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Article

Influence of Steel Plate Roughness on the Frictional Properties of Cereal Kernels

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Abstract: The aim of this study was to determine the correlation between the external friction angle of cereal kernels and the roughness of a steel friction plate. The experiment was performed on the kernels of five principal cereals: wheat, rye, barley, oats and triticale. Flat seed units composed of three spaced kernels joined by adhesive tape were analyzed in each experimental variant. The external friction angle of flat seed units was determined on 9 steel friction plates with different roughness. Measurements were performed in 3 replications with a photosensor device which registered the external friction angle of cereal kernels. On friction plates with surface roughness Ra=0.36 to Ra=6.72, the average values of the angle of external friction ranged from 17.56° in rye kernels to 34.01° in oat kernels. The greatest similarities in the angle of external friction were observed between wheat and triticale kernels, whereas the greatest differences were noted between barley and oat kernels and between barley and triticale kernels. Friction plates made of ST3S steel should be characterized by the lowest surface roughness to minimize energy consumption during grain processing. The optimal surface roughness of steel friction plates was determined at Ra=0.9.

Keywords: cereal kernels; steel; surface roughness; angle of external friction

1. Introduction

Cereals are a group of flowering grasses of the family *Poaceae.* The fruit of grasses are kernels which are characterized by high starch content and are used in the production of foodstuffs and feedstuffs and in industrial processing. The main cereal-derived foods are flour, grits, oil and syrup. Cereals play vital roles in many industries, including milling, distilling, brewing and pharmaceutical processing. Cereal processing requires a thorough knowledge of the physical properties of seeds/kernels, including frictional properties which influence seed transport, proportioning, mixing, compaction and processing [1-4].

Friction is generally defined as a combination of phenomena that occur at the point of contact between two physical objects and result from the mutual movement of contacting surfaces. Friction causes moving objects to lose their energy, and their surfaces are deformed at the point of contact. In solids, surface deformation is caused mainly by the formation of grooves and abrasion [2,3]. Friction is difficult to explain, and several theories have been proposed to describe this phenomenon with varying degrees of precision. Three groups of theories have been postulated: mechanical, molecular and mechanical/molecular. According to the most advanced theories, friction is a phenomenon with a dual mechanical and molecular nature [1-3,5]. The most recent theory of friction has been developed by Frączek [1] who postulated that friction force has three components: deformation, adhesion and cohesion. According to Frączek, the deformation component is linked with changes in the shape of surface asperities that tug each other. Deformation is directly proportional to the applied load, and it is determined by surface roughness and elasticity of the materials that form a friction pair and by the moisture content of plant materials. The adhesion component accounts for

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the contact between the surface layers of two physical objects, and its value is determined by sliding velocity, duration of frictional contact and surface microhardness of plant material. Adhesion is a power function of load. The cohesion component is related to the mutual attraction between the molecules of a friction pair. It is determined by the real area of contact and the microhardness of plant material. Therefore, the proposed theory accounts for deformations caused by tugging between surface asperities, forces of attraction and cohesion between the surfaces that come into contact. External friction is influenced by the properties of materials that form a friction pair, in particular the ratio of roughness densities of two surfaces, the ratio of roughness of two surfaces, the ratio of elastic moduli, and the product of real contact area and seed hardness. Similar explanations of friction phenomena have been proposed by Horabik [6], Molenda and Horabik [7], Afzalinia and Roberge [3] and Bakun-Mazor et al. [8].

According to the literature [1,3,5,6,8,9-11], the frictional properties of seeds are determined by the parameters of the friction surface (type, roughness), frictional conditions (normal load, sliding distance, sliding velocity, seed orientation relative to the direction of movement), seed properties (moisture content, species, variety, ripeness, variations in shape) and external conditions (temperature and humidity).

Molenda et al. [5], Frączek [1] and Horabik [6] observed that the geometric structure of a surface and the roughness of biological materials influence the frictional properties of seeds. Despite the above, most researchers indicate only the type of structural materials, such as concrete, steel or wood, without describing their manufacturing precision. For this reason, published data should be interpreted with caution because they do not account for differences in surface smoothness which influence adhesion.

The aim of this study was to determine the correlation between the external friction angle of the kernels of five cereal species and the roughness of a steel friction plate, and to generate data for grain processing models.

2. Materials and Methods

2.1. Sample preparation

The experiment was performed on the kernels of the five principal cereal species: wheat cv. *Batuta*, rye cv. *Dańkowskie Diament*, barley cv. *Rataj*, oat cv. *Bingo* and triticale cv. *Berenika*. Grain was harvested in the Region of Warmia and Mazury in northern Poland. The kernels of every cereal species were separated from the threshed mass, harvested in 2016 with a combined harvester. The obtained grain was stored in a closed container at room temperature for around 5 months. The relative moisture content of stored grain was determined on a drying scale with a MAX 5-/WH halogen lamp (Radwag Radom, Poland). The analyzed parameter was similar across the analyzed cereal species in the range of 9.5% to 10.2%.

Fifty kernels of every tested cereal species were selected by the survey sampling method [12], and their physical properties (basic dimensions and mass) were determined. Fifty flat seed units (Figure 1) were prepared for every experimental variant (9 friction plates). Every flat seed unit was composed of three spaced kernels that were placed on the friction plate with the crease down and joined with adhesive tape.

2.2. Physical properties

Kernel length *L* and kernel width *W* were determined with the use of the MWM 2325 workshop microscope (PZO Warszawa, Poland) to the nearest 0.02 mm (one measurement consisted of two readouts from a thickness gauge with 0.01 mm resolution). Kernel thickness *T* was measured with a device comprising a dial indicator (MasterTools, Kraków, Poland) with 0.01 mm resolution. The above measurements were performed according to the method described by Kaliniewicz et al. [13]. Kernel mass was determined on the WAA 100/C/2 weighing scale (Radwag Radom, Polska) to the nearest 0.1 mg.

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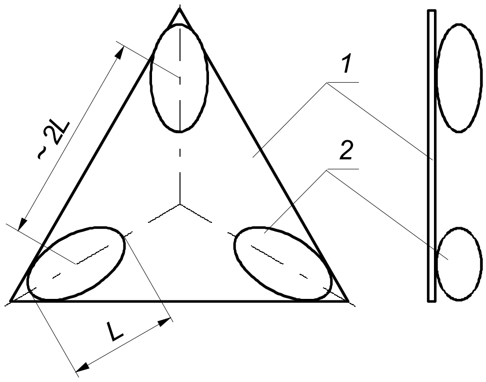

Figure 1. Diagram of an "ideally flat seed unit" [14]: 1 – adhesive tape; 2 – kernel; *L* – kernel length.

The dimensions of cereal kernels were used to determine the following parameters:

- geometric mean diameter *D*, aspect ratio *R* and sphericity index *Φ* [15]:

$$D = (T \times W \times L)^{1/3} \tag{1}$$

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

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

- density ρ (on the assumption that kernel shape resembles an ellipsoid):

$$\rho = \frac{6 \times m}{\pi \times T \times W \times L} \tag{4}$$

Flat seed units were used to measure the angle of external friction α of cereal kernels. The measurements were performed with a device equipped with photodetectors (Figure 2) [11,16]. Friction plates made of ST3S steel were fixed to an adjustable arm of the above device. The geometrical product specifications (GPS) of friction plates were measured with the Diavite DH-5 (Bülach, Switzerland) surface roughness tester. The results of the measurements are presented in Table 1. Flat seed units were placed on a horizontally inclined plate, just above the light level of the top photodetector. The adjustable arm was lifted with constant angular velocity of $1.25°\cdot s^{-1}$. When kernel motion was initiated, the light beam was interrupted and the arm was automatically paused. The angle of inclination was measured to the nearest 0.01°. Every flat seed unit was measured in 3 replications, and the results were used to calculate the average values. After the angle of external friction had been measured in 5 successive flat seed units, the plate was wiped with cotton wool saturated with petroleum ether (Chempur Piekary Śląskie, Polska) to remove cutin.

2.3. Statistical analysis

The measured angles of external friction were processed in Statistica PL v. 12.5 at a significance level of α=0.05. The differences between the measured angles of external friction were determined by one-way analysis of variance (ANOVA). The normality of each group was verified by the Shapiro-Wilk test, and the equality of variances was assessed with Levene's test. Where the null hypothesis postulating equal average values of external friction angles was rejected, the significance of differences were determined and homogenous groups were identified with the use of Duncan's test [17](Rabiej, 2012).

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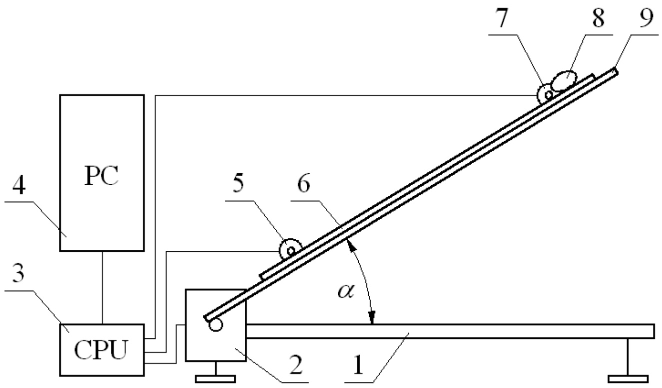

Figure 2. Device for measuring the frictional properties of cereal kernels [11]: 1 – base of inclined plane, 2 – stepper motor, 3 – CPU controller, 4 – computer, 5 – bottom phototube, 6 – friction plate, 7 – top phototube, 8 – kernel, 9 – adjustable arm.

Table 1. Structural parameters of steel friction plates.

Plate	Roughness parameters (μm)					
	Ra	*Rz*	*R*max	*R3z*	*Rt*	*Rq*
1	0.36	2.8	4.1	2.0	4.2	0.49
2	0.47	3.2	4.2	2.6	4.4	0.61
3	0.90	4.6	6.5	3.9	6.5	1.10
4	1.28	6.9	9.1	5.4	11.3	1.62
5	2.45	15.4	18.3	11.7	18.4	3.28
6	3.70	22.7	29.1	17.0	29.1	4.90
7	4.78	23.6	36.8	19.3	39.1	6.48
8	5.66	27.4	37.8	23.2	40.8	7.38
9	6.72	36.9	53.9	29.2	53.9	9.11

Ra – arithmetical mean deviation of a profile, *Rz* – height of peaks at 10 points along a profile, *R*max –maximum peak height, *R3z* – average roughness profile along 5 successive sampling lengths, *Rt* – total profile height (between the highest peak and the lowest valley), *Rq* – root mean square of profile deviations.

3. Results

3.1. Experimental material

The physical parameters of kernels of the evaluated cereal species are presented in Table 2. The standard error of the mean did not exceed 0.3 mm in basic dimensions and 3 mg in mass. Average thickness was identical in wheat, barley and triticale kernels, and it was similar in rye and oat kernels. Barley kernels were characterized by the greatest average width, and rye kernels – by the smallest average width. The above results contributed to similar ratios between the mass and geometric mean diameter of kernels in these cereal species. Wheat kernels were shortest, and oat kernels were longest. As a result, wheat and oat kernels were also characterized by extreme average values of the aspect ratio and the sphericity index. The kernels of the analyzed cereal species were arranged in the following descending order based on their average density: wheat, triticale, rye, barley and oats.

3.2. Angle of external friction

The angle of external friction of the evaluated cereal kernels (Table 3) ranged from 13.71° in rye to 44.92° in oats. The average angle of external friction ranged from 17.56° (rye kernels on a steel plate with surface roughness *Ra*=0.90 μm) to 34.01° (oat kernels on a steel plate with surface roughness *Ra*=6.72 μm). The standard error of the mean did not exceed 1.3°. The above results indicate that the angle of external friction is largely determined by the surface roughness of the steel plate. With the exception of wheat, the smallest angle of external friction was noted on a steel plate

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with surface roughness *Ra*=0.90 μm. The difference between the largest and the smallest angle of external friction of cereal kernels on the evaluated steel plates ranged from 11.35° (barley) to 15.55° (rye). The differences in the average angles of external friction on the same steel plate were not significant. Similar observations were made in the analysis of variance which supported the identification of homogeneous groups of external friction angles and where significant differences in the evaluated parameter were not noted between cereal species on any of the tested steel plates. Subject to plate roughness, the difference between the largest and the smallest angle of external friction ranged from 1.22° (steel plate with surface roughness *Ra*=0.36 μm) to 5.46° (steel plate with surface roughness *Ra*=6.72 μm).

Table 2. Physical parameters of kernels of the evaluated cereal species (mean value ± standard deviation).

Physical parameter[a]	Cereal species				
	Wheat $x \pm SD$	**Rye** $x \pm SD$	**Barley** $x \pm SD$	**Oats** $x \pm SD$	**Triticale** $x \pm SD$
Moisture (% dry basis)	9.5 ± 0.02	9.7 ± 0.02	10.2 ± 0.03	9.9 ± 0.03	9.7 ± 0.02
Thickness (mm)	3.1 ± 0.16	2.6 ± 0.17	3.1 ± 0.14	2.7 ± 0.16	3.1 ± 0.21
Width (mm)	3.6 ± 0.23	2.8 ± 0.22	3.9 ± 0.16	3.3 ± 0.21	3.3 ± 0.22
Length (mm)	6.7 ± 0.30	7.9 ± 0.41	9.3 ± 0.47	11.5 ± 0.91	8.3 ± 0.39
Mass (mg)	52.0 ± 6.66	35.8 ± 4.52	58.3 ± 7.16	51.6 ± 9.35	53.2 ± 8.52
Geom. mean diam. (mm)	4.2 ± 0.17	3.9 ± 0.19	4.8 ± 0.16	4.7 ± 0.23	4.4 ± 0.21
Aspect ratio (%)	53.4 ± 2.92	35.0 ± 3.07	41.8 ± 2.40	29.1 ± 2.38	40.3 ± 2.62
Sphericity index (%)	62.6 ± 1.69	48.9 ± 2.43	51.9 ± 2.07	40.9 ± 2.00	53.1 ± 2.26
Density (g cm^{-3})	1.34 ± 0.05	1.19 ± 0.08	0.99 ± 0.06	0.96 ± 0.19	1.21 ± 0.11

[a] Moisture values are based on three replications. The remaining parameters are based on 50 replications.

Table 3. Distribution of external friction angles of cereal kernels and significant differences between the angles.

Cereal species	Roughness parameter *Ra* (μm)	Angle of external friction (°)				
		Value of parameter			Standard deviation of trait	Coefficient of variation (%)
		minimum	maximum	average		
Wheat	0.36	17.58	21.06	18.99^{aA}	0.78	4.12
	0.47	19.64	28.67	22.97^{bC}	2.06	8.97
	0.90	17.02	25.08	19.65^{aC}	1.57	8.01
	1.28	18.11	28.33	22.55^{bBC}	2.00	8.85
	2.45	21.69	35.04	25.38^{cB}	2.20	8.66
	3.70	26.98	41.86	31.50^{eB}	3.36	10.67
	4.78	24.62	34.67	28.42^{dBC}	2.86	10.07
	5.66	26.33	43.65	32.67^{fC}	4.04	12.36
	6.72	25.52	41.01	32.52^{efBC}	3.20	9.85
Rye	0.36	16.82	22.46	19.52^{bB}	1.08	5.55
	0.47	17.54	30.43	22.33^{dC}	2.05	9.20
	0.90	13.71	20.26	17.56^{aA}	1.35	7.67
	1.28	16.38	26.47	20.61^{cA}	1.94	9.41
	2.45	21.55	31.04	25.63^{eB}	1.93	7.51
	3.70	24.62	38.69	30.79^{fB}	3.52	11.42
	4.78	25.57	41.05	31.01^{fD}	2.93	9.45
	5.66	23.01	36.61	30.79^{fAB}	2.91	9.43
	6.72	27.86	44.53	33.11^{gCD}	3.14	9.49

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Table 3. Distribution of external friction angles of cereal kernels and significant differences between the angles – cont.

Cereal species	Roughness parameter *Ra* (μm)	Angle of external friction (°)				
		Value of parameter			Standard deviation of trait	Coefficient of variation (%)
		minimum	maximum	average		
Barley	0.36	18.31	22.72	20.21^{bC}	1.01	5.02
	0.47	15.66	24.02	20.31^{bA}	1.65	8.14
	0.90	14.36	24.63	18.80^{aB}	2.00	10.66
	1.28	16.68	29.32	22.12^{cB}	3.13	14.19
	2.45	22.23	34.44	26.12^{dB}	2.63	10.07
	3.70	22.48	35.10	28.00^{eA}	3.28	11.69
	4.78	19.41	33.07	26.06^{dA}	3.07	11.79
	5.66	23.35	38.05	30.15^{fA}	3.24	10.73
	6.72	24.64	33.54	28.55^{eA}	2.83	9.90
Oats	0.36	16.47	21.14	18.99^{bA}	1.00	5.29
	0.47	17.64	26.11	21.18^{cB}	1.83	8.62
	0.90	15.05	20.47	17.71^{aA}	1.24	7.02
	1.28	18.53	29.73	23.42^{dC}	2.48	10.58
	2.45	20.32	32.68	24.13^{dA}	2.53	10.49
	3.70	26.00	41.13	30.46^{fB}	3.66	12.01
	4.78	22.59	36.30	29.53^{eC}	3.32	11.34
	5.66	24.61	44.92	31.73^{gBC}	4.37	13.78
	6.72	25.75	42.63	34.01^{hD}	4.49	13.21
Triticale	0.36	17.29	22.35	19.09^{aA}	0.87	4.58
	0.47	19.03	27.22	22.35^{cC}	1.78	7.98
	0.90	15.55	23.20	18.15^{aA}	1.47	8.08
	1.28	16.61	25.33	20.29^{bA}	2.20	10.84
	2.45	18.39	29.85	23.55^{dA}	2.33	9.89
	3.70	24.57	41.36	30.83^{fB}	3.90	12.65
	4.78	24.28	37.10	27.84^{eB}	2.54	9.12
	5.66	27.06	43.43	32.18^{gBC}	3.55	11.02
	6.72	27.14	39.98	31.22^{fgB}	3.20	10.24

a, b, c, d, e, f, g, h – different letters denote significant differences in the average values of the angle of external friction of same-species grain on the tested friction plates; A, B, C, D – different letters denote significant differences in the average values of the angle of external friction of cereal kernels on the same friction plate.

3.3. Correlation between plate roughness and the angle of external friction of cereal kernels

Due to the similarities in the frictional properties of cereal kernels, one homogeneous group was created for further analyses. The changes in the external friction angle of kernels tested on plates with various surface roughness are presented in Figure 3. In general, the average angle of external friction increased with a rise in parameter *Ra* within the adopted range of plate roughness values. The above function cannot be described with a simple equation because the angle of external friction increased or decreased relative to the general change trend in selected points. Such characteristic points were the average values of the external friction angle on steel plates with surface roughness *Ra*=0.47 (21.83°), *Ra*=0.9 (18.37°), *Ra*=3.7 (30.32°) and *Ra*=4.78 (28.52°). The smallest variations in the values of external friction angles were observed on a steel plate with surface roughness *Ra*=0.36, and the greatest variations were noted on a plate with surface roughness *Ra*=5.66.

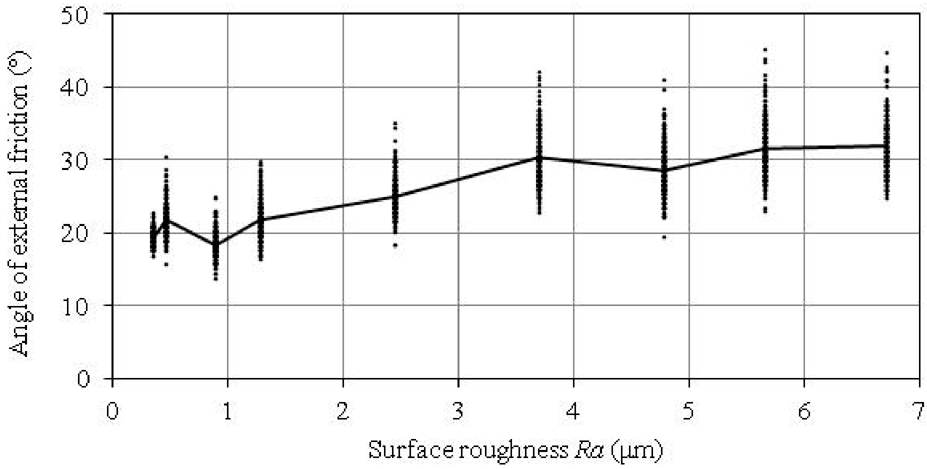

Figure 3. Relationship between the angle of external friction of cereal kernels and surface roughness of a friction plate.

4. Discussion

The dimensions and mass of kernels of the analyzed cereal species did not differ significantly from the values given in the literature [18-21]. The kernels of wheat cv. *Batuta* resembled the kernels of wheat cv. *Boroudeur* [22], *Korweta* [18], *Pehlivan* [23], *Baekjoong* and *Keumkang* [21]. In terms of physical properties, the kernels of rye cv. *Dańkowskie Diament* were similar to the kernels of rye cv. *Dańkowskie Złote* [18], and the kernels of barley cv. *Rataj* – to the kernels of barley cv. *Tiffany* [19].

The range of variations in the external friction angle of cereal seeds on steel plates with different surface roughness overlapped, and no single cereal species differed from the others in this respect. The highest number of minimal values of the external friction angle was noted in rye kernels (on 5 steel plates), and the highest number of maximal values – in wheat kernels (on 4 steel plates). The range of variations in the above parameter (17.56° to 34.01°) and the corresponding range of values of external friction coefficients (0.316 to 0.675) are similar to the values given in the literature [5,11,20,24-27].

The roughness of a friction plate significantly determines the external friction angle of seeds. In general, the angle of external friction increases with a rise in plate roughness, which is partially consistent with the theory postulated by Frączek [1]. According to the cited author, structural materials are generally much harder than biological materials; therefore, their surface asperities are not deformed within a short period of time. When a friction plate comes into contact with cereal kernels, the asperities on plate surface are embedded into kernel surface and surface grooves are produced. Microprotrusions on plate surface produce “scratches”, cut asperity peaks and chisel out fragments of biological material. Therefore, an increase in plate roughness increases the deformation component of the friction force, which increases the angle of external friction. If the remaining components of the friction force were constant values, the angle of external friction would be a linear function of plate roughness. In this experiment, a linear function was not observed because the friction force is also influenced by adhesion and cohesion components. According to many authors [1,5,6,28], adhesion has the greatest influence on friction. Surface asperities in cereal kernels and structural materials can move the kernel’s center of gravity towards or away from the friction plate, which increases or decreases cohesion, respectively. The degree of fit between asperities on the surface of two materials changes the real contact area between a seed and a friction plate, which also influences adhesion. The synergistic effects between surface asperities can be observed when plate roughness is *Ra*=0.47 and *Ra*=3.70, and the external friction angle of cereal seeds increases steeply at these points (Figure 3). Differences in the surface asperities of a friction plate and a seed are particularly manifested when plate roughness is *Ra*=0,90, and they are less pronounced when plate roughness is *Ra*=4.78. The average value of the external friction angle decreases in the above points.

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According to Frączek [1], surface asperities in cereal kernels are determined not only by species, but also by cultivar, and kernels with various surface roughness can be encountered within the same cultivar. The above observation could explain the differences in the external friction angles of cereal kernels on various steel plates. In this study, the coefficient of external friction on steel plates ranged from 4.12% to 14.19%, and the corresponding ranges of values on the tested plates overlapped.

5. Conclusions

The results of this study indicate that the angle of external friction of cereal kernels is significantly influenced by the roughness of the friction plate. In the tested range of plate roughness values, the angle of external friction ranges from 17.56° in rye kernels to 34.01° in oat kernels. In most cases, the external friction angle is smallest on a plate with surface roughness *Ra*=0.90, and largest on a plate with surface roughness *Ra*=5.66. The difference between the largest and smallest angle of external friction on a given plate ranges from 3.48° to 20.31°.

Wheat kernels are most similar and barley kernels are least similar to other cereal species in terms of their external friction angles. The above indicates that wheat kernels constitute good reference material for describing the frictional properties of cereal grain. Wheat and triticale kernels are most similar in terms of their angles of external friction (absence of significant differences in 7 out of 9 cases). Significant differences in the analyzed parameter were noted between barley and oat kernels, and between barley and triticale kernels on each friction plate.

The surfaces that come into direct contact with cereal kernels should be made of carefully selected structural materials, and they should be characterized by high manufacturing precision to reduce energy consumption during grain processing. Friction plates made of ST3S steel should be characterized by the lowest possible surface roughness. The external friction angle of cereal kernels relative to the general change trend decreases visibly on a steel plate with roughness *Ra=0.9*

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

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