sustainability

MDPI

Article

An Analysis of Selected Physical Properties of Ancient Wheat Species

Ewelina Kolankowska *, Dariusz Jan Choszcz and Piotr Markowski

Department of Heavy Duty Machines and Research Methodology, University of Warmia and Mazury, Olsztyn 10-957, Poland; dariusz.choszcz@uwm.edu.pl (D.J.C.); piotr.markowski@uwm.edu.pl (P.M.)

* Correspondence: ewelina.kolankowska@uwm.edu.pl

Received: 3 October 2017; Accepted: 26 October 2017; Published: 28 October 2017

Abstract: Recent years have witnessed a revived interest in ancient wheats on account of their health-promoting properties. The aim of this study was to determine selected physical properties of hulled and hulless kernels of ancient wheats for optimizing the parameters of seed processing operations such as husking, cleaning, and sorting. The geometric parameters (length, width and thickness), mass, and angle of external friction (on steel and PVC) of hulled and hulless spelt, emmer, and einkorn kernels were determined. The spikelets and kernels of ancient wheats are characterized by similar physical properties and differ most considerably in mass.

Keywords: spelt; emmer; einkorn; physical properties

1. Introduction

Emmer (*Triticum dicoccon* (Schrank) Schübl.), einkorn (*Triticum monococcum* L.), and the most widely known spelt (*Triticum spelta* L.) are ancient species of wheat. Emmer is the oldest ancient wheat species, and it was one of the first domesticated cereals in the Middle East, where it was cultivated already 10,000 BCE. Einkorn appeared nearly a millennium later in the Balkans and the Middle East. Spelt was first farmed around 7000–8000 BCE, and it was probably also domesticated in the Middle East. Ancient wheats have lower yields and are more difficult to process than common wheat, which is why they gradually disappeared or were preserved only in small areas in Poland and Europe. In recent years, interest in ancient wheats has been revived, in particular in organic farms [1–5]. Hulled wheats enjoy growing popularity on account of their health-promoting properties and growing levels of consumer awareness about the benefits of a diverse diet [6]. Ancient wheats are a valuable source of biologically active compounds that deliver health benefits [7–13]. Emmer grain is rich in fiber, protein, magnesium, and vitamins. Einkorn is a valuable source of proteins, lipids, vitamins, minerals (iron, zinc, phosphorus, potassium, manganese), and amino acids that are essential for the healthy function of the nervous system. Spelt grain has a bitter and nutty flavor, and it contains highly available proteins, unsaturated fatty acids, B and PP group vitamins and minerals (zinc, potassium, calcium, iron). The kernels of ancient wheats are enclosed by tough husks, which protect grain against pollution and radiation [14,15]. Einkorn ears are flatter than emmer ears, they have awned spikelets with typically two to three flowers and one kernel per spikelet. Spelt is characterized by long stems and awned or awnless ears with two flowers and one or two kernels per spikelet or, in rare cases, three kernels per spikelet [15].

Emmer, einkorn, and spelt have hulled grain that is not dehusked during threshing. Ancient wheats are harvested in the fully ripe stage as spikelets, which complicates the selection of the optimal working parameters in combine harvesters [16]. The kernels of ancient wheats are enveloped by thick husks that are not removed during harvest and require further processing. They are dehusked in devices that are not designed for this purpose, and modified clove hullers are usually used in organic farms.

The aim of this study was to determine selected physical properties of hulled and hulless kernels of ancient wheats for optimizing the parameters of seed processing operations such as husking, cleaning, and sorting. Knowledge of the physical properties of kernels and their correlations is required for designing grain-processing machines.

2. Materials and Methods

The experiment was performed on ancient wheat species cultivated in certified organic farms. Spelt (*Triticum spelta* L.) was produced in an organic farm in Praslity, municipality of Dobre Miasto in the Region of Warmia and Mazury. Emmer (*Triticum dicoccon* (Schrank) Schübl.) and einkorn (*Triticum monococcum* L.) were purchased from an organic farm in Pokrzydowo, municipality of Zbiczno in the Kujawsko-Pomorskie Region (Figure 1). Hulled forms of wheat were analyzed. Ancient wheats were grown on brown soil of quality classes II and III, developed from medium-heavy and light loam (representing good wheat complex and defective wheat complex, respectively, in the Polish soil classification system).

Figure 1. Spikelets and kernels of ancient wheats: (**a**) spelt; (**b**) emmer; (**c**) einkorn.

The basic geometric properties of kernels and spikelets were determined by the survey sampling method [17] in randomly selected batches of 300 spikelets. Selected physical properties were determined for both individual spikelets and the isolated kernels.

The length and width of spikelets and isolated kernels were determined with the use of the MWM 2325 workshop microscope within an accuracy of 0.02 mm, thickness was measured using a thickness gauge with an indicator within an accuracy of 0.01 mm, and mass was determined with the RADWAG WAA 100/C/2 laboratory weighing scale within an accuracy of 0.1 mg, as described by Kaliniewicz et al. [18].

The angles of static friction of spikelets and kernels on steel (roughness Ra = 0.46 µm) and PVC (roughness Ra = 1.05 µm) were measured to the nearest 1°, on a horizontal plane with an adjustable angle of inclination, according to the method described in [19]. Spikelets and kernels were always placed on the friction plate with the longitudinal axis perpendicular to the direction of movement.

The following parameters were calculated for every spikelet and kernel:

- geometric mean diameter, aspect ratio and sphericity index [20]:

$$D_g = (T \cdot W \cdot L)^{\frac{1}{3}} \tag{1}$$

$$R = \frac{W}{L} \times 100 \tag{2}$$

$$\Phi = \frac{(T \cdot W \cdot L)^{\frac{1}{3}}}{L} \times 100 \tag{3}$$

- mass per unit area [21]:

$$m_D = \frac{m}{D_g}. \tag{4}$$

The results of measurements and calculations were processed statistically in the Statistica v. 13 program with the use of descriptive statistical methods, nonparametric tests, and correlation analysis [22,23]. The Kruskal–Wallis test was performed to determine significant differences between the analyzed parameters when empirical data were not normally distributed. This test is conducted when the analyzed trait does not have normal distribution and does not meet the assumption of homogeneity of variance. All calculations were performed at a significance level of 0.05.

3. Results and Discussion

Three hundred randomly selected spikelets of ancient wheats were analyzed in each batch. A total of 580 spelt kernels, 538 emmer kernels, and 343 einkorn kernels were obtained for further analysis. Spelt and emmer spikelets contained two kernels, whereas einkorn spikelets contained one kernel, which was reflected in the total number of analyzed kernels.

The physical parameters and the calculated indicators of spikelets and isolated kernels are presented in Table 1. The greatest variations were observed in the mass of spikelets and kernels. The coefficient of variation for spikelet mass ranged from 22.67% (einkorn) to 35.13% (emmer), and for kernel mass from 19.35% (einkorn) to 25.29% (emmer). The sphericity index of spikelets was the least varied trait for which the coefficient of variation was determined at 7.89% in spelt, 6.03% in emmer, and 4.86% in einkorn. Spikelet dimensions were determined in the following range of values:

thickness—from 2.06 (einkorn) to 5.58 (einkorn);
width—from 1.91 (spelt) to 7.21 (spelt);
length—from 8.52 (spelt) to 18.48 (spelt).

Table 1. Statistical distribution of the physical properties and the calculated indicators of spikelets and kernels.

Species	Physical Property/Indicator	Spikelets					Kernels				
		x_{min}	x_{max}	X	S	V_s	x_{min}	x_{max}	X	S	V_s
Spelt	T	2.74	5.25	3.72	0.433	11.64	1.47	3.83	2.67	0.272	10.20
	W	1.91	7.21	4.88	0.991	20.30	1.43	4.13	3.16	0.291	9.20
	L	8.52	18.48	11.57	1.675	14.48	2.31	10.54	8.35	0.843	10.10
	m	40.80	193.20	95.29	31.006	32.54	10.10	64.40	42.93	9.336	21.75
	γ_s	8.78	25.00	17.09	2.778	16.25	0.00	28.00	20.07	2.075	10.34
	γ_p	7.68	29.00	16.49	4.168	25.27	0.00	33.00	24.58	2.742	11.16
	D_g	3.90	7.59	5.92	0.738	12.47	2.65	4.89	4.12	0.342	8.29
	R	20.43	59.47	42.27	7.027	16.63	14.27	132.47	38.32	7.388	19.28
	Φ	39.28	62.10	51.40	4.055	7.89	35.04	114.82	49.71	5.471	11.01
	m_D	7.38	27.82	15.89	4.121	25.93	2.94	18.34	10.32	1.701	16.48
Emmer	T	2.12	4.10	3.02	0.354	11.71	0.95	3.00	2.35	0.231	9.82
	W	3.22	6.88	4.64	0.688	14.82	1.10	3.68	2.49	0.322	12.93
	L	8.63	15.99	12.09	1.357	11.23	1.93	11.99	7.29	0.710	9.75
	m	16.40	147.90	63.84	22.426	35.13	2.90	50.20	27.26	6.893	25.29
	γ_s	15.00	34.00	23.81	4.299	18.06	17.00	34.00	23.80	3.039	12.77
	γ_p	19.00	41.00	28.33	4.175	14.74	22.00	37.00	28.61	3.323	11.61
	D_g	4.01	7.61	5.53	0.637	11.52	1.62	4.41	3.49	0.325	9.32
	R	20.59	54.47	38.44	4.212	10.96	18.43	119.69	34.38	5.826	16.95
	Φ	31.89	55.82	45.80	2.760	6.03	32.77	110.74	48.06	4.461	9.28
	m_D	3.49	19.44	11.26	2.915	25.89	1.46	11.67	7.72	1.392	18.04
Einkorn	T	2.06	5.58	2.61	0.285	10.91	1.33	3.37	2.28	0.274	12.04
	W	2.68	5.16	3.82	0.418	10.96	1.63	4.73	3.04	0.409	13.45
	L	9.11	14.82	11.68	0.865	7.41	2.05	10.50	7.45	0.699	9.38
	m	26.90	82.00	47.14	10.685	22.67	11.80	49.60	31.94	6.181	19.35
	γ_s	17.00	33.00	23.97	3.391	14.15	17.00	34.00	24.06	3.585	14.90
	γ_p	19.00	36.00	27.36	3.506	12.81	17.00	34.00	24.02	3.464	14.42
	D_g	4.10	6.12	4.87	0.365	7.50	2.27	4.48	3.71	0.293	7.91
	R	21.07	43.21	32.70	2.753	8.42	21.01	142.93	41.39	9.526	23.01
	Φ	36.35	55.36	41.77	2.029	4.86	38.39	110.97	50.13	5.760	11.49
	m_D	6.46	14.43	9.58	1.477	15.41	4.04	12.86	8.56	1.256	14.67

Kernels were characterized by the lowest variation in terms of width for spelt (9.20%), sphericity index for emmer (9.28%), and geometric mean diameter for einkorn (7.91%), which could be related to the number of kernels per spikelet. Kernel dimensions were determined in the following range of values:

thickness—from 0.95 (emmer) to 3.83 (spelt);
width—from 1.10 (emmer) to 4.13 (spelt);
length—from 1.93 (emmer) to 11.99 (spelt).

The results of linear correlation analysis of the physical properties and the calculated indicators of spikelets and kernels are presented in Tables 2 and 3. The most correlated physical properties were mass and width in spelt and emmer spikelets (0.649 and 0.928, respectively) and length and thickness in einkorn spikelets (0.832). Mass and thickness were the most highly correlated physical parameters in ancient wheat kernels (spelt—0.821; emmer—0.850; einkorn—0.591).

Table 2. Pearson's coefficient of linear correlation between the physical properties and the calculated indicators of ancient wheat spikelets.

Species	Physical Property/Indicator	T	W	L	m	γ_s	γ_p	D_g	R	Φ	m_D
Spelt	T	1.000	0.331	0.343	0.537	−0.367	−0.234	0.635	0.127	0.366	0.370
	W		1.000	0.587	0.649	0.102	0.333	0.884	0.756	0.352	0.421
	L			1.000	0.452	0.097	0.239	0.808	−0.074	−0.453	0.200
	m				1.000	−0.204	−0.081	0.705	0.428	0.291	0.937
	γ_s					1.000	0.595	−0.030	0.040	−0.206	−0.224
	γ_p							0.193	0.205	−0.110	−0.179
	D_g							1.000	0.437	0.150	0.430
	R								1.000	0.803	0.355
	Φ									1.000	0.302
	m_D										1.000
Emmer	T	1.000	0.818	0.704	0.874	−0.266	−0.142	0.922	0.388	0.451	0.817
	W		1.000	0.696	0.928	−0.195	−0.143	0.937	0.650	0.497	0.890
	L			1.000	0.716	−0.185	−0.092	0.864	−0.083	−0.216	0.614
	m				1.000	−0.214	−0.209	0.932	0.527	0.447	0.981
	γ_s					1.000	0.093	−0.234	−0.081	−0.109	−0.198
	γ_p						1.000	−0.138	−0.114	−0.107	−0.233
	D_g							1.000	0.386	0.299	0.863
	R								1.000	0.923	0.588
	Φ									1.000	0.513
	m_D										1.000
Einkorn	T	1.000	0.711	0.832	0.579	−0.160	−0.149	0.920	0.312	0.982	0.435
	W		1.000	0.607	0.320	−0.200	−0.080	0.782	−0.322	0.649	−0.085
	L			1.000	0.337	−0.128	−0.111	0.852	0.360	0.774	0.738
	m				1.000	−0.111	−0.136	0.708	0.609	0.506	0.149
	γ_s					1.000	−0.049	−0.186	0.018	−0.145	0.010
	γ_p						1.000	−0.140	−0.093	−0.149	−0.073
	D_g							1.000	0.337	0.841	0.404
	R								1.000	0.285	0.723
	Φ									1.000	0.417
	m_D										1.000

Table 3. Pearson's coefficients of linear correlation between the physical properties and the calculated indicators of kernels isolated from the spikelets of ancient wheats.

Species	Physical Property/Indicator	T	W	L	m	γ_s	γ_p	D_g	R	Φ	m_D
Spelt	T	1.000	0.665	0.398	0.821	−0.189	−0.050	0.815	0.120	0.270	0.746
	W		1.000	0.438	0.778	−0.109	0.056	0.838	0.239	0.229	0.644
	L			1.000	0.584	0.005	0.126	0.785	−0.663	−0.660	0.367
	m				1.000	−0.102	0.052	0.864	0.061	0.118	0.947
	γ_s					1.000	0.232	−0.114	−0.074	−0.110	−0.085
	γ_p						1.000	0.062	−0.101	−0.128	0.030
	D_g							1.000	−0.206	−0.147	0.670
	R								1.000	0.974	0.248
	Φ									1.000	0.303
	m_D										1.000
Emmer	T	1.000	0.626	0.473	0.850	−0.139	−0.252	0.813	0.184	0.296	0.812
	W		1.000	0.551	0.803	−0.037	−0.082	0.889	0.424	0.274	0.700
	L			1.000	0.617	0.078	−0.136	0.799	−0.400	−0.509	0.469
	m				1.000	−0.044	−0.149	0.896	0.233	0.214	0.966
	γ_s					1.000	0.061	−0.034	−0.095	−0.142	−0.043
	γ_p						1.000	−0.178	0.016	−0.048	−0.180
	D_g							1.000	0.080	0.011	0.773
	R								1.000	0.944	0.326
	Φ									1.000	0.331
	m_D										1.000
Einkorn	T	1.000	0.081	0.179	0.591	−0.104	−0.158	0.601	−0.050	0.245	0.464
	W		1.000	0.195	0.589	−0.066	−0.016	0.708	0.509	0.338	0.403
	L			1.000	0.416	−0.050	−0.082	0.651	−0.621	−0.696	0.165
	m				1.000	−0.103	−0.104	0.797	0.165	0.200	0.917
	γ_s					1.000	0.075	−0.118	0.020	−0.005	−0.075
	γ_p						1.000	−0.120	0.017	−0.022	−0.083
	D_g							1.000	−0.042	−0.030	0.500
	R								1.000	0.930	0.303
	Φ									1.000	0.344
	m_D										1.000

The above relationships may vary because environmental conditions and agronomic practices (climate, location, fertilization, cultivations measures, etc.) during the growing season affect crop yield and quality, including kernel plumpness and the physical properties of seeds (length, width, thickness, and mass). The above factors exert varied effects on the physical properties of seeds [24]. Growing conditions have the greatest effect on average seed length, and a lesser impact on seed thickness and width, which leads to changes in the relationships between the analyzed traits. In the processes of seed cleaning and sorting, impurities cannot always be effectively separated based on only one discriminating trait. In practice, impurities are successively separated with the use of different working elements, based on several traits. Knowledge of the relationships between these traits is needed to determine correlations between two or three selected parameters of seeds, which can be used to estimate the load of the separator's working elements and predict separation efficiency [24]. Correlations exist not only between discriminating traits but also between certain qualitative traits, which supports the separation of the most valuable seeds.

The results of the Kruskal–Wallis test (Tables 4 and 5) revealed significant differences between the mean values of the analyzed traits (Figures 2 and 3) and the calculated indicators in the spikelets and kernels of ancient wheats. Significant differences in spikelet length were not observed between spelt and einkorn, and significant differences in the angle of external friction on PVC were not noted between spelt and emmer. Spelt and emmer kernels did not differ significantly in the angles of external friction on steel, and spelt and einkorn kernels did not differ significantly in the values of the sphericity index.

Table 4. Pearson's coefficient of linear correlation between the physical properties and the calculated indicators of kernels isolated from ancient wheat spikelets.

Thickness *T* (Kruskal–Wallis Test) **H (2, *N* = 900) = 600.1485; *p* = 0.0000**			
	Probability of multiple comparisons		
Species	Spelt R = 719.49	Emmer R = 431.43	Einkorn R = 200.58
Spelt	-	0.000000	0.000000
Emmer	0.000000	-	0.000000
Einkorn	0.000000	0.000000	-
Width *W* (Kruskal–Wallis test) **H (2, *N* = 900) = 251.4257; *p* = 0.0000**			
	Probability of multiple comparisons		
Species	Spelt R = 574.52	Emmer R = 518.03	Einkorn R = 258.95
Spelt	-	0.023366	0.000000
Emmer	0.023366	-	0.000000
Einkorn	0.000000	0.000000	-
Length *L* (Kruskal–Wallis test) **H (2, *N* = 900) = 36.9749; *p* = 0.0000**			
	Probability of multiple comparisons		
Species	Spelt R = 393.92	Emmer R = 520.78	Einkorn R = 436
Spelt	-	0.000000	0.129971
Emmer	0.000000	-	0.000228
Einkorn	0.129971	0.000228	-
Mass *m* (Kruskal–Wallis test) **H (2, *N* = 900) = 391.3057; *p* = 0.0000**			
	Probability of multiple comparisons		
Species	Spelt R = 666.55	Emmer R = 437.68	Einkorn R = 247.28
Spelt	-	0.000000	0.000000
Emmer	0.000000	-	0.000000
Einkorn	0.000000	0.000000	-
Angle of external friction on steel γ_s (Kruskal–Wallis test) **H (2, *N* = 900) = 445.4547; *p* = 0.0000**			
	Probability of multiple comparisons		
Species	Spelt R = 192.68	Emmer R = 567.28	Einkorn R = 591.53
Spelt	-	0.759712	0.000000
Emmer	0.759712	-	0.000000
Einkorn	0.000000	0.000000	-
Angle of external friction on PVC γ_p (Kruskal–Wallis test) **H (2, *N* = 900) = 528.3836; *p* = 0.000**			
	Probability of multiple comparisons		
Species	Spelt R = 170.76	Emmer R = 608.20	Einkorn R = 572.54
Spelt	-	0.000000	0.000000
Emmer	0.000000	-	0.278862
Einkorn	0.000000	0.278862	-
Geometric mean diameter D_g (Kruskal–Wallis test) **H (2, *N* = 900) = 323.1927; *p* = 0.000**			
	Probability of multiple comparisons		
Species	Spelt R = 613.87	Emmer R = 496.80	Einkorn R = 240.82
Spelt	-	0.000000	0.000000
Emmer	0.000000	-	0.000000
Einkorn	0.000000	0.000000	-

Table 4. *Cont.*

Aspect ratio *R* (Kruskal–Wallis test) H (2, *N* = 900) = 399.2394; *p* = 0.000			
Species	Probability of multiple comparisons Spelt R = 625.82	Emmer R = 510.87	Einkorn R = 214.81
Spelt	-	0.000000	0.000000
Emmer	0.000000	-	0.000000
Einkorn	0.000000	0.000000	-
Sphericity index Φ (Kruskal–Wallis test) H (2, *N* = 900) = 584.7465; *p* = 0.000			
Species	Probability of multiple comparisons Spelt R = 702.42	Emmer R = 459.67	Einkorn R = 189.41
Spelt	-	0.000000	0.000000
Emmer	0.000000	-	0.000000
Einkorn	0.000000	0.000000	-
Mass per unit area m_D (Kruskal–Wallis test) H (2, *N* = 900) = 382.2566; *p* = 0.000			
Species	Probability of multiple comparisons Spelt R = 671.41	Emmer R = 420.37	Einkorn R = 259.72
Spelt	-	0.000000	0.000000
Emmer	0.000000	-	0.000000
Einkorn	0.000000	0.000000	-

Table 5. Significance of differences between the mean values of the analyzed physical properties and calculated indicators of kernels isolated from ancient wheat spikelets.

Thickness *T* (Kruskal–Wallis Test) H (2, *N* = 1460) = 495.6762; *p* = 0.0000			
Species	Probability of multiple comparisons Spelt R = 1028.2	Emmer R = 579.38	Einkorn R = 463.66
Spelt	-	0.000000	0.000000
Emmer	0.000000	-	0.000215
Einkorn	0.000000	0.000215	-
Width *W* (Kruskal–Wallis test) H (2, *N* = 1460) = 694.2800; *p* = 0.0000			
Species	Probability of multiple comparisons Spelt R = 993.89	Emmer R = 354.12	Einkorn R = 874.37
Spelt	-	0.000000	0.000095
Emmer	0.000000	-	0.000000
Einkorn	0.000095	0.000000	-
Length *L* (Kruskal–Wallis test) H (2, *N* = 1460) = 615.7204; *p* = 0.0000			
Species	Probability of multiple comparisons Spelt R = 1064.40	Emmer R = 471.03	Einkorn R = 572.04
Spelt	-	0.000000	0.000000
Emmer	0.000000	-	0.001585
Einkorn	0.000000	0.001585	-

Table 5. *Cont.*

Mass m (Kruskal–Wallis test) H (2, N = 1460) = 679.7536; p = 0.0000			
	Probability of multiple comparisons		
Species	Spelt R = 1070.20	Emmer R = 422.31	Einkorn R = 638.61
Spelt	-	0.000000	0.000000
Emmer	0.000000	-	0.000000
Einkorn	0.000000	0.000000	-
Angle of external friction on steel γ_s (Kruskal–Wallis test) H (2, N = 1460) = 512.6743; p = 0.0000			
	Probability of multiple comparisons		
Species	Spelt R = 423.36	Emmer R = 933.78	Einkorn R = 931.53
Spelt	-	1.000000	0.000000
Emmer	1.000000	-	0.000000
Einkorn	0.000000	0.000000	-
Angle of external friction on PVC γ_p (Kruskal–Wallis test) H (2, N = 1460) = 452.0002; p = 0.000			
	Probability of multiple comparisons		
Species	Spelt R = 581.78	Emmer R = 1035.1	Einkorn R = 505.03
Spelt	-	0.000000	0.022579
Emmer	0.000000	-	0.000000
Einkorn	0.022579	0.000000	-
Geometric mean diameter D_g (Kruskal–Wallis test) H (2, N = 1460) = 676.2755; p = 0.000			
	Probability of multiple comparisons		
Species	Spelt R = 1067.8	Emmer R = 419.87	Einkorn R = 646.52
Spelt	-	0.000000	0.000000
Emmer	0.000000	-	0.000000
Einkorn	0.000000	0.000000	-
Aspect ratio R (Kruskal–Wallis test) H (2, N = 1460) = 472.8347; p = 0.000			
	Probability of multiple comparisons		
Species	Spelt R = 830.23	Emmer R = 432.26	Einkorn R = 1028.8
Spelt	-	0.000000	0.000000
Emmer	0.000000	-	0.000000
Einkorn	0.000000	0.000000	-
Sphericity index Φ (Kruskal–Wallis test) H (2, N = 1460) = 123.1843; p = 0.000			
	Probability of multiple comparisons		
Species	Spelt R = 798.30	Emmer R = 573.20	Einkorn R = 862.1
Spelt	-	0.000000	0.078793
Emmer	0.000000	-	0.000000
Einkorn	0.078793	0.000000	-
Mass per unit area m_D (Kruskal–Wallis test) H (2, N = 1460) = 608.0013; p = 0.000			
	Probability of multiple comparisons		
Species	Spelt R = 1052.00	Emmer R = 439.64	Einkorn R = 642.14
Spelt	-	0.000000	0.000000
Emmer	0.000000	-	0.000000
Einkorn	0.000000	0.000000	-

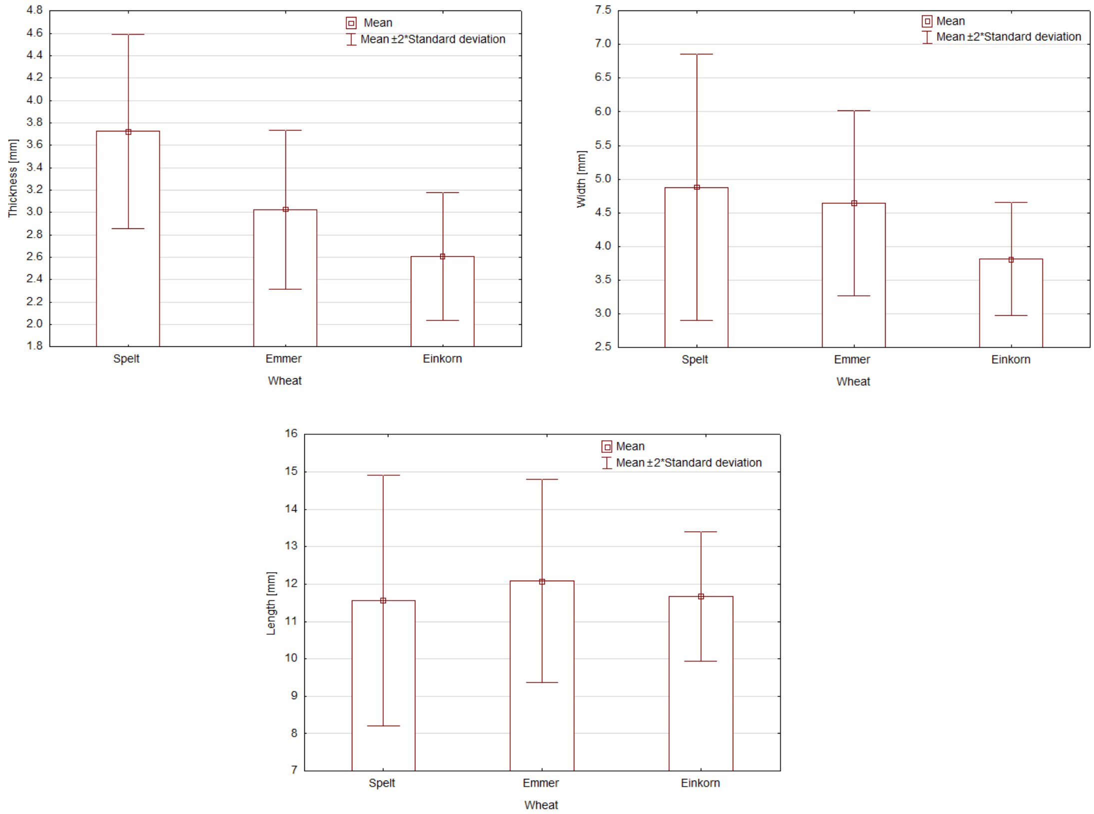

Figure 2. Geometric properties of ancient wheat spikelets.

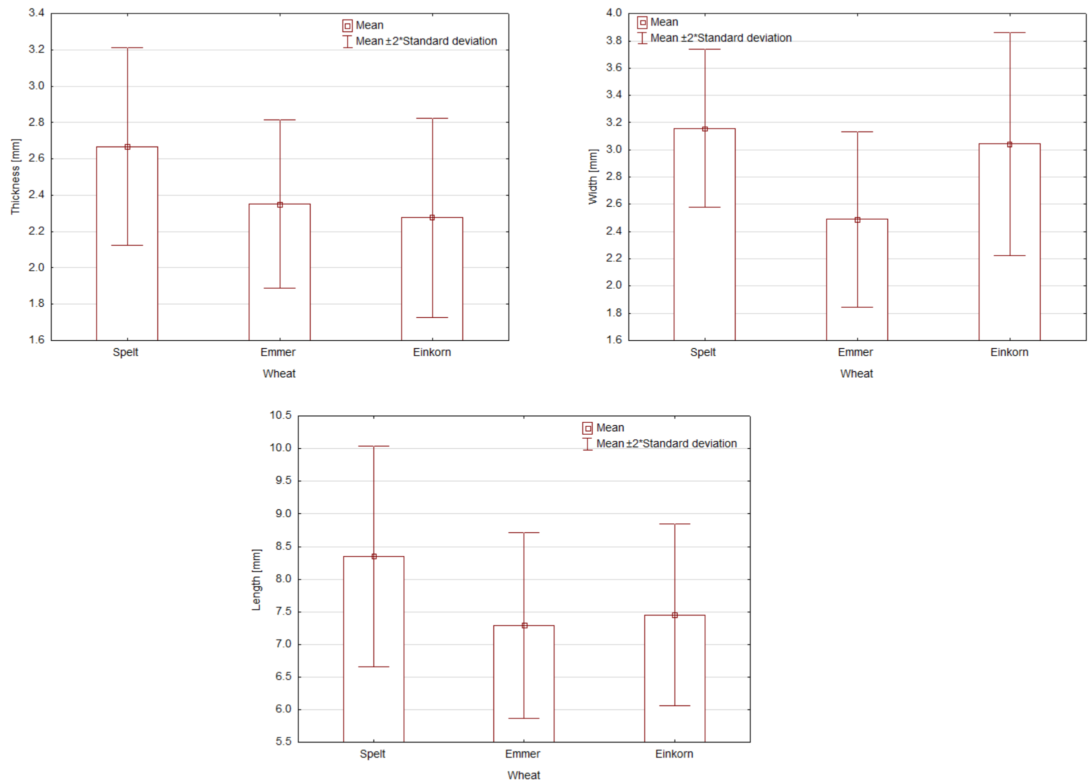

Figure 3. Geometric properties of ancient wheat kernels.

4. Conclusions

1. The kernels and spikelets of ancient wheats are characterized by similar coefficients of variation in the analyzed physical properties, and they differ most considerably in mass.
2. The most correlated physical properties of ancient wheat spikelets were width and mass in spelt and emmer, and length and width in einkorn. Ancient wheat kernels were most highly correlated in terms of mass and thickness. The observed correlations can be used to plan cleaning and sorting operations in ancient wheats.
3. The kernels of ancient wheats are difficult to husk; therefore, further research is required to optimize the threshing process.

Acknowledgments: The study was financed from the funds allocated to scientific research in 2015–2017, grant No. 16.610.001.-300.

Author Contributions: Ewelina Kolankowska and Dariusz Jan Choszcz conceived and designed the experiments; Ewelina Kolankowska performed the experiments; Ewelina Kolankowska, Dariusz Jan Choszcz and Piotr Markowski contributed to the literature study; Ewelina Kolankowska, Dariusz Jan Choszcz and Piotr Markowski analyzed the data; Ewelina Kolankowska, Dariusz Jan Choszcz and Piotr Markowski wrote the paper; Dariusz Jan Choszcz and Piotr Markowski critically revised it.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

D_g	geometric mean diameter, (mm)
m	mass, (mg)
m_D	mass per unit area, (g·m^{-1})
R	aspect ratio, (%)
S	standard deviation of a trait,
T, W, L	thickness, width, length, (mm)
V_s	coefficient of variation of a trait, (%)
X, x_{max}, x_{min}	mean, maximum and minimum value of a trait,
γ_s	angle of external friction on steel, (°)
γ_p	angle of external friction on PVC, (°)
Φ	sphericity index, (%)

References

1. Pająkowski, J. Przywracanie do uprawy starych gatunków zbóż nad Doliną Wisły. *Zesz. Probl. Postep. Nauk Roln.* **2004**, *497*, 105–109.
2. Pałys, E.; Łabuda, S. Yieldingand elemental composition of spelt wheat grain and straw. *Rachis Barley Wheat Newslett.* **1997**, *16*, 67–70.
3. Pałys, E.; Kuraszkiewicz, R. Wpływ terminów siewu na wybrane cechy i plon ziarna orkiszu (*Triticum aestiwm* ssp. *spelta*). *Biul. IHAR* **2003**, *228*, 71–80.
4. Bavec, F.; Rantasa, J.; Mlakar, S.; Grobelnik, J.M.; Bavec, M. Yield performance in spelt regarding to hulled and dehulled seeds sown at different rates and dates. *Bibl. Fragm. Agron.* **2006**, *11*, 43–44.
5. Lacko-Bartosova, M.; Redlova, M. The significance of spelt wheat cultivated in ecological forming in the Slovak Republic. In Proceedings of the Conference "Organic Farming 2007", Prague, Czech Republic, 6–7 February 2007.
6. Moudry, J.; Konvalina, P.; Stehno, Z.; Capouchova, I.; Moudry, J., Jr. Ancient wheat species can extend biodiversity of cultivated crops. *Sci. Res. Essays* **2011**, *6*, 4273–4280.
7. Bavec, F.; Bavec, M. *Organic Production and Use of Alternative Crops*; CRC/Taylor & Francis: Boca Raton, FL, USA, 2007.
8. Lampi, A.M.; Nurmi, T.; Ollilainen, V.; Piironen, V. Tocopherols and tocotrienols in wheat genotypes in the HEALTHGRAIN diversity screen. *J. Agric. Food Chem.* **2008**, *21*, 9716–9721. [CrossRef] [PubMed]

9. Li, L.; Shewry, P.R.; Ward, J.L. Phenolic acids in wheat varieties in the HEALTHGRAIN diversity screen. *J. Agric. Food Chem.* **2008**, *21*, 9732–9739. [CrossRef] [PubMed]
10. Nurmi, T.; Nystrom, L.; Edelmann, M.; Lampi, A.M.; Piironen, V. Phylosterols in wheat genotypes in the HEALTHGRAIN diversity screen. *J. Agric. Food Chem.* **2008**, *21*, 9710–9715. [CrossRef] [PubMed]
11. Piironen, V.; Edelmann, M.; Kariluoto, S.; Bedo, Z. Folate in wheat genotypes in the HEALTHGRAIN diversity screen. *J. Agric. Food Chem.* **2008**, *21*, 9726–9731. [CrossRef] [PubMed]
12. Serpen, A.; Gokmen, V.; Karagoz, A.; Koksel, H. Phytochemical quantification and total antioxidant capacities of emmer (*Triticum dicoccum* Schränk) and einkorn (*Trittcum momcoccum* L.) wheat landraces. *J. Agric. Food Chem.* **2008**, *16*, 7285–7292. [CrossRef] [PubMed]
13. Suchowilska, E.; Wiwart, M.; Borejszo, Z.; Packa, D.; Kandler, W.; Krska, R. Discriminant analysis of selected yield components and fatty acid composition of chosen *Trittcum monococcum*, *Trittcum dicoccum* and *Trittcum spelta* accessions. *J. Cereal Sci.* **2009**, *2*, 310–315. [CrossRef]
14. Babalski, M.; Przybylak, Z.; Przybylak, K. *Uzdrawiające Ziarna Zbóż*; Eko Media: Bydgoszcz, Poland, 2013; ISBN 9788363537128.
15. Tyburski, J.; Babalski, M. *Uprawa Pszenicy Orkisz*; CDR: Radom, Poland, 2006; ISBN 83-601S5-26-3.
16. Choszcz, D.J.; Konopka, S.; Zalewska, K. Characteristics of physical properties of selected varieties of spelt. *Inżynieria Rol.* **2010**, *4*, 23–28.
17. Greń, J. *Statystyka Matematyczna Modele i Zadania*; PWN: Warszawa, Poland, 1984; ISBN 8301036990.
18. Kaliniewicz, Z.; Markowski, P.; Anders, A.; Rawa, T.; Liszewski, A.; Fura, S. Correlations between the germination capacity and selected attributes of European larch seeds (*Larix deciduas* Mill). *Tech. Sci.* **2012**, *15*, 229–242.
19. Konopka, S. Studiem on the choice of material used for making bars of a cylindrical slotted sieve. *Tech. Sci.* **2000**, *3*, 25–32.
20. Mohsenin, N.N. *Physical Properties of Plant and Animal Materials*; Gordon and Breach Science Public: New York, NY, USA, 1986.
21. Kaliniewicz, Z. Analysis of frictional properties of cereal seeds. *Afr. J. Agric. Res.* **2013**, *8*, 5611–5621.
22. Rabiej, M. *Statystyka z Programem Statistica [Statisctics in Statistica Software]*; Helion: Gliwice, Poland, 2012; ISBN 9788324641109. (In Polish)
23. Stanisz, A. *Przystępny Kurs Statystyki w Oparciu o Program STATISTICA PL na Przykładach z Medycyny. Tom 1. Statystyki Podstawowe*; StatSoft Polska: Kraków, Poland, 2007.
24. Grochowicz, J. *Maszyny Do Czyszczenia i Sortowania Nasion*; Państwowe Wydawnictwo Rolnicze i Leśne: Warszawa, Poland, 1971.