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Communication

Physical Properties of Seeds of Eleven Fir Species

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Abstract: *Research Highlights:* The correlations between the analyzed physical properties of seeds and seed mass were determined. The results were analyzed to determine most effective seed separation devices for the evaluated fir species. *Background and Objectives:* Information about the variations and correlations between the physical properties of seeds is essential for designing and modeling seed processing operations such as seed separation. The aim of this study was to determine the range of variations in the basic physical properties of seeds of selected fir species, and to identify the correlations between these attributes for the needs of the seed sorting processes. *Materials and Methods:* Terminal velocity, thickness, width, length, the angle of external friction and mass were determined in the seeds of 11 fir species. The measured parameters were used to calculate the geometric mean diameter, three aspect ratios, sphericity index and the specific mass of each seed. *Results:* The average values of the basic physical properties of the analyzed seeds were determined in the following range: terminal velocity – from 4.8 to 7.1 m s^{-1}, thickness – from 1.76 to 3.22 mm, width – from 3.29 to 5.57 mm, length – from 5.44 to 11.06 mm, angle of external friction – from 26 to 33°, and mass – from 7.9 to 48.3 mg. The seeds of Sierra white fir where most similar, whereas the seeds of balsam fir differed most considerably from the seeds of the remaining fir species. *Conclusions:* Fir seeds should be sorted primarily with the use of mesh sieves with longitudinal openings to obtain fractions with similar seed mass and to eliminate the need for dewinging.

Keywords: *Abies*; separation traits; correlation; sorting; fractions

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1. Introduction

All fir species are indigenous to the northern hemisphere. They thrive in temperate and cool climates at altitudes not exceeding 4700 m a.s.l. Firs are distributed mainly in the following regions [1-7]:

- North America (from Alaska to the Mexican border) – 9 species,
- Central America (Mexico, Guatemala, Honduras and Salvador) – 6 species,
- Mediterranean Region and the adjacent areas, including Southern and Central Europe to the north, Western Asia (Asia Minor, Caucasus, Syria and Lebanon) to the east, and West Africa (Morocco, Algeria and Tunisia) to the south – 8 species,
- Siberia and Eastern Asia (Amur, China, Korea, Japan, Taiwan and the Himalayas) – 17 species.

Firs belong to the family *Pinaceae* and are characterized by a conical crown and a whorled branching pattern. The needles are flattened, usually green and glossy. In the vast majority of fir species, rows of stomata covered with two whitish lines of waxy coating are visible on the underside

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of needles [2,5,6,8,9]. Firs are widely used as Christmas trees on account of their ornamental properties, including evergreen needles, conical shape and regular branching pattern [10-15]. Extracts from the bark, needles and seeds of many fir species have anticarcinogenic, anti-inflammatory, antibacterial and antifungal properties, and they are used in the treatment of respiratory and gastrointestinal disorders. Firs are also used in the production of essential oils and cosmetics [16-18]. Cervids often feed on young fir needles, especially during the winter when other sources of food are scarce [19-21].

Firs begin to produce seeds at the age of 12 to 50 years in low-density stands, and somewhat later in dense stands. Fir cones have a length of 7.5 to 25 cm, and their shape and size vary across species. Cones can be cylindrical or ovate-oblong, and they are often covered with resin. They mature in flowering years and break apart on trees, leaving the central stem on the branch. Fir seeds have wings for effective propagation, and wings are shed together with seed scales and bract scales [2,8,22]. The released seeds have irregular triangular shape, and seed wings are brittle and easily damaged. Despite the above, wings are strongly attached to seeds, and wing fragments are often retained on seeds. Fir seeds are classified as orthodox and have to be stored at low temperature (not higher than 4°C) after their relative moisture content has to be reduced below 12%, preferably to around 8%. Long-term seed storage requires much lower temperatures, sometimes as low as -18°C. Most fir species have dormant seeds, and dormancy is broken after cold-moist stratification [2,23-25].

Firs reproduce sexually via seeds, and their breeding usually begins in nurseries. Tree nurseries have limited space; therefore, only seeds of the highest quality should be used to guarantee the profitability of seedling production [26,27]. Nursery seeds should be characterized by a large proportion of healthy seeds that germinate quickly and produce robust seedlings. According to many authors [28-33], seed mass significantly influences germination efficiency, but plumper seeds do not always germinate faster than smaller seeds. Practical experience indicates that plant uniformity can be improved by sorting seeds and sowing selected seed fractions to provide seedlings with equal opportunities for growth and to limit competition [34]. However, in large production plants, seeds are difficult to sort based on their mass only. Seeds can be sorted with the use of vibratory and vibratory-pneumatic separated [35], but only if the particles differ in mass, but have similar dimensions, or if they differ in dimensions, but have similar mass. Fir seeds that differ in both mass and dimensions are not always effectively separated. For this reason, other parameters that are highly correlated with seed mass have to be identified to facilitate sorting operations.

The aim of this study was to determine the range of variations in the basic physical properties of seeds of selected fir species, and to identify the correlations between these attributes for the needs of seed sorting processes.

2. Materials and Methods

2.1. Sample preparation

The basic physical properties of seeds of 11 fir species were analyzed (Figure 1): balsam fir (*Abies balsamea* (L.) P. Mill.), corkbark fir (*Abies lasiocarpa* var. *arizonica* (Hook.) Nutt.), Forrest's fir (*Abies forrestii* Coltm.-Rog.), grand fir (*Abies grandis* (Doug. ex D. Don) Lindl.), Japanese fir (*Abies firma* Sieb. & Zucc.), Korean fir (*Abies koreana* E. H. Wilson), noble fir (*Abies procera* Rehd.), Sierra white fir (*Abies concolor* var. *lowiana* (Gord.) Lemm.), silver fir (*Abies alba* P. Mill.), subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) and white fir (*Abies concolor* (Gord.) Lindl. ex Hildebr.). Seeds were obtained in 2017 from Dendrona in Pęcice, a supplier of tree, shrub, perennial plant and herbaceous plant seeds.

Analytical specimens were obtained from samples of approximately 100 g from each seed batch. Seed samples for analysis were obtained by halving [29]. Every batch of seeds was halved, and one half was randomly selected for successive halving. The above procedure was repeated to produce samples of around 100 seeds each.

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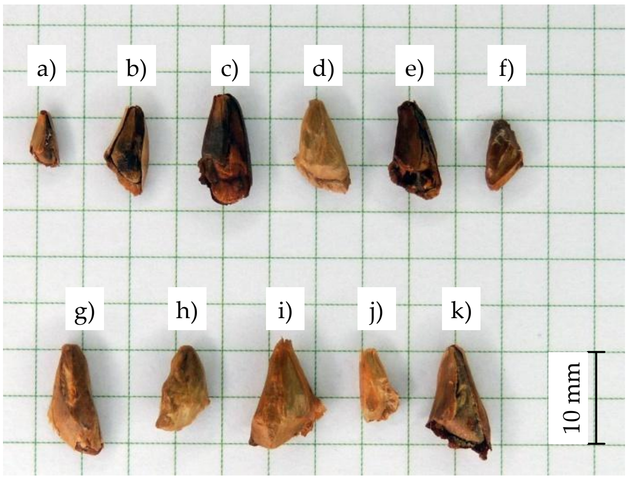

Figure 1. Seeds of: a) balsam fir, b) corkbark fir, c) Forrest's fir, d) grand fir, e) Japanese fir, f) Korean fir, g) noble fir, h) Sierra white fir, i) silver fir, j) subalpine fir, k) white fir.

2.2. Physical properties

The physical properties of seeds were measured based on the method described by Kaliniewicz and Poznański [36] and Kaliniewicz et al. [37]. Terminal velocity (v) was determined in the Petkus K-293 pneumatic classifier (PETKUS Technologie GmbH, Germany); seed length (L) and seed width (W) were measured under the MWM 2325 laboratory microscope; seed thickness (T) was determined with a clock thickness gauge; the angle of external friction (γ) was determined on a steel friction plate (surface roughness – Ra=0.48 µm) positioned on a horizontal plane; and seed mass (m) was determined on the WAA 100/C/2 laboratory scale (RADWAG Radom, Polska). The angle of external friction was expressed as the mean value of two measurements where seeds were arranged in different positions: with the longitudinal axis parallel and perpendicular to the direction of movement on the steel friction plate.

The results of the above measurements were used to calculate the geometric mean diameter D, aspect ratios (T/W, T/L i W/L) and the sphericity index Φ [38] of every seed:

$$D = (T \cdot W \cdot L)^{\frac{1}{3}} \quad (1)$$

$$\Phi = \frac{D}{L} \cdot 100 \quad (2)$$

Specific mass m_D was determined for each seed [39]:

$$m_D = \frac{m}{D} \quad (3)$$

To evaluate the effects of sorting operations, seeds were divided into three roughly equal size fractions based on their terminal velocity and thickness: fraction I – seeds with the lowest terminal velocity or thinnest seeds, fraction II – seeds with average terminal velocity or average thickness, fraction III – seeds with the highest terminal velocity or thickest seeds. Terminal velocity was measured to the nearest 5 m s^{-1}, and seed thickness was measured to the nearest 0.1 mm.

2.3. Statistical analysis

The measured physical parameters and the calculated indicators were processed in Statistica PL v. 13.3 software (StatSoft Poland Ltd., Cracow, Poland) at a significance level of α=0.05. The differences between the measured properties and calculated indicators were determined by one-way analysis of variance (ANOVA). If the null hypothesis postulating that the average values of a given parameter or indicator are equal was rejected, the significance of differences was determined with the use of Duncan's test and homogenous groups were identified. The degree of correlations

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between the analyzed seed parameters was evaluated with the use of Pearson's correlation coefficient, and the functions describing the correlations were determined by regression analysis [40] (Rabiej 2012). These equations were selected by testing the functions available in the Statistica package. The function that most closely resembled the cloud of measurement points and was characterized by a high coefficient of determination was selected. Only the equations with a minimum coefficient of determination of 0.6 were presented in the paper.

3. Results and Discussion

3.1. Experimental material

The accuracy with which the mean values of the analyzed physical parameters are determined can be inferred from their standard error of the estimate based on the size of the sample, standard deviation of the examined parameter and Student t-values at a given significance level. The analyzed samples consisted of 101 to 118 seeds; therefore, the standard error of the estimate of the mean values of the evaluated physical properties of fir seeds did not exceed: 0.2 m s^{-1} for terminal velocity, 0.1 mm for seed thickness, 0.2 mm for seed width, 0.3 mm for seed length, 1° for the angle of external friction, and 0.5 mm (balsam fir) to 2.5 mm (Forrest's fir) for seed mass.

The physical properties of the analyzed seeds are presented in Table 1. The average terminal velocity ranged from 4.8 m s^{-1} (balsam fir) to 7.1 m s^{-1} (silver fir). The following fir species formed homogeneous groups in terms of terminal velocity: 1) balsam fir and subalpine fir, 2) grand fir, Japanese fir and Sierra white fir, 3) corkbark fir and Sierra white fir, 4) corkbark fir, Forrest's fir and Korean fir. The average terminal velocity of silver fir seeds was comparable to that presented by Kaliniewicz et al. [41], and somewhat higher than that determined by Tylek [42,43] in seeds from southern Poland.

Table 1. Statistical distribution of the physical properties (mean value ± standard deviation) of seeds of selected fir species and significant differences between species.

Fir species	Property					
	Terminal velocity *v* (m s^{-1})	**Thickness *T* (mm)**	**Width *W* (mm)**	**Length *L* (mm)**	**Angle of external friction *γ* (°)**	**Mass *m* (mg)**
Balsam fir	4.8±0.7 ^{a}	1.78±0.19 ^{a}	3.29±0.46 ^{a}	5.44±0.46 ^{a}	33±5 ^{e}	7.9±2.4 ^{a}
Corkbark fir	5.7±0.6 ^{cd}	1.99±0.27 ^{c}	3.90±0.52 ^{b}	6.90±0.72 ^{c}	26±3 ^{a}	16.2±4.8 ^{c}
Forrest's fir	5.7±0.9 ^{d}	2.32±0.33 ^{d}	5.39±0.84 ^{e}	10.95±1.54 ^{f}	27±3 ^{ab}	35.7±13.2 ^{f}
Grand fir	5.4±0.8 ^{b}	2.31±0.24 ^{d}	4.81±0.64 ^{d}	9.41±0.85 ^{d}	31±4 ^{d}	26.4±6.5 ^{e}
Japanese fir	5.4±0.8 ^{b}	1.99±0.29 ^{bc}	3.94±0.68 ^{b}	9.63±1.06 ^{d}	30±5 ^{d}	20.9±6.1 ^{d}
Korean fir	5.8±0.9 ^{d}	1.76±0.22 ^{a}	3.46±0.57 ^{a}	5.79±0.68 ^{b}	28±3 ^{bc}	11.6±3.4 ^{b}
Noble fir	6.1±0.6 ^{e}	2.59±0.28 ^{e}	4.43±0.69 ^{c}	11.06±1.07 ^{f}	27±3 ^{ab}	36.5±9.6 ^{f}
Sierra white fir	5.5±0.7 ^{bc}	2.29±0.24 ^{d}	4.91±0.78 ^{d}	9.48±1.03 ^{d}	27±4 ^{ab}	28.5±7.4 ^{e}
Silver fir	7. 2±0.9 ^{g}	3.22±0.39 ^{f}	5.57±0.83 ^{e}	10.83±1.02 ^{f}	28±5 ^{bc}	48.3±12.9 ^{h}
Subalpine fir	4.9±0.7 ^{a}	1.91±0.27 ^{b}	3.95±0.62 ^{b}	7.04±0.82 ^{c}	29±4 ^{c}	12.9±3.7 ^{b}
White fir	6.4±0.7 ^{f}	2.58±0.30 ^{e}	5.40±0.85 ^{e}	10.41±1.12 ^{e}	27±3 ^{ab}	42.6±9.4 ^{g}

^{a,b,c,d,e,f,g,h} – superscript letters denote significant differences between the corresponding properties.

The average seed thickness ranged from 1.76 mm (Korean fir) to 3.22 mm (silver fir). The following fir species formed homogeneous groups in terms of seed thickness: 1) balsam fir and Korean fir, 2) Japanese fir and subalpine fir, 3) corkbark fir and Japanese fir, 4) Forrest's fir, grand fir and Sierra white fir, 5) noble fir and white fir. The following fir species formed homogeneous groups in terms of seed width: 1) balsam fir and Korean fir, 2) corkbark fir, Japanese fir and subalpine fir, 3) grand fir and Sierra white fir, 4) Forrest's fir, silver fir and white fir. The average seed width ranged from 3.29 mm (balsam fir) to 5.57 mm (silver fir), and the average seed length – from 5.44 mm (balsam fir) to 11.06 mm (noble fir). The following fir species formed homogeneous groups in terms of seed length: 1) corkbark fir and subalpine fir, 2) grand fir, Japanese fir and Sierra white fir, 3) Forrest's fir, noble fir and silver fir. The seeds of silver fir were somewhat larger than those analyzed by Tracz and Barzdajn [44], Tylek [43] and Kaliniewicz et al. [41], but their dimensions were within the range of average values noted in Poland [29]. The evaluated seeds were similar to selected batches of Normann fir seeds in terms of length [27,45], and they were similar to pindrow fir seeds in terms of length and width [46]. The analyzed Korean fir seeds were approximately 10% larger than those studied by Song et al. [47].

Relatively minor variations were noted in the values of the angle of external friction which ranged from 26° (corkbark fir) to 33° (balsam fir). Six fir species formed a homogeneous group in terms of the angle of external friction: Forrest's fir, Korean fir, noble fir, Sierra white fir, silver fir and white fir. Balsam fir seeds differed most considerably from the remaining fir species in this respect.

In the studied fir species, seed mass (Figure 2, Table 1) ranged from 2.8 mg (balsam fir) to 78.6 mg (silver fir), and average seed mass ranged from 7.9 to 48.3 mg. The following fir species formed homogeneous pairs in terms of seed mass: 1) Korean fir and subalpine fir, 2) grand fir and Sierra white fir, 3) Forrest's fir and noble fir. According to the literature [29,33,48-50], seed mass is largely influenced by environmental conditions, genetic traits, tree age and, above all, geographic location. If the above factors are not taken into account, the average mass of silver fir seeds is somewhat lower than that reported by Tylek [51], Balian [33] and Gradečki-Poštenjak and Ćelepirović [50], and similar to that noted by Skrzyszewska and Chłanda [26] and Kaliniewicz et al. [41]. The average mass of Sierra white fir and subalpine fir seeds was somewhat lower (by approx. 17% and 3%, respectively), whereas the average mass of grand fir seeds was higher (by approx. 32%) than that observed by Veech et al. [52] in the corresponding species.

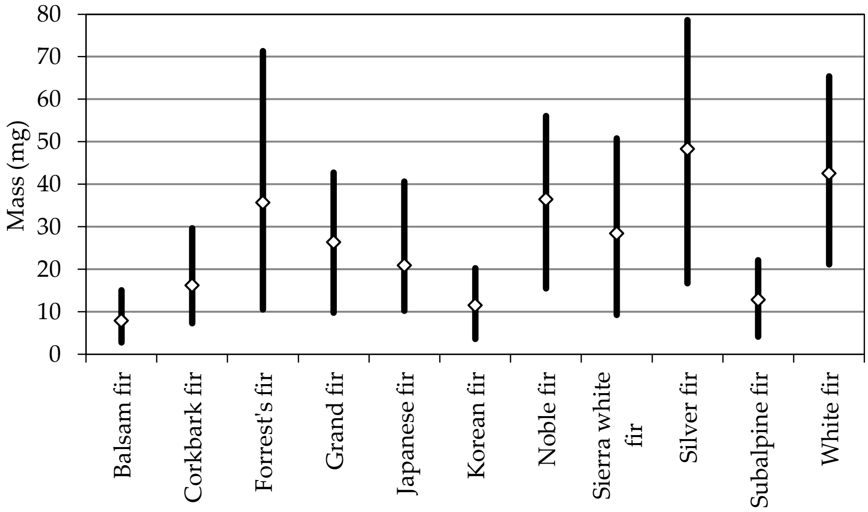

Figure 2. Range of variations in seed mass in selected fir species.

Silver fir was characterized by the largest seeds (geometric mean diameter – 5.77 mm), and balsam fir produced the smallest seeds (geometric mean diameter – 3.16 mm) (Table 2). No significant differences in the values of the geometric mean diameter were noted between the following species: 1) balsam fir and Korean fir, 2) corkbark fir and subalpine fir, 3) grand fir and Sierra white fir, 4) Forrest's fir and white fir.

The average aspect ratios were determined in the following range of values: *T*/*W* – from od 43.76% (Forrest's fir) to 59.83% (noble fir); *T*/*L* – from 20.78% (Japanese fir) to 32.80% (balsam fir); *W*/*L* – from 40.11% (noble fir) to 60.58% (balsam fir). Aspect ratios were similar in the seeds of grand fir, Sierra white fir and white fir, i.e. species that belong to the section *Grandis* [2].

The highest values of the sphericity index were determined in balsam fir (58.20%), and the lowest values – in Japanese fir (43.86%). Eight homogeneous groups were identified in terms of the sphericity index, and the following species formed common groups: 1) grand fir, Sierra white fir and white fir, 2) silver fir and subalpine fir.

Table 2. Statistical distribution of the calculated indicators (mean value ± standard deviation) of seeds of selected fir species and significant differences between species.

Fir species	Indicator					
	Geom. mean diameter *D* (mm)	Aspect ratio *T/W* (%)	Aspect ratio *T/L* (%)	Aspect ratio *W/L* (%)	Sphericity index *Φ* (%)	Specific mass m_D ($g\ m^{-1}$)
Balsam fir	3.16±0.27 ^{a}	54.97±7.91 ^{d}	32.80±3.17 ^{g}	60.58±8.29 ^{d}	58.20±3.73 ^{h}	2.48±0.62 ^{a}
Corkbark fir	3.76±0.37 ^{b}	51.77±8.45 ^{c}	28.98±3.55 ^{e}	56.79±7.42 ^{c}	54.62±3.51 ^{f}	4.26±0.94 ^{c}
Forrest's fir	5.13±0.57 ^{f}	43.76±8.04 ^{a}	21.41±3.39 ^{a}	49.75±7.66 ^{b}	47.18±3.95 ^{c}	6.82±2.01 ^{g}
Grand fir	4.69±0.36 ^{d}	48.78±7.69 ^{b}	24.71±3.14 ^{c}	51.29±3.64 ^{b}	50.07±3.34 ^{d}	5.60±1.20 ^{e}
Japanese fir	4.20±0.41 ^{c}	51.78±11.29 ^{c}	20.78±3.26 ^{a}	41.35±7.98 ^{a}	43.86±4.12 ^{a}	4.92±1.12 ^{d}
Korean fir	3.26±0.36 ^{a}	51.80±8.41 ^{c}	30.61±4.11 ^{f}	59.85±8.08 ^{d}	56.60±4.12 ^{g}	3.49±0.80 ^{b}
Noble fir	5.01±0.45 ^{e}	59.83±10.64 ^{e}	23.58±2.88 ^{b}	40.11±5.59 ^{a}	45.40±3.03 ^{b}	7.22±1.54 ^{h}
Sierra white fir	4.72±0.43 ^{d}	47.66±8.45 ^{b}	24.31±3.00 ^{bc}	52.01±7.84 ^{b}	50.00±3.64 ^{d}	5.98±1.30 ^{f}
Silver fir	5.77±0.51 ^{g}	58.94±10.26 ^{e}	29.83±3.33 ^{ef}	51.61±7.54 ^{b}	53.40±3.45 ^{e}	8.29±1.76 ^{i}
Subalpine fir	3.74±0.36 ^{b}	49.62±10.39 ^{bc}	27.37±4.07 ^{d}	56.51±9.27 ^{c}	53.41±4.32 ^{e}	3.39±0.77 ^{b}
White fir	5.24±0.50 ^{f}	48.77±8.15 ^{b}	25.03±3.40 ^{c}	52.02±7.13 ^{b}	50.50±3.61 ^{d}	8.08±1.36 ^{i}

^{a,b,c,d,e,f,g,h,i} – superscript letters denote significant differences between the corresponding properties.

The average specific mass of fir seeds varied widely from 2.48 $g\ m^{-1}$ (balsam fir) to 8.29 $g\ m^{-1}$ (silver fir). The above indicates that balsam fir and silver fir seeds were characterized by the largest and smallest proportions of the seed coat, respectively, in seed mass, and that they contained empty spaces not filled with parenchymal tissue. The following species formed homogeneous pairs in terms of average seed mass: 1) Korean fir and subalpine fir, 2) silver fir and white fir.

Species pairs characterized by significant similarities in all physical parameters were not identified. The seeds of grand fir and Sierra white fir were most similar, and they did not differ significantly in the values of terminal velocity, basic dimensions, mass, geometric mean diameter, aspect ratios or sphericity index. In general, balsam fir seeds were most different, whereas Sierra white fir seeds were most similar to the seeds of the remaining fir species. Therefore, the seeds of Sierra white fir can be regarded as representative of the pine family and used to differentiate between the seeds of different fir species. The W/L aspect ratio (4 homogeneous groups) was the least differentiating trait, whereas specific mass (9 homogeneous groups) was the most differentiating attribute in the analyzed fir species.

3.2. Correlations between seed parameters

In further analysis, the measured parameters of fir seeds were pooled into a single experimental group. An analysis of the linear correlations between the basic physical properties of seeds (Table 3) revealed that seed mass, geometric mean diameter and specific mass were most correlated, whereas the angle of external friction was least correlated with the remaining parameters. The strongest correlation was noted between seed mass and specific mass (0.98), whereas the weakest correlation was observed between terminal velocity and the sphericity index (0.01). Fifty-five out of the 66 compared pairs of traits were significantly correlated at a significance level of 0.05. The correlation coefficient was practically significant (minimum 0.4) in 28 cases. The dimensions and mass of the analyzed fir seeds were more strongly correlated than in Turkish fir seeds [27], Cilician fir and Nordmann fir seeds [45] and silver fir seeds [41].

The correlations between seed parameters were determined by testing various regression functions. Linear, quadratic and power functions best fit empirical data (equations with the highest coefficient of determination) (Figure 3). The coefficient of determination reached the threshold value (0.6) in only 5 equations, and an equation with the highest percentage of explained variation (0.87) was obtained for the correlation between seed mass and geometric mean diameter. The percentage of explained variation was also high for the correlation between seed length and seed mass (0.78), followed by the correlation between seed thickness and seed mass (0.70).

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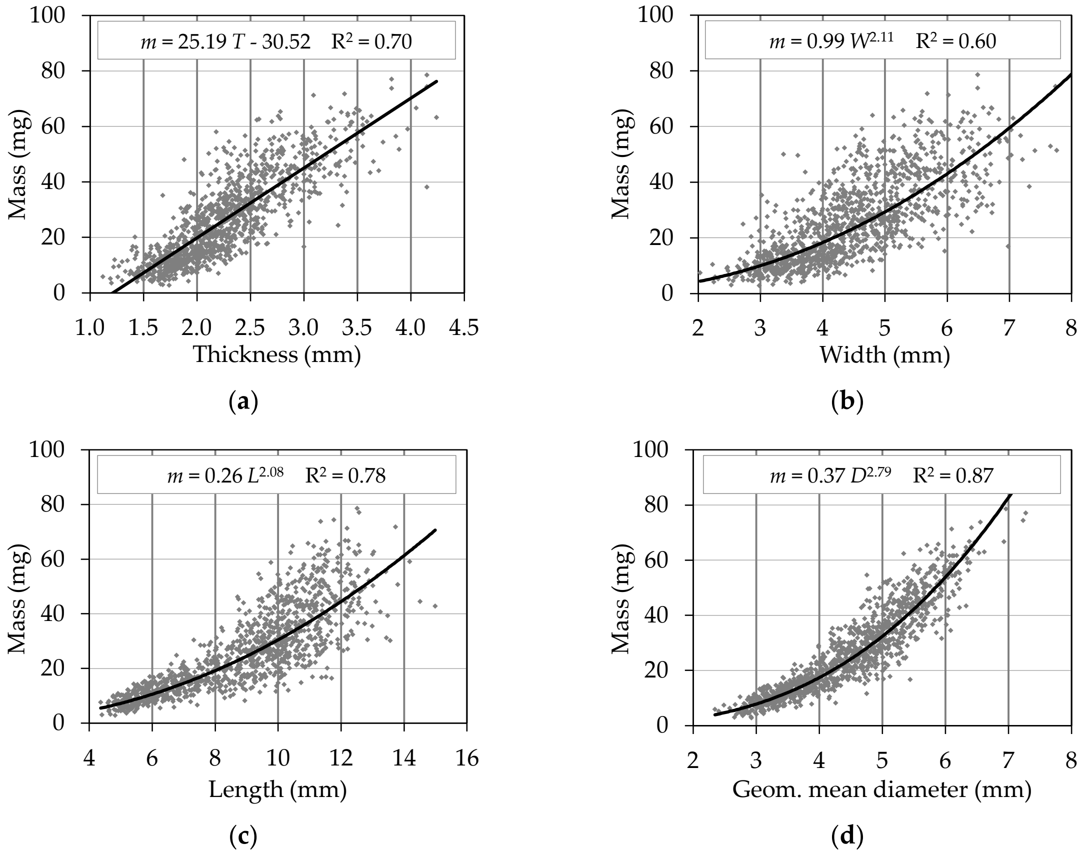
Table 3. Coefficients of linear correlation between the physical properties (indicators) of fir seeds.

Property	*v*	*T*	*W*	*L*	*γ*	*m*	*D*	*T/W*	*T/L*	*W/L*	*Φ*
T	0.64 *	1									
W	0.33 *	0.60 *	1								
L	0.39 *	0.69 *	0.69 *	1							
γ	-0.28 *	-0.25 *	-0.26 *	-0.23 *	1						
m	0.70 *	0.84 *	0.75 *	0.82 *	-0.28 *	1					
D	0.51 *	0.86 *	0.87 *	0.91 *	-0.28 *	0.92 *	1				
T/W	0.31 *	0.38 *	-0.48 *	-0.03	0.02	0.05	-0.05	1			
T/L	0.16 *	0.14 *	-0.30 *	-0.60 *	0.04	-0.22 *	-0.30 *	0.47 *	1		
W/L	-0.16 *	-0.24 *	0.19 *	-0.55 *	0.02	-0.26 *	-0.24 *	-0.52 *	0.49 *	1	
Φ	0.01	-0.06	-0.05	-0.67 *	0.03	-0.27 *	-0.31 *	-0.03	0.86 *	0.86 *	1
m_D	0.75 *	0.78 *	0.67 *	0.79 *	-0.30 *	0.99 *	0.85 *	0.08 *	-0.24 *	-0.31 *	-0.31 *

v – terminal velocity, *T* – thickness, *W* – width, *L* – length, *γ* – angle of external friction, *m* – mass, *D* – geometric mean diameter, *T/W*, *T/L* and *W/L* – aspect ratios, *Φ* – sphericity index, m_D – specific mass.
* – mean significant correlation at the 0.05.



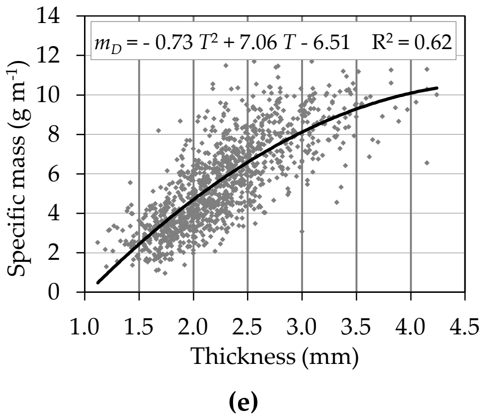


Figure 2. Relationships between the selected physical parameters of fir seeds: (**a**) Thickness and mass; (**b**) Width and mass; (**c**) Length and mass; **d**) Geometrical mean diameter and mass; (**d**) Thickness and specific mass.

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3.3. Seed separation

According to many authors [2,26,46,50,53-55], fir seeds differ in germination capacity which can range from 0 to approximately 90% in freshly harvested seeds. The above can be attributed to the fact fir seeds are characterized by a high proportion of empty seeds [2,26,33,50,56,57] which can reach 70% in some cases. Empty seeds are difficult to separate because similarly to filled seeds, they contain resin globules whose specific gravity is similar to that of filled seeds. The ranges of seed mass values overlap in empty and filled seeds, but empty and filled seeds differ in average mass, and this trait can be potentially used in the separation of fir seeds [26,33,43]. The mass of fir seeds was most significantly influenced by seed thickness and seed length (Table 3 and Figure 3). Therefore, the above parameters should be regarded as the primary distinguishing features in seed separation processes, and fir seeds should be sorted with the use of mesh sieves with longitudinal openings or with a seed grader. According to the authors, a seed grader is less effective because indented pockets on the surface of the cylinder are more suitable for separating elliptical seeds [35] rather than triangular seeds. Seed thickness should be regarded as a distinguishing feature because this parameter was highly correlated with specific mass (coefficient of determination of 0.62). Sorting operations based on seed thickness will produce seed fractions with different content of parenchymal tissue. The resulting fractions should be sown separately to improve germination rates and germination efficiency.

Table 4. Coefficients of linear correlation between seed mass and the remaining physical properties of fir seeds.

Fir species	Coefficient of Correlation between Seed Mass m and:				
	Terminal velocity v	Thickness T	Width W	Length L	Angle of Exter. Frict. γ
Balsam fir	0.797 *	0.669 *	0.416 *	0.650 *	-0.499 *
Corkbark fir	0.626 *	0.675 *	0.579 *	0.698 *	-0.149
Forrest's fir	0.786 *	0.617 *	0.494 *	0.691 *	-0.119
Grand fir	0.677 *	0.486 *	0.308 *	0.321 *	-0.218 *
Japanese fir	0.659 *	0.659 *	0.398 *	0.503 *	-0.556 *
Korean fir	0.587 *	0.705 *	0.541 *	0.647 *	-0.232 *
Noble fir	0.718 *	0.645 *	0.517 *	0.474 *	-0.079
Sierra white fir	0.582 *	0.580 *	0.496 *	0.432 *	-0.258 *
Silver fir	0.578 *	0.625 *	0.487 *	0.596 *	-0.042
Subalpine fir	0.657 *	0.552 *	0.430 *	0.624 *	-0.282 *
White fir	0.453 *	0.472 *	0.540 *	0.649 *	-0.196 *

* – mean significant correlation at the 0.05.

A detailed analysis of the linear correlations between seed mass and the remaining physical attributes of seeds (Table 4) revealed that seeds of selected fir species can also be sorted with a pneumatic separator. The above applies particularly to the seeds of balsam fir, Forrest's fir, grand fir, noble fir, Sierra white fir and subalpine fir. According to Załęski [29] and Tylek [42,43,51,58], terminal velocity should be the primary distinguishing trait in the process of separating silver fir seeds.

The results of the analysis (Table 5) indicate that fir seeds can also be effectively separated based on their terminal velocity. In most cases, the resulting seed fractions were characterized by uniform seed mass. Before sorting, the coefficient of variation of seed mass ranged from around 22% (white fir) to around 37% (Forrest's fir), and it decreased after sorting, particularly in fractions II and III. Fraction III seeds (8 out of 11 cases) and fraction II seeds (3 out of 11 cases) were least varied in terms of mass. The coefficient of variation of seed mass in each separated fraction differed across fir species from around 12% (fraction III, noble fir) to around 36% (fraction I, Sierra white fir). Seed mass was the most reliable separation trait in noble fir seeds in fraction III (change of 54.4%) and the least reliable trait in Sierra white fir seeds in fraction I (change of 36.2% relative to unsorted material). The average increase in the homogeneity of seeds separated into three fractions based on terminal velocity ranged from approximately 4.1% (Sierra white fir) to approximately 32.5% (noble fir).

Table 5. Coefficient of variation of seed mass in three seed fractions separated based on terminal velocity.

Fir species	Seed fraction	Percentage (%)	Mass (mg)	Coefficient of Variation (%) of Seed Mass	
				Fraction	Total
Balsam fir	I ($v<4.5$ m s^{-1})	30.7	5.46	25.91	30.10
	II ($v=4.5÷5.5$ m s^{-1})	56.4	8.63	18.10	
	III ($v>5.5$ m s^{-1})	12.9	10.77	19.31	
Corkbark fir	I ($v<5.5$ m s^{-1})	28.8	12.54	31.13	29.49
	II ($v=5.5÷6.0$ m s^{-1})	44.2	15.24	20.09	
	III ($v>6.0$ m s^{-1})	27.0	21.01	18.59	
Forrest's fir	I ($v<5.0$ m s^{-1})	16.8	20.67	32.37	36.90
	II ($v=5.0÷6.0$ m s^{-1})	42.1	31.51	29.62	
	III ($v>6.0$ m s^{-1})	41.1	46.17	21.23	
Grand fir	I ($v<5.0$ m s^{-1})	19.4	19.10	27.29	24.45
	II ($v=5.0÷5.5$ m s^{-1})	35.2	25.72	16.44	
	III ($v>5.5$ m s^{-1})	45.4	30.06	18.34	
Japanese fir	I ($v<5.0$ m s^{-1})	24.5	15.79	24.23	29.13
	II ($v=5.0÷5.5$ m s^{-1})	30.4	18.77	22.87	
	III ($v>5.5$ m s^{-1})	45.1	25.21	20.55	
Korean fir	I ($v<5.0$ m s^{-1})	17.0	7.62	29.59	29.54
	II ($v=5.0÷6.0$ m s^{-1})	36.8	11.19	27.38	
	III ($v>6.0$ m s^{-1})	46.2	13.27	20.34	
Noble fir	I ($v<5.5$ m s^{-1})	18.3	23.75	21.80	26.35
	II ($v=5.5÷6.5$ m s^{-1})	69.2	37.88	19.53	
	III ($v>6.5$ m s^{-1})	12.5	47.36	12.03	
Sierra white fir	I ($v<5.0$ m s^{-1})	15.7	20.56	35.59	26.13
	II ($v=5.0÷5.5$ m s^{-1})	39.2	27.08	19.47	
	III ($v>5.5$ m s^{-1})	45.1	32.41	20.10	
Silver fir	I ($v<6.5$ m s^{-1})	26.3	37.49	32.85	26.61
	II ($v=6.5÷7.5$ m s^{-1})	51.7	49.65	21.21	
	III ($v>7.5$ m s^{-1})	22.0	58.21	14.85	
Subalpine fir	I ($v<4.5$ m s^{-1})	24.5	9.67	32.08	28.70
	II ($v=4.5÷5.0$ m s^{-1})	33.0	11.93	22.76	
	III ($v>5.0$ m s^{-1})	42.5	15.40	18.35	
White fir	I ($v<6.0$ m s^{-1})	26.9	36.37	22.01	22.16
	II ($v=6.0÷6.5$ m s^{-1})	37.5	41.88	21.46	
	III ($v>6.5$ m s^{-1})	35.6	48.04	16.18	

In most cases (excluding 3 cases in fraction I), seed thickness was also a reliable parameter for sorting seeds into fractions with similar mass (Table 6). The coefficient of variation of seed thickness differed across fir species from around 16% (fraction III, silver fir) to around 35% (fraction I, Forrest's fir), and silver fir seeds in fraction III were characterized by the most uniform thickness (change of 40% relative to unsorted material). The average increase in the homogeneity of seeds separated into three fractions based on seed thickness ranged from around 2.6% (grand fir) to around 24.7% (Japanese fir).

The homogeneity of fir seeds separated into three fractions based on terminal velocity or seed thickness indicates that a pneumatic separator should be used primarily for sorting balsam fir, corkbark fir, Forrest's fir, grand fir, noble fir and white fir seeds, whereas a mesh sieve with longitudinal openings is most suitable for sorting Japanese fir, Korean fir, Sierra white fir, silver fir and subalpine fir seeds. A mesh sieve appears to be the preferred solution for sorting fir seeds because the resulting fractions do not have to be dewinged before storage (seed wings do not disrupt the separation process), whereas dewinging operations increase the risk of damage to resin ducts and make seeds more susceptible to infection [51]. It should also be noted that the elimination of resin globules, for example during rapid dewinging, leads to a rapid deterioration in seed quality [2,22,59].

The obtained seed fractions should be analyzed for germination capacity and sown in the most appropriate locations. Seeds of fractions I and II, with the potentially lowest germination capacity, can be sown in rows or broadcast in conventional nurseries (by choosing the most appropriate sowing rate), whereas fraction III seeds can be sown individually in beds or containers.

Table 6. Coefficient of variation of seed mass in three seed fractions separated based on thickness.

Fir species	Seed fraction	Percentage (%)	Mass (mg)	Coefficient of Variation (%) of Seed Mass	
				Fraction	Total
Balsam fir	I (*T*≤1.60 mm)	18.8	5.99	21.30	30.10
	II (*T*=1.61÷1.80 mm)	40.6	7.09	27.06	
	III (*T*>1.80 mm)	40.6	9,68	21.15	
Corkbark fir	I (*T*≤1.80 mm)	23.1	11.75	28.20	29.49
	II (*T*=1.81÷2.10 mm)	43.3	15.85	23.62	
	III (*T*>2.10 mm)	33.6	19.81	20.38	
Forrest's fir	I (*T*≤2.10 mm)	26.2	24.36	35.05	36.90
	II (*T*=2.11÷2.50 mm)	41.1	36.04	28.01	
	III (*T*>2.50 mm)	32.7	44.40	29.43	
Grand fir	I (*T*≤2.10 mm)	22.2	22.00	30.51	24.45
	II (*T*=2.11÷2.40 mm)	42.6	26.36	19.08	
	III (*T*>2.40 mm)	35.2	29.23	21.88	
Japanese fir	I (*T*≤1.80 mm)	27.5	15.22	18.78	29.13
	II (*T*=1.81÷2.10 mm)	32.4	21.28	25.12	
	III (*T*>2.10 mm)	40.1	24.58	21.92	
Korean fir	I (*T*≤1.60 mm)	19.8	8.00	31.17	29.54
	II (*T*=1.61÷1.80 mm)	45.3	11.38	24.40	
	III (*T*>1.80 mm)	34.9	13.77	20.44	
Noble fir	I (*T*≤2.40 mm)	28.8	28.72	26.12	26.35
	II (*T*=2.41÷2.70 mm)	37.5	35.85	22.27	
	III (*T*>2.70 mm)	33.7	43.83	16.36	
Sierra white fir	I (*T*≤2.10 mm)	25.5	24.54	25.33	26.13
	II (*T*=2.11÷2.40 mm)	45.1	27.41	23.28	
	III (*T*>2.40 mm)	29.4	33.47	22.11	
Silver fir	I (*T*≤3.00 mm)	26.3	38.09	31.36	26.61
	II (*T*=3.01÷3.40 mm)	44.9	47.32	20.12	
	III (*T*>3.40 mm)	28.8	59.28	16.03	
Subalpine fir	I (*T*≤1.80 mm)	34.9	10.25	27.33	28.70
	II (*T*=1.81÷2.10 mm)	36.8	13.40	25.43	
	III (*T*>2.10 mm)	28.3	15.34	19.38	
White fir	I (*T*≤2.40 mm)	30.8	37.69	18.58	22.16
	II (*T*=2.41÷2.70 mm)	32.7	42.69	19.92	
	III (*T*>2.70 mm)	36.5	46.61	21.98	

4. Conclusions

Balsam fir produced the smallest seeds, and silver fir produced the largets seeds.

Sierra white fir seeds were most similar, and balsam fir seeds differed most considerably from the remaining fir species.

Specific mass (9 homogeneous groups) was the most differentiating attribute, whereas the *W*/*L* aspect ratio (4 homogeneous groups) was the least differentiating trait in the analyzed fir species.

Fir seeds should be sorted primarily with the use of mesh sieves with longitudinal openings to obtain fractions with similar seed mass.

The seeds of balsam fir, corkbark fir, Forrest's fir, grand fir, noble fir and white fir can also be sorted with pneumatic separators.

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