Selected Physical and Mechanical Properties of Hemp Seeds

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The basic physical properties of hemp seeds were measured to determine the correlations between these properties to facilitate the planning of seed sorting operations. The basic dimensions (length, width, and thickness), terminal velocity, angle of external friction, and mass were determined in the selected seeds. The seeds were subjected to a uniaxial compressive strength test to determine the force required to damage a seed, the corresponding displacement, and the energy consumed during the trial. The seed sorting was based on the basic dimensions of the seeds in order to divide the seeds into groups with similar average mass. The hemp seeds were most effectively sorted with the use of a screen with slotted apertures. The optimal set of screens should separate approximately 11% to 24% of the seeds into a fraction with the lowest seed thickness, and approximately 16% to 21% of the seeds into a fraction with the highest seed thickness. The basic seed dimensions significantly influenced the specific mass of the individual hemp seeds, and the corresponding correlations are most effectively described by power functions.

Keywords: Cannabis sativa L.; Properties; Size; Range of variation; Correlations; Planning sorting processes

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INTRODUCTION

Cannabis (*Cannabis sativa* L.) has earned a negative reputation on account of the hallucinogenic properties of one of its botanical varieties, *Cannabis sativa* L. var. *indica*. It is legal to grow industrial hemp (*Cannabis sativa* L. var. *sativa*) as long as the total content of Δ9 tetrahydrocannabinol (THC) and tetrahydrocannabinolic acid in the flowers and the achenes (with resin) does not exceed roughly 0.2% to 0.3% on a dry matter basis (Kaniewski *et al*. 2017; Campbell *et al*. 2019; Popa *et al*. 2019). Cannabis is a valuable raw material for the textile, food processing, chemical, cellulose, pharmaceutical, and cosmetic industries, and to produce construction materials and propagating material (Amaducci *et al*. 2015; Salentijn *et al*. 2015; Andre *et al*. 2016; Schluttenhofer and Yuan 2017). Cannabis is an annual, monoecious, or dioecious, wind-pollinated plant (Deleuran and Flengmark 2005; Galasso *et al*. 2016; Baldini *et al*. 2018; Campbell *et al*. 2019). The monoecious varieties are commonly grown for industrial processing on account of their uniform flowering cycle (Kaniewski *et al*. 2017; Popa *et al*. 2019). The monoecious varieties of cannabis are characterized by a short growing season and rapid growth. They can reach 4 meters in height and can be cultivated on most soil types with enough moisture content (Salentijn *et al*. 2015; Kaniewski *et al*. 2017; Baldini *et al*. 2018). The monoecious cannabis species have a high transpiration rate, so field crops should be irrigated in dry summer months. Cannabis thrives in moderate climates, and it can retard the growth of selected weeds (Amaducci *et al*. 2015; Kaniewski *et al*. 2017).

Industrial hemp improves soil fertility, removes and stabilizes contaminants in soil, and it can be grown in former mining and metallurgy sites to purify contaminated soils (Kaniewski *et al*. 2017). Industrial hemp is cultivated primarily to produce textiles, cellulose, and composite materials. Hemp fabrics have hygroscopic properties, a smooth structure, they dry easily, they do not accumulate static electricity, and they are hypo-allergenic and non-irritating to the skin (Cassano *et al*. 2013; Hao *et al*. 2014; Schluttenhofer and Yuan 2017).

Cannabis achenes are also a valuable industrial resource. They are composed of approximately 20% to 25% protein and 28% to 35% oil that is abundant in unsaturated fatty acids. Cannabis achenes also contain phytic acid, choline, trigonelline, lecithin, chlorophyll, vitamins B, C, E, and K, tocopherols, iron, calcium, zinc, phosphorus, potassium, and magnesium (Latif and Anwar 2009; Baldini *et al*. 2018). Hemp seed oil is also a rich source of nutrients, and it is widely used in the food, pharmaceutical, and cosmetic industries (Schluttenhofer and Yuan 2017; Kurek-Górecka *et al*. 2018).

A thorough knowledge of the physical and mechanical properties of seeds is required to plan and perform seed processing operations (Boac *et al*. 2010; Sologubik *et al*. 2013). The structure and operating parameters of processing machines are largely determined by the seed properties. Based on the evaluated properties, seeds are classified by those that are the most suitable for industrial processing and the production of propagating material, food, or feed. Only certified seeds that have been graded based on their size should be planted to guarantee uniform field emergence and uniform stands, which are easier to cultivate and harvest (Chaisurisri *et al*. 1994; Kaliniewicz and Tylek 2019). According to many authors (Norden *et al*. 2009; Nik *et al*. 2011; Sulewska *et al*. 2014), the seed mass has a high correlation to the germination and establishment success, although the larger seeds do not always germinate faster than the smaller seeds. The seed mass is also an important consideration during the oil production. According to Galasso *et al*. (2016), the seed mass significantly influences the content of α-linolenic acid, the proteins, and the antioxidant properties of seeds. These observations suggest that seeds should be sorted based on their mass, so that the resulting seed fractions can be processed separately or used for different purposes. However, sorting processes based on seed mass are difficult to implement in industrial practice due to considerable variations in seed size and mass. For this reason, other physical parameters that are significantly correlated with the seed mass are used in sorting and cleaning operations (Kaliniewicz *et al*. 2016b, 2019; Kaliniewicz and Tylek 2019). Therefore, the specific attributes of the processed seeds, the variations in the physical properties of seeds, and the correlations between these properties should be thoroughly examined before planning industrial operations (Kaliniewicz and Tylek 2019).

In consideration of this, the aim of this study was to determine the basic physical properties of hemp seeds and to identify the correlations between the evaluated attributes for the needs of planning seed sorting operations.

EXPERIMENTAL

Sample Preparation

Seeds were purchased at a local agricultural market in Olsztyn, Poland in September 2019 (Fig. 1) from two producers. The first batch of hemp seeds was comprised of the *Fedora* variety, while the second hemp variety could not be identified. The seeds that belonged to the unidentified variety were purchased because they were considerably larger than the other seeds at the market. Approximately 1 kg of each seed variety were stored in a laboratory at room temperature (approximately 22 °C) for approximately one month to stabilize their relative moisture content.

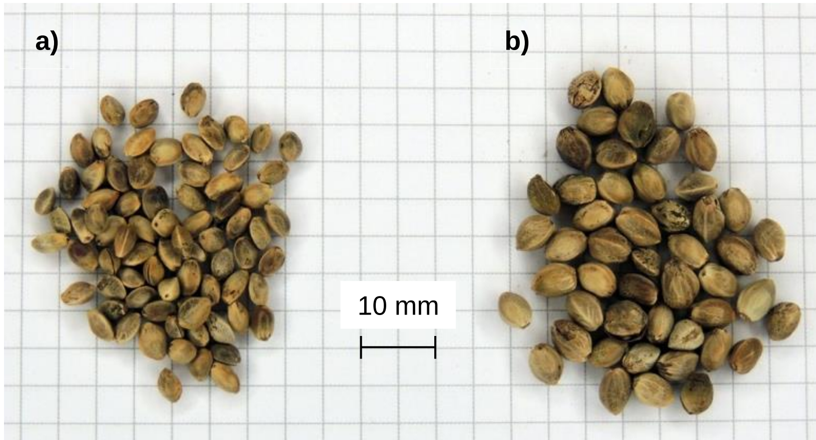


Fig. 1. The a) *Fedora* and b) unidentified hemp seed varieties.

Each seed batch was divided into two equal parts for the analysis. One part was selected randomly and further halved. The halving procedure was repeated to obtain analytical samples containing 100 to 200 seeds from each batch. The resulting analytical samples were composed of 159 *Fedora* hemp seeds and 126 unidentified hemp seeds. The remaining seeds were divided into samples that were analyzed for their relative moisture content on a drying scale with a MAX 5-/WH halogen lamp (Radwag, Radom, Poland).

Physical Properties

The physical properties of the seeds were measured according to the procedure described by Kaliniewicz *et al*. (2016a) with the use of a Petkus K-293 pneumatic separator (Petkus Technologie GmbH, Wutha-Farnroda, Germany), a MWM 2325 laboratory microscope (PZO, Warsaw, Poland), a self-designed dial gauge to measure the seed thickness, an inclined plane with a steel friction plate with a porosity of Ra=0.52 µm, and a WAA 100/C/2 laboratory weighing scale (Radwag, Radom, Poland). The terminal velocity (v), the thickness (T), the width (W), the length (L), the mass (m), and the angle of external friction (γ) for the seeds were determined. The angle of external friction was measured by the average value of two measurements conducted with the seeds positioned perpendicular and parallel to the inclination of the steel friction plate. The above parameters were measured with an accuracy of 0.11 m/s, 0.01 mm, 0.02 mm, 0.02 mm, 0.1 mg, and 1°, respectively.

The geometric mean diameter (D), the aspect ratio (R), the sphericity index (Φ), and the specific mass (m_D) were calculated for each seed, based on the correlations described by Kaliniewicz *et al*. (2013).

Based on their mass, the seeds of each hemp variety were divided into three size classes with an almost identical number of seeds in each class: small seeds (class 1), medium-sized seeds (class 2), and large seeds (class 3).

Mechanical Properties

After the physical measurements, the seeds were subjected to a uniaxial compressive strength test in the Instron Mecmesin Multi Test 1-i tensile and compression test system (Norwood, MA). Each seed was placed in the loadcell and compressed until it cracked. The moment of seed rupture was characterized by a rapid decrease in the registered load. The crosshead speed was set at 10 mm/min, and the applied load ranged from 0 kN to 1 kN. The test was conducted at room temperature (approximately 22 °C). The mechanical properties of the seeds were measured and recorded in the Emperor^{TM} Force Testing System program (Mecmesin Ltd., West Sussex, UK). A strain-stress curve was plotted for each seed. A point on the curve that denoted a rapid decrease in the compressive load was used to calculate the force required to fracture a seed (F), the displacement (δ), and the impact energy (E) (work done to fracture the seed).

Statistical Analysis

The results were processed with Statistica PL v. 13.3 software (TIBCO, Paolo Alto, CA) at a significance level of α=0.05. The variations in the physical properties of both varieties of hemp seeds were determined by independent t-test. The data distribution was checked for normality by the Shapiro-Wilk test, and the homogeneity of variance was determined by Levene's test. The strength of the relationships between the properties of the hemp seeds was determined by calculating the Pearson correlation coefficients. The regression equations were generated by testing the functions available in the program. The equation that was closest to the point cloud and characterized by a high coefficient of determination in its simplest functional form was selected. Only the regression equations with a coefficient of determination with a minimum 0.8 were presented in this study.

RESULTS AND DISCUSSION

Physical Properties

The average values and the standard deviation of the physical properties of the two hemp seed varieties are presented in Table 1. The accuracy of the measurements was determined by the standard error of the estimate, which was computed based on the sample size, the standard deviation of the analyzed property, and the value of the t-statistic at the adopted level of significance. Due to the sample size, the standard error of the estimate of the average values of the measured physical properties did not exceed a terminal velocity of 0.2 m/s, basic dimensions of 0.1 mm, a seed mass of 1.5 mg, and a 1° angle of external friction.

The analyzed seed varieties differed in nearly all the analyzed physical properties. The relative moisture content was the only parameter that did not differ significantly between the evaluated batches, which could be attributed to the fact that the seeds were stored for a relatively long time under identical conditions before the experiment. The hemp seeds of the unidentified variety were larger than the *Fedora* seeds due to the higher aspect ratio (approximately 15%) and sphericity index (approximately 12%). These attributes, combined with higher seed mass (approximately 158%) and higher specific mass (approximately 81%) were likely responsible for the fact that the average angle of external friction was around 13% lower in the unidentified variety than in the *Fedora* variety seeds.

Table 1. Selected Physical Properties (Mean Value ± Standard Deviation) of the Hemp Seeds and the Significance of the Differences

Physical Properties	Variety	
	Fedora	Unidentified
Moisture Content (% w.b.)	8.06 ± 0.14[a]	8.12 ± 0.09[a]
Terminal Velocity (m/s)	8.86 ± 0.57[a]	11.18 ± 0.99[b]
Thickness (mm)	2.69 ± 0.25[a]	4.16 ± 0.37[b]
Width (mm)	3.12 ± 0.30[a]	4.55 ± 0.37[b]
Length (mm)	4.78 ± 0.40[a]	6.09 ± 0.49[b]
Mass (mg)	18.34 ± 3.07[a]	47.28 ± 8.54[b]
Angle of External Friction (°)	18.25 ± 3.03[a]	15.89 ± 2.08[b]
Geometric Mean Diameter (mm)	3.42 ± 0.24[a]	4.86 ± 0.35[b]
Aspect Ratio (%)	65.58 ± 6.92[a]	75.03 ± 5.73[b]
Sphericity Index (%)	71.76 ± 4.09[a]	80.05 ± 3.98[b]
Specific Mass (g/m)	5.34 ± 0.62[a]	9.66 ± 1.28[b]
a, b – Different letters denote significant differences in the selected parameters between the hemp varieties		

The hemp seeds of the unidentified variety were heavier and more spherical in shape than the *Fedora* variety seeds. Therefore, the *Fedora* seeds also had a higher average terminal velocity (approximately 11.2 m/s). A similar correlation was reported by Sacilik *et al*. (2003), where it was reported that the terminal velocity of the small and light seeds was approximately 38% lower than the *Fedora* variety hemp seeds. The terminal velocity of the unidentified seeds was similar to that of barley seeds (Markowski *et al*. 2010) and black pine seeds (Kaliniewicz and Tylek 2019).

The analyzed seed batches had significant differences in the basic dimensions and, consequently, the geometric mean diameter. The hemp seeds that were evaluated by other authors (Sacilik *et al*. 2003; Taheri-Garavand *et al*. 2012) had basic dimensions that were similar to the *Fedora* variety seeds and sphericities that were similar to the unidentified variety hemp seeds. The *Fedora* hemp seeds resembled the seeds of selected wheat (Boac *et al*. 2010; Başlar *et al*. 2012) and barley cultivars (Boac *et al*. 2010; Sologubik *et al*. 2013) in terms of thickness and width, and they were similar to black locust seeds in terms of width and length (Kaliniewicz *et al*. 2016b). In turn, the hemp seeds of the unidentified variety resembled small-leaved lime seeds (Kaliniewicz *et al*. 2016b) in terms of thickness and width and selected lines of narrow-leafed lupine seeds (Lema *et al*. 2005) in terms of width and length. The geometric mean diameter of the *Fedora* hemp seeds was similar to that reported in sorghum and rice seeds (Boac *et al*. 2010) and black pine seeds (Kaliniewicz and Tylek 2019). The seeds of the unidentified variety were similar to the sphericity of acha seeds (Philip and Atiko 2012). Due to higher sphericity index values, the unidentified hemp seeds will probably take longer to dry in heated air (Markowski *et al*. 2010) than the *Fedora* variety hemp seeds.

As previously mentioned, the analyzed hemp varieties differed considerably in the average seed mass. The average mass of the *Fedora* variety seeds was only somewhat higher than 18 mg, and similar values were reported by Galasso *et al*. (2016), Schluttenhofer and Yuan (2017), and Taheri-Garavand *et al*. (2012) in selected landraces of fiber hemp. The seeds that were analyzed by Sacilik *et al*. (2003) and Baldini *et al*. (2018) were somewhat lighter. However, Baldini *et al*. (2018) examined seeds that were harvested only from side branches, whereas the main stem was analyzed for the content of essential oil. The *Fedora* variety seeds had a mass that resembled rice seeds (Boac *et al*.

2010), black locust seeds (Kaliniewicz *et al*. 2016b), and black pine seeds (Kaliniewicz and Tylek 2019). The *Fedora* variety seeds had a specific mass that resembled Morinda spruce seeds (Kaliniewicz *et al*. 2018), grand fir seeds (Kaliniewicz *et al*. 2019), and black pine seeds (Kaliniewicz and Tylek 2019). The unidentified variety hemp seeds were significantly heavier (approximately 47 mg), and their specific mass was nearly double that of the *Fedora* seeds. Heavier seeds generally contain more parenchymal tissue and are characterized by a lower proportion of the seed coat in the total seed mass. The unidentified variety hemp seeds had a mass that was similar to the seeds of selected wheat (Boac *et al*. 2010) and barley cultivars (Boac *et al*. 2010; Markowski *et al*. 2010).

The angle of external friction is an important parameter for designing the inclination angle of chutes and spouts in seed transport and storage. The inclination angle of seed processing lines should be somewhat larger than the angle of external friction of a given seed species to guarantee the uninterrupted movement of seeds. The angle of external friction was approximately 13% greater in the *Fedora* variety seeds. This parameter is largely determined by the surface porosity, which is rarely indicated in research studies. If the porosity of the steel friction plate is disregarded, similar angles of external friction (corresponding to the coefficient of external friction in the range of 0.28 to 0.33) were reported by Sacilik *et al*. (2003) and Taheri-Garavand *et al*. (2012) in hemp seeds with comparable moisture content. In other plant species, similar values of the angle of external friction were noted in rapeseed (Izli *et al*. 2009), barley seeds (Boac *et al*. 2010; Sologubik *et al*. 2013), wheat, oat and canola seeds (Boac *et al*. 2010), and black locust seeds (Kaliniewicz *et al*. 2016b).

Mechanical Properties

The results of the uniaxial compressive strength test are presented in Table 2. Like the analyses of the physical properties of the seeds, the values of the displacement, force, and impact energy were approximately 19%, 82%, and 116% higher in the unidentified hemp seeds than in the *Fedora* variety hemp seeds. Taheri-Garavand *et al*. (2012) reported somewhat higher average force and impact energy values in the hemp seeds purchased from a local store in Iran than those noted in the *Fedora* hemp seeds. In both studied hemp varieties, the rupture force was higher than that reported in rapeseed (Izli *et al*. 2009).

Table 2. Selected Mechanical Properties (Mean Value ± Standard Deviation) of the Hemp Seeds and the Significance of Differences

Property	Variety	
	Fedora	Unidentified
Displacement (mm)	0.73 ± 0.15[a]	0.87 ± 0.18[b]
Force (N)	23.07 ± 6.10[a]	41.93 ± 12.99[b]
Energy (mJ)	8.24 ± 3.23[a]	17.79 ± 8.35[b]
a, b – Different letters denote significant differences in the selected parameters between the hemp varieties		

The impact energy that causes irreversible damage to hemp seeds was similar to that observed in wheat seeds (Başlar *et al*. 2012), but the corresponding force was higher in hemp seeds. This implies that hemp seeds have a more elastic structure and can undergo greater displacement before rupture than cereal seeds.

Relationships between Properties

The results of the linear correlation analysis of the physical and mechanical properties of the fiber hemp seeds are presented in Table 3. Nearly 1/3 of the compared observations (51 out of 156) produced practically significant results (R > 0.4). The correlation coefficient was higher than 0.6 in 26 of the comparisons, and it exceeded 0.8 in 12 of the comparisons. The geometric mean diameter was most highly correlated with the remaining seed parameters, mainly because it was calculated based on the principal seed dimensions and is considered in calculations of the sphericity index. In the group of directly measured properties, the seed mass was bound by the strongest correlations with the remaining seed properties, including the basic seed dimensions, the geometric mean diameter, and the specific mass. The angle of external friction was least correlated with the remaining seed attributes, which indicates that this parameter should not be used as the primary distinguishing feature in seed separation processes. Similar observations were made in studies analyzing the seeds of selected tree species (Kaliniewicz *et al*. 2016a,b, 2018, 2019).

Table 3. Correlations between the Evaluated Properties of Hemp Seeds

Variety		Properties											
		v	*T*	*W*	*L*	*m*	*γ*	*D*	*R*	*Φ*	m_D	*δ*	*F*
Fedora	*T*	+1	×										
	W	+1	+2	×									
	L	+1	+3	+2	×								
	m	+2	+4	+3	+4	×							
	γ	-2	-1	-1	-1	-1	×						
	D	+2	+5	+4	+4	+5	-1	×					
	R	+1	-1	+4	-3	-1	-1	+1	×				
	Φ	+1	+2	+3	-3	-1	-1	+1	+5	×			
	m_D	+2	+3	+2	+4	+5	-1	+3	-2	-2	×		
	δ	-1	+1	-1	+1	+1	+1	+1	-1	-1	+1	×	
	F	+1	+2	+1	+2	+2	-1	+2	-2	-2	+2	+4	×
	E	+1	+1	-1	+2	+2	+1	+1	-2	-2	+2	+5	+5
Unidentified	*T*	+3	×										
	W	+3	+4	×									
	L	+2	+3	+3	×								
	m	+3	+4	+4	+4	×							
	γ	-1	-1	-1	+1	-1	×						
	D	+3	+5	+5	+5	+5	+1	×					
	R	+1	+2	+3	-3	+1	-1	+1	×				
	Φ	+2	+3	+3	-3	+1	-1	+1	+5	×			
	m_D	+3	+4	+3	+3	+5	-1	+4	+1	+1	×		
	δ	+1	+1	+1	+1	+1	-1	+2	-1	-1	+1	×	
	F	+2	+2	+2	+2	+3	-1	+2	-1	+1	+3	+4	×
	E	+1	+2	+2	+2	+2	-1	+2	-1	+1	+2	+5	+5

v – terminal velocity, *T* – thickness, *W* – width, *L* – length, *m* – mass, *γ* – angle of external friction, *D* – geometric mean diameter, *R* – aspect ratio, *Φ* – sphericity index, m_D – specific mass, *δ* – displacement, *F* – force, *E* – energy.
The calculated values of the correlation coefficient were divided into five groups: 1) 0 to 0.20, 2) 0.21 to 0.40, 3) 0.41 to 0.60, 4) 0.61 to 0.80, and 5) 0.81 to 1.00.

The regression analysis of the relationships between the directly measured seed properties demonstrated that linear and power functions were characterized by the highest coefficient of determination and produced the best fit to the empirical data (Fig. 2). The coefficient of determination exceeded 0.8 in four comparisons, and it was highest for the correlation between the seed thickness and seed mass (R^2 = 0.95). The seed mass increased by approximately 460% (from approximately 13 mg to approximately 72 mg) with a rise in the seed thickness (from approximately 2.3 mm to approximately 5.1 mm). The highest values of the coefficient of determination for the relationship between the seed thickness and the seed mass were also reported in common beech seeds (Kaliniewicz *et al*. 2016b), Sitka and white spruce seeds (Kaliniewicz *et al*. 2018), and Japanese, Korean, and silver fir seeds (Kaliniewicz *et al*. 2019). Somewhat lower (but still high) values of the coefficient of determination were noted for the relationship between the seed mass and the seed dimensions, and the lowest value was found for the correlation between the seed mass and the seed length. Only the correlation between the seed thickness and the seed width was characterized by a desirable value of the coefficient of determination. An increase in the value of one parameter led to a proportional increase in the value of the other parameter. The seed width increased by approximately 98% (from approximately 2.7 mm to approximately 5.4 mm) and the seed thickness increased by approximately 120% (from approximately 2.3 mm to approximately 5.1 mm). The variations in the size of the hemp seeds were accompanied by a somewhat different rates of change in the seed thickness and width.

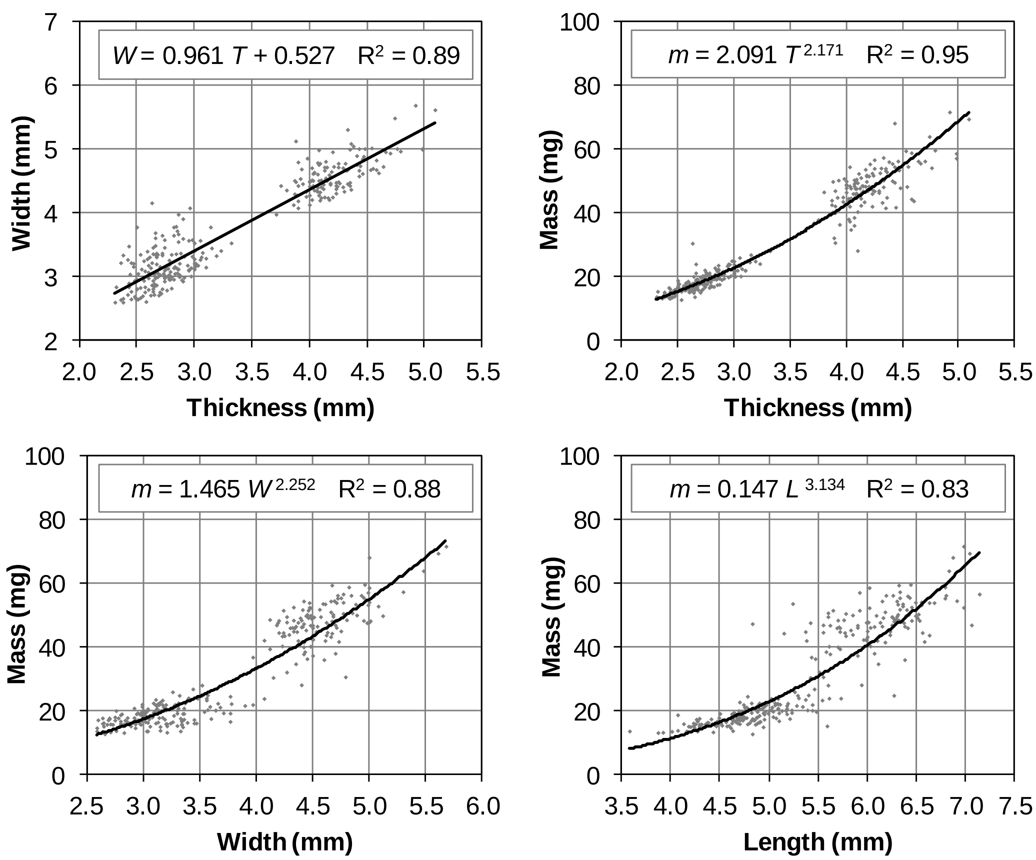


Fig. 2. The relationships between the basic physical properties of the seeds.

Seed Separation

The results of the performed analysis revealed that the seed mass was bound by the strongest correlation with basic seed dimensions, a weaker correlation with the terminal velocity, and the weakest correlation with the angle of external friction. According to Grochowicz (1994), only the properties that are most highly correlated with the analyzed parameter (the seed mass) should be considered in the seed separation process. Therefore, an attempt was made to determine the influence exerted by the basic seed dimensions during the separation process of the hemp seeds. The seeds of each hemp variety were analyzed separately due to the considerable differences in size (Table 4). The *Fedora* variety hemp seeds were divided into three size fractions, which, in most cases, decreased the variation in the seed mass (excluding the fraction characterized by the greatest seed width), which increased the seed uniformity in terms of mass. In the unidentified hemp seeds, the coefficient of variation of the seed mass decreased in the two largest fractions and increased in the smallest fraction. The analysis revealed that the seed thickness was the most reliable parameter for seed sorting operations, which was previously confirmed by the highest value of the coefficient of determination for the relationship between the seed mass and the seed thickness. Previous studies of spruce seeds (Kaliniewicz et al. 2018) and fir seeds (Kaliniewicz et al. 2019) also demonstrated that the separation processes based on seed thickness produced fractions that were most uniform in terms of seed mass.

Table 4. Coefficient of Variation of the Seed Mass in Three Seed Fractions

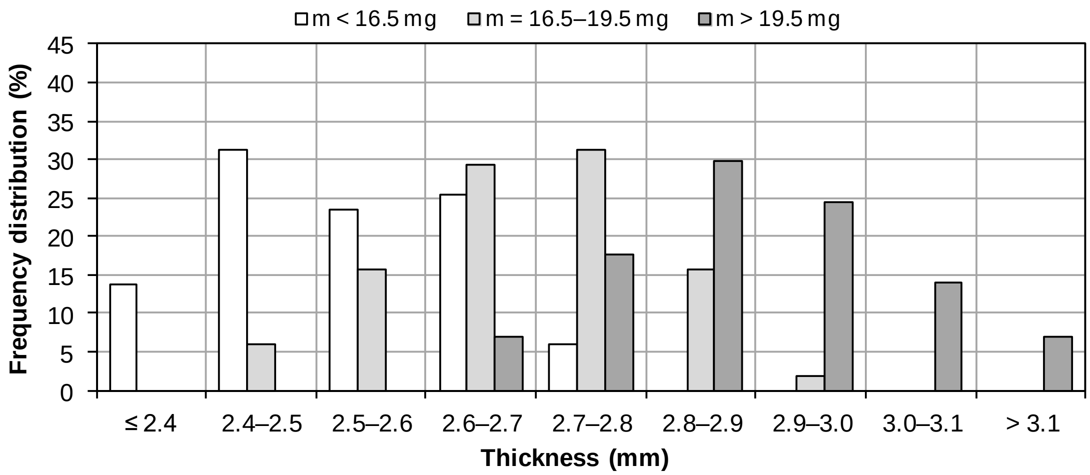
Seed Variety	Seed Fraction	Percentage (%)	Coefficient of Variation (%) of Seed Mass	
			Fraction	Total
Fedora	I (*T* ≤ 2.60 mm)	28.93	11.74	16.73
	II (*T*=2.61-2.80 mm)	38.36	11.16	
	III (*T* > 2.80 mm)	32.71	10.75	
	I (*W* ≤ 2.95 mm)	29.56	11.50	
	II (*W* = 2.96-3.20 mm)	36.48	13.14	
	III (*W* > 3.20 mm)	33.96	17.93	
	I (*L* ≤ 4.65 mm)	33.96	10.49	
	II (*L* = 4.66-4.90 mm)	32.08	11.41	
	III (*L* > 4.91 mm)	33.96	12.98	
Unidentified	I (*T* ≤ 4.05 mm)	30.95	19.21	18.06
	II (*T*=4.06-4.25 mm)	35.71	10.72	
	III (*T* > 4.25 mm)	33.34	13.11	
	I (*W* ≤ 4.40 mm)	29.37	21.44	
	II (*W* = 4.41-4.65 mm)	31.75	11.26	
	III (*W* > 4.65 mm)	39.68	14.07	
	I (*L* ≤ 5.90 mm)	32.54	20.61	
	II (*L* = 5.91-6.30 mm)	31.75	12.88	
	III (*L* > 6.30 mm)	35.71	12.65	

Three ranges of seed mass values were used to divide the hemp seeds of both varieties into size fractions with a nearly identical number of seeds. Small seeds (class 1) were comprised of seeds lighter than 16.5 mg for the *Fedora* variety and 45.0 mg for the unidentified variety. Medium seeds (class 2) were comprised of seeds between 16.5 mg and 19.5 mg for the *Fedora* variety and 45.0 to 50.0 mg for the unidentified variety. Large seeds (class 3) were comprised of seeds heavier than 19.5 mg or 50.0 mg for the *Fedora* and unidentified seeds, respectively.

The histograms depicting the distribution of size classes in the sorting operations based on the seed thickness are presented in Fig. 3. The *Fedora* variety hemp seeds were divided into the three fractions with the use of a sieve separator composed of two screens with slotted apertures (2.6 mm and 2.9 mm). Fraction I (the thinnest seeds) contained approximately 29% of the seeds from the entire batch, including approximately 69% and

22% of the small and medium seeds, respectively. Fraction II (the medium-thickness seeds) contained approximately 54% of the seeds from the entire batch, including approximately 31%, 76%, and 54% of the small, medium, and large seeds, respectively. Fraction III (the thickest seeds) contained approximately 17% of the seeds from the entire batch, including approximately 2% and 46% of the medium and large seeds, respectively.

a)



b)

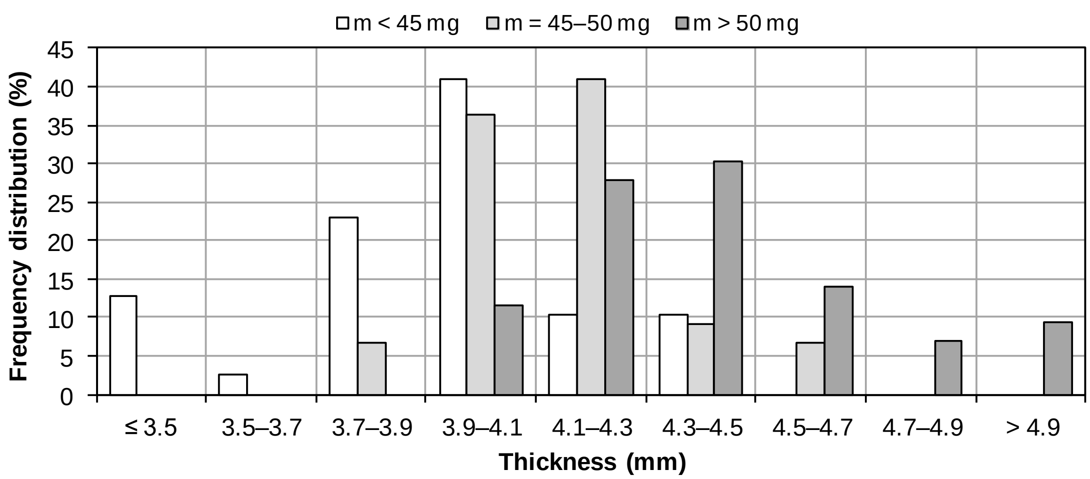


Fig. 3. The distribution of the seed thickness in the a) *Fedora* and b) unidentified hemp seed varieties.

The fraction with the thinnest seeds (Fraction I) did not contain large seeds, and the fraction with the thickest seeds (Fraction III) did not contain small seeds. The top screen separated fraction III seeds containing approximately 21% of the processed seed batch. The bottom screen separated fraction I seeds which accounted for around 24% of the total seed batch, as well as fraction II seeds containing approximately 55% of the sorted seeds. Slotted screens in the sieve separator do not have to vibrate vertically but can be set in reciprocal motion to ensure that seeds are turned on the smallest side and fall into the openings. When the sieve separator is set into motion, the separated seeds roll down the inclined chutes and spouts, and are collected in the respective hoppers.

The screens that are used to separate the hemp seeds of the unidentified variety should have different slotted apertures, measuring 3.9 mm and 4.5 mm. As discussed previously, the fraction with the thinnest seeds will not contain the large seeds, and the fraction with the thickest seeds will not contain the small seeds. The hemp seeds were further separated into fractions. Fraction I (the thinnest seeds) contained approximately 14% of the seeds from the entire batch, including approximately 39% of the small seeds and approximately 7% of the medium seeds. Fraction II (the medium seeds) contained approximately 73% of the seeds from the entire batch, including approximately 61%, 86%, and 70% of the small seeds, medium seeds, and large seeds, respectively. Fraction III (the thickest seeds) contained approximately 13% of the seeds from the entire batch, including approximately 7% of the medium seeds and approximately 30% of the large seeds. The hemp seeds of the unknown variety were divided into Fractions I, II, and III, which contained approximately 11%, 73%, and 16% of the seeds, respectively.

CONCLUSIONS

1. The seed sorting processes that rely on the basic seed dimensions as the distinguishing characteristics support the division of hemp seeds into fractions with uniform specific seed mass.
2. The hemp seeds are most effectively separated into uniform fractions with the use of a sieve with slotted apertures. The size of the screens should be adjusted to ensure that the thinnest seeds account for approximately 11% to 24% and the thickest seeds should account for approximately 16% to 21% of total seed mass. More frequent large seeds should be separated into fewer extreme fractions.
3. The specific mass of the individual hemp seeds was significantly influenced by their basic dimensions, and the correlations between these properties are most effectively described by power functions. The seed mass was most highly correlated with the seed thickness, and the coefficient of determination that described this relationship reached 0.95.
4. An analysis of the basic properties of the hemp seeds demonstrated the strongest correlation between the seed thickness and the seed width. An increase in the seed size was accompanied by a somewhat greater increase in the seed thickness rather than the seed width.

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