread to Europe, including Austria, southern Germany and Switzerland, and it migrated along the Black Sea coast and the Danube [1,2]. In Europe, spelt replaced einkorn (T. monococcum) and emmer (T. dicoccum) during the last glacial period, but it was superseded by the threshable bread wheat (T. aestivum) in the first millennium CE. Despite the above, spelt continued to be cultivated as a niche species until the modern period [3]. In the second half of the 20th century, the interest in spelt has been revived on account of its health benefits, high nutritional value and suitability for breeding programs aiming to develop varieties characterized by high grain quality and high resistance to pathogens. At present, spelt is grown mainly in Germany, Austria and Switzerland, where it occupies a total area of around 100,000 ha [4]. European varieties of spelt belong to Iberian and Bavarian eco-geographic groups which could have evolved independently over the centuries [5-7].

Winter spelt is the predominant cultivated form of spelt. A total of 67 spelt varieties, including 7 conservation varieties, are listed in the Common Catalogue of Varieties of Agricultural Plant Species [8]. The Polish National List of Agricultural Plant Varieties (NLI) contains two spelt varieties: the...
winter variety Rokosz, listed in 2012, and two Polish spring variety Wirtas and Kuiavia, listed in 2015 and 2018 [9-11]. Polish spelt varieties are also listed in the CCA [8].

Spelt has a unique genetic composition, and it is easily crossed with bread wheat (Triticum aestivum). For these reasons, spelt is used in breeding programs as a source of important performance traits for breeding modern varieties of bread wheat. Traditional crossbreeding by genetic recombination is generally recognized as a safe method of increasing genetic diversity. Screening panels of ancient wheats (obtained from gene banks) and the selection of the best accessions for the production of varieties with satisfactory quality traits constitute a separate research pathway [12]. The authors have initiated a research program entitled “An evaluation of Triticum spelta, T. dicoccum and T. monococcum collections for variations in grain quality, resistance to Fusarium pathogens and suitability for breeding new varieties adapted to sustainable farming systems” to address the growing interest in spelt in organic farms and the limited number of spelt varieties. The presented study is a part of the above research program which aims to increase the genetic diversity of spring spelt varieties.

The aim of this study was to evaluate F5 hybrids of spring spelt with the use of cluster analysis.

2. Materials and Methods

2.1. Material

The experimental material comprised F5 hybrids of T. spelta (♀) x T. spelta (♂) which were obtained by crossing 5 parental forms of spring spelt (Table 1). The parental forms were characterized by high yields, satisfactory chemical composition of grain and high resistance to spike and kernel infections. In terms of morphology, the parental forms differed mainly in spike structure and color: O11 – white and awnless, O13, K17, K18 – white and awned, K20 – anthocyanin-pigmented and awned. The parental forms were crossed in 7 combinations, K17 x O11, O13 x O11, K20 x K18, K20 x K17, K20 x O11, K20 x O13 and K17 x O13, in the greenhouse of the University of Warmia and Mazury in Olsztyn in 2007 in accordance with the standard protocol for the crossbreeding of wheat [13].

F1 generation plants were not selected. The spikelets from all F1 spikes were sown in a field in 2009. Every row represented the F2 progeny of one F1 spike – a total of 172 hybrids. The spikes from each row of F2 generation were harvested separately and sorted. The basic selection criterion was spike weight, and around 50% of small and light spikes and spikes infected by fungal pathogens were eliminated. The spikes from each row of F2 generation were weighed before and after selection. Two spikelets were removed from every selected spike. One spikelet was sown, and the other was kept as reserve material. The remaining spikes were threshed with the Wintersteiger LD 180
laboratory thresher, and threshed grained was used in chemical analyses. A total of 46 hybrids were selected for further breeding: K17xO11 – 6; O13xO11 – 7; K20xK18 – 8; K20xK17 – 6; K20xO11 – 7; K20xO13 – 7 and K17xO13 – 5.

The spikelets from the selected 46 hybrids were sown in a field, and superior individuals were selected based on the following criteria: resistance to lodging, grain yield and/or awnless spikes. A total of 264 individuals were selected from 46 hybrids in two cycles to produce 111 – F5 hybrids (F5 breeding lines) of spring spelt.

2.2. Yield components and resistance to lodging

Each F5 breeding line was evaluated for yield-related biometric traits and chemical composition of grain. The following parameters were measured: plant height after heading [cm]; length of internodes at full maturity [cm]; spike length [cm]; number of spikelets per spike; spike weight [g]; spike density (number of spikelets per 10 cm of rachis); number of kernels per spike; kernel weight per spike [g]; grain/spike weight ratio [%]; 1000-kernel weight [g].

A total of 30 spikes/culms per each F5 breeding line were analyzed. Plant height was measured after heading, from the ground to the tip of 30 typical culms. Spikes were threshed manually for biometric measurements. Spring wheat cv. Parabola (bread wheat of quality class A, entered into the NLI in 2006) was used as the reference. The grain characteristics of spelt and spring wheat cv. Parabola are presented in Figure 1.

Figure 1. Kernels and kernel cross-sections of bread wheat (Triticum aestivum) cv. Parabola and K17 spelt (Triticum spelta) stained with Lugol’s iodine (scale bar = 2 mm).

Spelt breeding line, their parental forms and bread wheat cv. Parabola were evaluated for susceptibility to lodging under field conditions on a 5-point grading scale (1° - no lodging, plants standing erect; 5° - complete lodging, top internodes damaged) on two dates during the growing season: (1) after heading, and (2) before harvest. Every hybrid group was evaluated for susceptibility to lodging based on median values.

2.3. Chemical analysis of grain
Grain was subjected to chemical analysis to determine the content of protein, fat, ash and fiber on a dry matter basis. Threshed, dehulled and cleaned spelt grain was ground in the Cyclotec 1093 laboratory mill (FOSS, Denmark) to produce samples with 1.0 mm particle size. The analyses were carried out in the Chemical Laboratory of the Department of Plant Breeding and Seed Production of the University of Warmia and Mazury in Olsztyn.

Crude protein content (N x 5.7) was determined according to Kjeldahl’s method using the Büchi System (K-424 digestion unit and B-324 distillation unit, Switzerland) according to standard PN-EN ISO 20483:2014. Crude fat was extracted by the Soxhlet method using the Büchi Extraction System B-811 with petroleum ether according to standard PN-EN ISO 734-1:2008. Ash content was determined in the Thermostep thermogravimetric analyzer (ELTRA GmBH, Germany) according to standard PN-G-04560:1998. Crude fiber content was determined using the Fibertec 2010 system (FOSS, Denmark) and the Weende method after extraction with 1.25% H$_2$SO$_4$ and 1.25% NaOH.

Protein, fat, ash and fiber content was determined in two replications. The results are expressed in percentage terms on a dry matter basis (% DM).

### 2.4. Field experiment

The successive generations of F1-F5 hybrids, their parental forms and bread wheat cv. Parabola (reference) were sown in a field at the Agricultural Experiment Station in Balcyny near Ostróda (53°35'49''N, 19°51'20''E; 136.9 m a.s.l) which is operated by the University of Warmia and Mazury in Olsztyn. F5 hybrids were sown in the first 10 days of April and harvested in the last 10 days of August. The average temperature during the growing season of 2016 was similar to the long-term average (Figure 2a). Precipitation levels were characterized by greater variation. Total precipitation during the growing season reached 380.7 mm, with a peak in July, and it exceeded the long-term average (316.8 mm) (Figure 2b). The experiment had a completely randomized design, and all breeding lines were sown in a single replication. Plot size was 3 m$^2$. Spikelets were sown manually in three rows with 20 cm spacing between rows. A single dose of N/P/K fertilizer was applied before sowing at 40/25/80 kg ha$^{-1}$. Fungicides and growth promoters were not applied. Weeds and pests were controlled chemically.

![Weather conditions (a) Average temperature (°C); (b) Total rainfall (mm).](image)

### 2.5. Statistical analysis

The F5 hybrids of spelt and their parental forms were evaluated based on 18 quantitative traits. Cluster analysis was used to group the studied objects (spelt hybrids) and evaluate multiple traits (variables). Different units of measurement were used in the study, therefore, data had to be standardized.
In the first stage of the analysis, the number of the analyzed traits was reduced. Some of the traits were highly correlated, and they had to be eliminated to avoid collinearity. Highly correlated traits were combined into groups by tree clustering. Ward’s method with a distance measure was used to create $1-r$ clusters, where $r$ is the coefficient of correlation between variables X and Y. The group of 18 variables was reduced to 11 variables with minimum information loss, which facilitated the interpretation of results. The above approach is not widely used, but it reduces the number of variables as effectively as principal component analysis (PCA) and factor analysis.

In the second stage, two-way joining analysis was used to group objects (spelt hybrids) and variables (traits) simultaneously and create a logical system of clusters. A heatmap and a dendrogram were developed (heatmap-tree). Every column in the map represents a given trait, and value of that trait after standardization is mapped with different colors. Every row in the heatmap represents a different spelt hybrid. Heatmap rows were arranged based on the measured distances between the experimental treatments in the dendrogram.

Group means were compared by orthogonal contrast analysis at $p < 0.05$. All analyses were performed in the Statistica (data analysis software system), version 13 [14].

3. Results

3.1. Characteristics of F2 hybrids of spring spelt

K17xO11 hybrids were obtained by crossing white and awned K17 spelt with white and awnless O11 spelt. In the F2 generation of K17xO11 hybrids, most spikes were awnless and morphologically similar to the O11 paternal form. Spike length ranged from 15 to 19 cm. Spikes had brittle rachis and were easily damaged. Spike weight was determined at 92-654 g before selection and 42-329 g after selection, with an average of 316 g and 171 g, respectively. K17xO11 hybrids were characterized by the highest average spike weight after initial selection (Figure 3). K17xO11 hybrids were also characterized by the highest average content of ash and crude fiber as well as the second highest average protein content after K17xO13 hybrids (Table 2). Six K17xO11 hybrids were selected for further breeding.

![Figure 3. Average spike weight in all 172 F2 hybrids before and after selection and in 46 hybrids selected for further breeding (mean ± SD).](image_url)

O13xO11 hybrids were obtained by crossing white and awned O13 spelt with white and awnless O11 spelt. In F2 hybrids, most spikes were awned, white and morphologically similar to the O13 maternal form. Spike length ranged from 13 to 19 cm. The awnless spikes of the O13xO11 hybrids were significantly heavier than awned spikes. Spike weight was determined at 57-570 g before selection and 33-300 g after selection with an average of 295 g and 149 g, respectively (Figure...
Symptoms of severe infection with Fusarium fungi were observed on the spikes of two O13xO11 hybrids. Seven hybrids were selected for further breeding.

Table 2. Content of protein, fat, ash and fiber (% DM) in the kernels of F2 spelt hybrids, their parental forms (O11, O13, K17, K18, K20) and bread wheat cv. Parabola (A). The specimens were harvested in 2009

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>K17 x O11</td>
<td>Mean ± SD</td>
<td>16.81 ± 0.84</td>
<td>1.75 ± 0.15</td>
<td>2.32 ± 0.18</td>
</tr>
<tr>
<td></td>
<td>Min. Max</td>
<td>15.77-18.61</td>
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<td>1.51-1.95</td>
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<tr>
<td></td>
<td>CV (%)</td>
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<td>8.5</td>
<td>8.0</td>
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<tr>
<td>O13 x O11</td>
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<td>16.29 ± 0.75</td>
<td>1.58 ± 0.22</td>
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<td>1.94-2.42</td>
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<td>CV (%)</td>
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<td>5.9</td>
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<td>K17 x K18</td>
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<td>15.48 ± 0.81</td>
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<td>1.53-2.28</td>
<td>1.80-2.25</td>
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<td>CV (%)</td>
<td>5.2</td>
<td>10.7</td>
<td>4.7</td>
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<tr>
<td>K20 x K18</td>
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<td>2.02 ± 0.24</td>
<td>2.13 ± 0.12</td>
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<td>1.89-2.38</td>
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<td></td>
<td>CV (%)</td>
<td>4.5</td>
<td>12.0</td>
<td>5.6</td>
</tr>
<tr>
<td>K20 x K17</td>
<td>Mean ± SD</td>
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<td>1.99 ± 0.20</td>
<td>2.01 ± 0.20</td>
</tr>
<tr>
<td></td>
<td>Min. Max</td>
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<td>1.66-2.49</td>
<td>1.66-2.53</td>
</tr>
<tr>
<td></td>
<td>CV (%)</td>
<td>5.2</td>
<td>9.9</td>
<td>10.0</td>
</tr>
<tr>
<td>K20 x O11</td>
<td>Mean ± SD</td>
<td>15.79 ± 0.75</td>
<td>1.75 ± 0.18</td>
<td>2.14 ± 0.26</td>
</tr>
<tr>
<td></td>
<td>Min. Max</td>
<td>14.80-17.37</td>
<td>1.20-2.18</td>
<td>1.79-2.80</td>
</tr>
<tr>
<td></td>
<td>CV (%)</td>
<td>4.7</td>
<td>10.0</td>
<td>12.2</td>
</tr>
<tr>
<td>K17 x O13</td>
<td>Mean ± SD</td>
<td>16.97 ± 0.95</td>
<td>1.50 ± 0.22</td>
<td>2.19 ± 0.13</td>
</tr>
<tr>
<td></td>
<td>Min. Max</td>
<td>15.66-18.64</td>
<td>1.04-1.73</td>
<td>2.04-2.45</td>
</tr>
<tr>
<td></td>
<td>CV (%)</td>
<td>5.6</td>
<td>14.7</td>
<td>5.8</td>
</tr>
<tr>
<td>Parents (O11, O13, K17, K18, K20)</td>
<td>Mean ± SD</td>
<td>17.20 ± 0.55</td>
<td>2.20 ± 0.27</td>
<td>2.32 ± 0.12</td>
</tr>
<tr>
<td></td>
<td>Min. Max</td>
<td>16.23-17.93</td>
<td>1.72-2.56</td>
<td>2.17-2.52</td>
</tr>
<tr>
<td></td>
<td>CV (%)</td>
<td>3.2</td>
<td>12.5</td>
<td>5.1</td>
</tr>
</tbody>
</table>

T. aestivum cv. Parabola

Mean 14.35 1.65 2.10 2.29

K20xK18 hybrids were obtained by crossing awned K20 spelt with strong anthocyanin pigmentation with awned and white K18 spelt. All spikes of F2 hybrids were awned, and most of them were characterized by anthocyanin pigmentation and satisfactory threshability. Spike length ranged from 15 to 21 cm. Spike weight was determined at 69-579 g before selection and 50-240 g after selection with an average of 342 g and 161 g, respectively (Figure 3). Severe symptoms of Fusarium infection were observed on the spikes of three K20xK18 hybrids. K20xK18 hybrids were...
characterized by the lowest average content of protein and crude fiber (Table 2). Eight hybrids were selected for further breeding.

K20xK17 hybrids were obtained by crossing awned K20 spelt with strong anthocyanin pigmentation with white and awned K17 spelt. The spikes of F2 hybrids were awned, and most of them were characterized by anthocyanin pigmentation and satisfactory threshability. Spike length ranged from 16 to 21 cm. Spike weight was determined at 23-460 g before selection and 18-223 g after selection with an average of 233 g and 120 g, respectively (Figure 3). K20xK17 hybrids were characterized by high average protein content and the highest fat content (Table 2). Six hybrids were selected for further breeding.

K20xO11 hybrids were obtained by crossing awned K20 spelt with strong anthocyanin pigmentation with white and awnless O11 spelt. In F2 hybrids, most spikes were awned and characterized by anthocyanin pigmentation. Spike length ranged from 17 to 22 cm. Spike weight was determined at 30-480 g before selection and 30-224 g after selection with an average of 206 g and 112 g, respectively (Figure 2). K20xO11 hybrids were characterized by the lowest average ash content and high fat content (Table 2). Seven hybrids were selected for further breeding.

K20xO13 hybrids were obtained by crossing awned K20 spelt with strong anthocyanin pigmentation with white and awned O13 spelt. The spikes of F2 hybrids were awned, and most of them were characterized by anthocyanin pigmentation. Spike length ranged from 10 to 19 cm. Spike weight was determined at 20-314 g before selection and 13-149 g after selection with an average of 202 g and 106 g, respectively (Figure 3). K20xO13 hybrids were characterized by a moderate content of the analyzed chemical components relative to the remaining hybrids (Table 2). Seven hybrids were selected for further breeding.

K17xO13 hybrids were obtained by crossing white and awned K17 spelt with white and awned O13 spelt. F2 hybrids had white and awned spikes. Spike length ranged from 16 to 19 cm. Spike weight was determined at 23-370 g before selection and 23-198 g after selection with an average of 179 g and 98 g, respectively. K17xO13 hybrids were characterized by the lowest average spike weight before and after selection (Figure 3), as well as the highest average protein content and the lowest fat content (Table 2). Five hybrids were selected for further breeding.

The hybrids selected for further breeding were characterized by the highest spike weight. The average spike weight in all 172 F2 hybrids was determined at 255±136 g before selection and 131±59 g after selection, and the average spike weight in the selected 46 hybrids was determined at 404±95 g and 193±48 g, respectively. The analyzed hybrids were characterized by minor variations in protein and ash content, and the values of the corresponding coefficients of variation were determined at 5.6% and 8.9%. Greater variations were observed in fat and fiber content, and the values of the corresponding coefficients of variation were determined at 14.7% and 16.2%.

3.2. Characteristics of F5 hybrids of spring spelt

In 2016, the F5 hybrids of spring spelt were evaluated under field and laboratory conditions relative to their parental forms and bread wheat cv. Parabola. The ripening period in July 2016 was characterized by high precipitation, a factor that contributes to lodging.

3.2.1. Plant height and susceptibility to lodging

Plant height after heading did not differ considerably between parental forms. Awnless O11 spelt was characterized by the lowest average height and the lowest susceptibility to lodging. Moderate values of the above traits were noted in awned O13, K17 and K18 spelt. K20 spelt produced the tallest plants which were most susceptible to lodging. The evaluated hybrids were divided into two height groups: shorter plants – K17xO11, K17xO13 and K20xO11, and taller plants – O13xO11, K20xK18, K20xO13 and K20xK17. Hybrids K17xO11, K20xK17 and K20xO13 were less susceptible to lodging (median value of 3.0 before harvest), whereas K20xO11 hybrids was most susceptible to lodging (median value of 5.0 before harvest) (Figure 4). All types of hybrids differed in their susceptibility to lodging.
Figure 4. Plant height in parental forms, F5 hybrids of spring spelt and bread wheat cv. Parabola (mean ± SD) and their susceptibility to lodging on a 5-point scale (after heading/before harvest).

* – lodging susceptibility (after heading/before harvest) of hybrids was presented in terms of median values.

The length of the top internode and the two lower internodes did not vary significantly in the analyzed 111 hybrids, and it was determined at 56.1 cm in the 5th internode (CV=6.6%), 23.1 cm in the 4th internode (CV=8.6%), and 14.2 cm in the 3rd internode (CV=9.2%). Greater variations were noted in the two lowest internodes at 9.9 cm in the 2nd internode (CV=13.9%) and 4.4 cm in the 1st internode (CV=23.5%). The position of the internodes relative to the ground was similar in hybrids that were most susceptible to lodging: the 1st and 2nd internode were positioned at an acute angle, the 3rd and 4th internode were nearly perpendicular, whereas the top internode deviated from the vertical line in a different plane than the 1st and 2nd internode. In those hybrids, the culm was also broken above the top node.

3.2.2. Grouping spelt hybrids and parental forms by cluster analysis

The cluster analysis produced four groups of spelt hybrids and their parental forms with similar values of the 11 analyzed traits:

1. **PH** – plant height after heading,
2. **SL** – spike length,
3. **SD** – spike density,
4. **KW** – kernel weight,
5. **NK** – number of kernels,
6. **TKW** – 1000-kernel weight,
7. **GS** – grain/spike weight ratio,
8. **PC** – protein content of kernels,
9. **FaC** – fat content of kernels,
10. **AC** – ash content of kernels,
11. **FiC** – fiber content of kernels.

The values of the 11 analyzed traits in 4 groups of hybrids were presented graphically in a dendrogram and a heatmap with the use of the following colors: green (low value), yellow (medium value), red (high value), as well as intermediate colors (Figure 5).
Figure 5. A heatmap and a dendrogram of F5 hybrids of spring spelt and their parental forms.


Group I was most distant from the remaining groups, and it consisted of 35 hybrids and parental forms K18 and K20, which accounted for 33% of the studied objects (Figure 5). K20 was the maternal form in all group I hybrids. Paternal forms were represented by K17 (34.3%), O11 (28.6%), K18 (20.0%) and O13 (17.1%). Group I was characterized by significantly higher average plant height (111.5 vs. 106.1 cm; p < 0.001), spike length (12.8 vs. 11.4 cm; p < 0.001), kernel weight (1.56 vs. 1.30 g; p < 0.001), number of kernels (31.9 vs. 27.8; p < 0.001), 1000-kernel weight (48.9 vs. 46.8 g; p < 0.001) and significantly higher fat content (2.23 vs. 2.03% DM; p < 0.001) than the remaining hybrids and parental forms. In comparison with the remaining hybrids, group I was characterized by significantly lower content of protein (16.60 vs. 17.03% DM; p = 0.033), ash (2.08 vs. 2.30% DM; p < 0.001) and fiber (1.97 vs. 2.17% DM; p = 0.001) (Table 3). Group I hybrids were highly susceptible to lodging. The frequency of hybrids most prone to lodging (4° and 5°) was determined at 0.41 after heading and 0.68 before harvest. The median values of susceptibility to lodging on a 5-point grading scale were determined at 3.0 after heading and 4.0 before harvest for group I hybrids and at 2.0 and 3.0, respectively, for the remaining hybrids.

Group II consisted of 22 hybrids where O13 was the dominant maternal form (68.2%) and O11 was the dominant paternal form (81.8%). Group II accounted for 19.6% of all studied objects (Figure 5). Average plant height was similar to group I hybrids (111.5 cm), whereas significantly lower values were noted for spike length (11.4 vs. 12.8 cm; p < 0.001), spike density (12.6 vs. 13.2; p = 0.001), kernel weight (1.24 vs. 1.56 g; p < 0.001), number of kernels (25.7 vs. 31.9; p < 0.001) and fat...
Table 3. Mean values ± standard deviation (mean ± SD) and coefficients of variation (CV %) of the 11 analyzed traits in F5 hybrids and their susceptibility to lodging (LO) evaluated on a 5-point scale in groups I-IV (refer to Figure 5 for symbols of the 11 evaluated traits).

<table>
<thead>
<tr>
<th>Group</th>
<th>PH</th>
<th>SL</th>
<th>SD</th>
<th>KW</th>
<th>NK</th>
<th>TKW</th>
<th>GS</th>
<th>PC</th>
<th>FaC</th>
<th>AC</th>
<th>FiC</th>
<th>LO</th>
</tr>
</thead>
<tbody>
<tr>
<td>G I</td>
<td>111.5±4.1</td>
<td>12.8±0.6</td>
<td>13.2±0.8</td>
<td>1.56±0.12</td>
<td>31.9±2.3</td>
<td>48.9±3.3</td>
<td>70.5±1.9</td>
<td>16.60±0.77</td>
<td>2.23±0.21</td>
<td>2.08±0.09</td>
<td>1.97±0.18</td>
<td>3.0/4.0</td>
</tr>
<tr>
<td>CV(%)</td>
<td>3.7</td>
<td>4.9</td>
<td>6.1</td>
<td>7.9</td>
<td>7.0</td>
<td>6.8</td>
<td>2.7</td>
<td>4.6</td>
<td>9.3</td>
<td>4.4</td>
<td>9.4</td>
<td>3.0/4.0</td>
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<tr>
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<td>111.5±7.2</td>
<td>11.4±0.5</td>
<td>12.6±0.3</td>
<td>1.24±0.09</td>
<td>25.7±1.8</td>
<td>48.3±1.2</td>
<td>70.7±1.7</td>
<td>17.52±0.94</td>
<td>1.99±0.22</td>
<td>2.27±0.08</td>
<td>1.89±0.18</td>
<td>3.0/4.0</td>
</tr>
<tr>
<td>CV(%)</td>
<td>6.5</td>
<td>4.4</td>
<td>2.6</td>
<td>7.6</td>
<td>6.9</td>
<td>2.5</td>
<td>2.4</td>
<td>5.3</td>
<td>11.0</td>
<td>3.6</td>
<td>9.3</td>
<td>3.0/4.0</td>
</tr>
<tr>
<td>G III</td>
<td>107.9±3.9</td>
<td>11.3±0.4</td>
<td>13.3±0.5</td>
<td>1.34±0.09</td>
<td>28.6±1.7</td>
<td>46.9±2.1</td>
<td>71.9±1.2</td>
<td>17.07±1.01</td>
<td>1.96±0.23</td>
<td>2.32±0.09</td>
<td>2.32±0.32</td>
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</tr>
<tr>
<td>CV(%)</td>
<td>3.6</td>
<td>3.9</td>
<td>4.0</td>
<td>7.0</td>
<td>6.1</td>
<td>4.5</td>
<td>1.7</td>
<td>5.9</td>
<td>11.9</td>
<td>3.6</td>
<td>13.8</td>
<td>2.0/3.0</td>
</tr>
<tr>
<td>G IV</td>
<td>96.8±5.3</td>
<td>11.6±0.9</td>
<td>13.2±0.7</td>
<td>1.30±0.11</td>
<td>29.0±2.5</td>
<td>44.9±3.8</td>
<td>70.2±2.1</td>
<td>16.40±0.90</td>
<td>2.19±0.14</td>
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<td>2.23±0.32</td>
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</tr>
<tr>
<td>CV(%)</td>
<td>5.5</td>
<td>7.6</td>
<td>5.3</td>
<td>8.2</td>
<td>8.5</td>
<td>8.5</td>
<td>3.0</td>
<td>5.5</td>
<td>6.2</td>
<td>6.4</td>
<td>14.6</td>
<td>2.0/3.0</td>
</tr>
<tr>
<td>G II-IV</td>
<td>106.1±7.8</td>
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<td>13.1±0.6</td>
<td>1.30±0.10</td>
<td>27.8±2.4</td>
<td>46.8±2.7</td>
<td>71.1±1.8</td>
<td>17.03±1.03</td>
<td>2.03±0.23</td>
<td>2.30±0.11</td>
<td>2.17±0.34</td>
<td>2.0/3.0</td>
</tr>
<tr>
<td>CV(%)</td>
<td>7.3</td>
<td>5.2</td>
<td>4.6</td>
<td>8.0</td>
<td>8.5</td>
<td>5.9</td>
<td>2.5</td>
<td>6.1</td>
<td>11.2</td>
<td>4.6</td>
<td>15.6</td>
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</tr>
<tr>
<td>T. aestivum</td>
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<td>17.2</td>
<td>2.10</td>
<td>41.7</td>
<td>50.0</td>
<td>79.3</td>
<td>15.29</td>
<td>1.52</td>
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</tr>
<tr>
<td>Parabola</td>
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</table>
characterized by significantly higher spike ure.

Agronomy groups: varieties containing the genetic material of spelt revealed high levels of genetic diversity, and the studied varieties were divided into two main levels of genetic diversity. However, qualitative and molecular analyses of 28 European varieties of spelt, including Ostro, Franckenkorn, Schwabenkorn, Oberkulmer Rotkorn, Zollernspelz, which are supports the selection of hybrids with varied performance traits.

The dendrogram (Fig 5) clearly indicates that group I objects were most distant from the remaining groups. Based on the heatmap, the observed differences were attributed mainly to the values of yield component traits. Group III and IV hybrids were most similar in yield component traits, and they were characterized by a high content of ash and fiber. Despite the presence of highly significant differences, the dendrogram indicates that group II objects were more similar to group III and IV objects than group I objects. Each of the four groups contained distinctive subgroups, which supports the selection of hybrids with varied performance traits.

The applied statistical method of grouping F5 hybrids and their parental forms produced 4 groups with the following characteristics:

- **Group I** – tall plants with satisfactory yield components, lower content of protein, ash and fiber relative to the remaining groups, high fat content, and high susceptibility to lodging;
- **Group II** – tall plants with unsatisfactory yield components, higher content of protein and ash relative to the remaining groups, lower content of fiber and fat, and high susceptibility to lodging;
- **Group III** – shorter plants with moderate yield components, high content of protein, ash and fiber, low fat content, and moderate susceptibility to lodging;
- **Group IV** – shortest plants with moderate yield components, moderate content of fat, ash and fiber, lower protein content relative to the remaining groups, and moderate susceptibility to lodging.

The dendrogram (Figure 5) clearly indicates that group I objects were most distant from the remaining groups. Based on the heatmap, the observed differences were attributed mainly to the values of yield component traits. Group III and IV hybrids were most similar in yield component traits, and they were characterized by a high content of ash and fiber. Despite the presence of highly significant differences, the dendrogram indicates that group II objects were more similar to group III and IV objects than group I objects. Each of the four groups contained distinctive subgroups, which supports the selection of hybrids with varied performance traits.

**4. Discussion**

There are no native varieties of spelt in Poland. Organic farms grow mainly winter varieties of spelt, including Ostro, Franckenkorn, Schwabenkorn, Oberkulmer Rotkorn, Zollernspelz, which are listed in the CCA [8]. According to [15], spelt varieties grown in Poland are characterized by low levels of genetic diversity. However, qualitative and molecular analyses of 28 European varieties of spelt revealed high levels of genetic diversity, and the studied varieties were divided into two main groups: varieties containing the genetic material of bread wheat, and true spelt that does not contain
the genetic material of bread wheat [16]. The first Polish variety of spring spelt, Wirtas, was introduced in 2015 [9, 17]. Wirtas is characterized by white and awnless spikes with brittle rachis, hulled kernels, long culms and low resistance to lodging. In a two-year study, the spikelet yield of spring spelt cv. Wirtas was determined at 76.4% and 83.8%, and dehulled grain yield – at 57.8% and 63.0% of that determined in bread wheat in treatments with lower (50 kg N ha\(^{-1}\)) and higher (100 kg N ha\(^{-1}\)) rates of nitrogen fertilization, which was equivalent to 4.85 t ha\(^{-1}\) and 5.32 t ha\(^{-1}\) spikelets and 3.67 t ha\(^{-1}\) and 4.00 t ha\(^{-1}\) dehulled grain, respectively. The grain/spikelet weight ratio was 74.8% [17].

Spring spelt cv. Wirtas is characterized by high resistance to adverse biotic and abiotic factors, low nutritional requirements and high-quality grain which is used in food and feed production. Wirtas is not suitable for high-input farming, but it is popular in organic farms.

The revived interest in spelt can be attributed to the high nutritional value of its grain which is rich in protein, macronutrients and micronutrients [18-25], resistance to fungal pathogens [4, 17, 26-30] and higher adaptability to varied environments and simplified farming systems in comparison with bread wheat [31-33]. The milling quality of spelt grain has been recently investigated by [24, 25, 34]. The suitability of ancient wheats, including spelt, for the production of functional foods has been discussed by [12].

4.1. Yield components

Spring grain yields are generally 37% lower than bread wheat yields [23]. Spelt grains are tightly enclosed by tough glumes and have to be dehulled before milling to separate the chaff from the grain. Spring cultivars of spelt (CDC Nexon, CDC Origin, CDC Zorba, CDC Silex) registered in 2002-2013 are grown in Canada [35]. The yield of spring spelt cultivars in eastern Canada was analyzed by [36]. The average yield of spring spelt spikelets/dehulled kernels in three locations was determined at 4052/2705 kg ha\(^{-1}\) (CDC Origin), 3850/2788 kg ha\(^{-1}\) (CDC Silex), 3705/2715 kg ha\(^{-1}\) (CDC Zorba) and 3200/2504 kg ha\(^{-1}\) (CDC Nexon). CDC Origin was characterized by the highest (34.5-37.6%) and CDC Nexon by the lowest (24.0-25.8%) percentage of hulls. In spring spelt cv. Wirtas, the percentage of hulls was determined at 25.2% [17].

Yield components (number of kernels, kernel weight, 1000-kernel weight) were most satisfactory in group I hybrids where K20 was the maternal form. Group I hybrids were characterized by long, loose and awned spikes with weak or relatively strong anthocyanin pigmentation. Spike length, spike weight, number of kernels, kernel weight per spike and 1000-kernel weight were highest in group I, but spike weight (2.11 vs. 2.63 g), kernel weight (1.56 vs. 2.10 g) and the number of kernels (31.9 vs. 41.7) in group I were lower than in bread wheat. In a study of 22 accessions of winter spelt, the average spike weight was determined at 1.75 g (1.1-2.5) g, kernel weight at 0.77 g (0.37-1.08 g), and the number of kernels per spike at 17.2 (10.5-22.7) [37]. In a study of 15 accessions of spring spelt, kernel weight per spike was determined at 1.02±0.29 g, and the number of kernels per spike at 24.2±6.1 [38]. The grain/spike weight ratio was lower in spelt hybrids than in bread wheat, and it was characterized by low variation. In F5 hybrids, the grain/spike weight ratio ranged from 65.9% to 74.5% with an average of 70.8%, and it was similar to that determined by other authors [17, 36-40].

4.2. Chemical composition of grain

According to a review article by [41], spelt kernels have higher protein content than bread wheat kernels. The weighted average and the range of protein content values in bread wheat and spelt kernels were determined at 14.9% DM (10.9-17.5) and 15.6% DM (9.8-25.5), respectively. Considerable variations in the protein content of spelt and bread wheat kernels were reported by different authors. All analyses were performed using the Kjeldahl method, therefore, the observed variability could be attributed to differences in growing conditions (environment and nitrogen fertilization) and genotype. In a study of 1019 spelt genotypes from various geographic regions, the protein content of kernels exceeded 30% DM. The analyzed parameter was determined at 18.5-21.8% DM in 20 genotypes with the highest Zn concentration, and it was highly stable in 6 tested environments [21]. The protein content of spring spelt cultivars grown in eastern Canada ranged...
from 14.2% to 15.4% DM [36]. The protein content of spring spelt cv. Wirtas grown in Poland was determined at 13.9% DM in treatments with a low rate of nitrogen fertilizer (N50 kg) and 14.8% DM in treatments with a high rate of nitrogen fertilizer (N100 kg) [17]. The grain of 30 varieties and breeding lines of winter spelt contained 15.80% protein on average (13.92-18.54), and the heritability of this trait was determined at 0.67 [25]. F5 hybrids of spring spelt were characterized by high protein content at 16.9% DM on average (14.5-19.4%). The average protein content of 19 varieties of spring bread wheat included in the Polish NLI was determined at 15.0% DM (13.7-16.0%) [42]. In this study, the highest average protein content of 17.5% DM was found in group II hybrids. In groups I and II, protein content was correlated with grain yield. In group I, higher grain yield was correlated with lower protein content, whereas in group II, lower grain yield was correlated with higher protein content. The protein content of bread wheat is negatively correlated with grain yield, which was confirmed by the results of previous research summarized in a review article by [43]. The correlation coefficient between grain yield and protein content, calculated based on average values for varied environmental conditions, ranged from \( r = -0.37 \) to \( r = -0.94 \) [23] observed a significant negative correlation between grain yield and protein content in bread wheat, durum wheat, spelt and emmer, where the corresponding values of the correlation coefficient were determined at: \(-0.87 \) \((p < 0.001)\), \(-0.58 \) \((p < 0.05)\), \(-0.83 \) \((p < 0.01)\) and \(-0.71 \) \((p < 0.01)\), respectively. Highly significant negative correlations between hulled yield and protein content \((r = -0.60, p < 0.001)\) were observed in 30 contemporary varieties and breeding lines of winter spelt in 6 locations in Germany [25].

Grain is not a rich source of lipids which make up only around 3% of the kernel. Lipids are more concentrated in the germ and the aleurone than in the endosperm. Most studies of free lipids have shown that spelt is more abundant in fat than bread wheat [41]. The weighted average and the range of fat (free lipids) content values were determined at 2.1% DM (1.1-3.7%) in bread wheat and 2.5% DM (1.4-5.2%) in spelt. The grain of F5 hybrids differed in fat content. The average fat content and the range of fat content values were determined at 2.09% (1.48-2.57%) in all hybrids and at 1.52% DM in bread wheat cv. Parabola. The highest average fat content was noted in group I hybrids (2.23% DM), whereas the average fat content of 19 spring wheat varieties included in the Polish NLI was higher at 2.70% DM (2.46-2.89%) [42].

Ash content represents the concentrations of minerals which determine the nutritional value of grain. According to numerous studies, spelt grain is a rich source of macronutrients and micronutrients [18-21, 25]. The macronutrient and micronutrient content of four species of spring wheat (einkorn, emmer, spelt and bread wheat) grown under the same conditions was analyzed by [22]. The ash content of common wheat grain for baking white bread should not exceed 1.7%. Spring wheat grain is generally more abundant in ash than winter wheat grain, and spelt grain contains more ash than bread wheat grain [44,45]. The average ash content of grain was determined at 2.22% DM (1.93-2.62%) in all hybrids and at 2.12% in bread wheat cv. Parabola. Group I hybrids were characterized by the lowest average ash content of 2.08% DM relative to the remaining groups (2.30% DM). The average protein content of spring and winter varieties of bread wheat in the Polish NLI was lower at 1.7% DM and 1.6% DM, respectively [42].

Whole wheat grain contains 11.5% to 15.5% of total dietary fiber (TDF) on a dry matter basis, and the major fiber components make up the cell wall. Crude fiber is a component of dietary fiber, and it contains cellulose, lignin and hemicelluloses, residues of acid and alkaline hydrolysis. According to [41], crude fiber levels are similar in bread wheat and spelt. The weighted average for the crude fiber content of bread wheat grain and spelt grain was determined at 2.4% DM [46] reported higher content of dietary fiber (14.96% DM vs. 11.18% DM) and its fractions (insoluble fiber, soluble fiber, arabinoxylan, β-glucan) in whole grains of bread wheat than in spelt grain. The average content of crude fiber was lower in F5 hybrids (2.09% DM) than in bread wheat (2.35% DM). In groups III and IV, crude fiber content was similar to that noted in bread wheat, but in groups I and II, the analyzed parameter was lower than in bread wheat. The above trait was characterized by the highest variation (CV=14.9%). Winter breeding lines of spelt had a higher average content of crude fiber, i.e. 3.3% DM on average [47].
Lodging is one of the main causes of annual fluctuations in spelt production. Old landraces and most commercial varieties of spelt are characterized by long and weak culms and, consequently, high risk of lodging [48]. In recent decades, the main aim of spelt breeding has been to decrease plant height and minimize lodging. The interest in spelt was revived in the 1970s and 1980s, mainly in Germany, Switzerland and Belgium, by screening panels of landraces from different gene banks for their agronomic performance. In the above countries, breeding programs focused on the introgression of reduced plant height from different varieties of bread wheat. Bread wheat and spelt hybrids were followed by successive backcrossing with different spelt landraces [4]. Oberkulmer Rotkorn, the German cultivar of winter spelt with culms longer than 140 cm, is the reference standard in analyses of lodging susceptibility. In spelt and bread wheat, a strong positive correlation is noted between plant height and resistance to lodging (r = 0.65, p < 0.001). Despite the above, spelt plants should not be shorter than 100-120 cm [4]. In this study, all F5 hybrids were prone to lodging. The hybrids where the tall and high-yielding K20 spelt was the parental form, in particular K20xO11 (average height of 104.6 cm), were most susceptible to lodging. K17xO11 and O13xO11 hybrids (average height of 102.8 cm and 113.6 cm, respectively) were less prone to lodging. The analyzed hybrids differed in height and susceptibility to lodging. In wheats, plant height is the most important, but not the only, determinant of susceptibility to lodging [49].

5. Conclusions

The applied grouping method supported the identification of 4 groups of hybrids with similar yield components and chemical composition of grain. Groups III and IV were most similar in terms of spike length, spike density, kernel weight, number of kernels per spike and the content of chemical components in grain, including ash and fiber. These hybrids are characterized by shorter plants and lower susceptibility to lodging, and they constitute promising material for breeding.

Heatmaps and dendrograms facilitate the selection of hybrids with satisfactory performance traits for breeding new varieties that meet various requirements (improved yield, high grain quality, lower susceptibility to lodging).

Author Contributions: conceptualization, D.P. and D.Z.; methodology, D.P. and D.Z.; formal analysis, D.P. and D.Z.; investigation, D.P., L.G., W.L. and D.Z.; writing—original draft preparation, D.P. and D.Z.; writing—review and editing, D.P. and D.Z.; visualization, D.P. and D.Z.; supervision, D.P.; project administration, D.P.; funding acquisition, D.P. and D.Z.

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Conflicts of Interest: The authors declare conflicts of interest.

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