

Communication

Variations and Correlations between the Physical Properties of Seeds of Eleven Spruce Species

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Abstract: Information about the variations and correlations between the physical properties of seeds is essential for designing and modeling seed processing operations. The aim of this study was to determine the variations in the basic physical properties of seeds of selected spruce species and to identify the correlations between these attributes for the needs of the seed sorting processes. Terminal velocity, thickness, width, length, mass and the angle of external friction were determined in the seeds of 11 spruce species. The measured parameters were used to calculate three aspect ratios, geometric mean diameter, sphericity index and specific mass of each seed. The average values of the basic physical properties of the analyzed seeds were determined in the following range: terminal velocity – 5.25 to 8.34 m s⁻¹, thickness – 1.10 to 2.32 mm, width – 1.43 to 3.19 mm, length – 2.76 to 5.52 mm, the angle of external friction – 23.1 to 30.0°, and mass – 2.29 to 18.57 mg. The seeds of Jezo spruce and Meyer's spruce were most similar to the seeds of other spruce species, whereas oriental spruce seeds differed most considerably from the remaining seeds. Our findings indicate that spruce seeds should be sorted primarily with the use of mesh sieves with longitudinal openings to obtain fractions with similar seed mass and to promote even germination.

Keywords: seeds; physical properties; range of variation; correlations; sorting

1. Introduction

Spruce (*Picea*) trees belong to the pine family (Pinaceae) and are characterized by a regular conical crown relative to other conifers. Depending on species, spruces reach the height of 20 m to nearly 100 m at full maturity [1,2]. Approximately 40 spruce species have been identified to date, and all of them reside in the northern hemisphere [1,3–7]. Spruces are the predominant tree species in extensive boreal forests [8–12]. They have higher soil requirements than pines, and they thrive on brown soil, sandy loam and loamy sand [7,13]. Spruces have high soil and air moisture requirements, and they are sensitive to frost. The discussed species is susceptible to strong winds on account of its shallow root system and thick crown. The risk of tree toppling is exacerbated when the tree stand is rapidly uncovered or considerably thinned. Spruces are shade-tolerant, and their canopies create a unique microclimate which is characterized by significant shading, lower temperature and higher humidity relative to the surroundings [2,11,14,15].

Spruces have more or less quadrangular, sharply pointed needles which are spirally arranged on all sides of the twig. Needle length ranges from 5 to 50 mm in various spruce species [1,5,7]. Needles are shed every 4 to 12 years, and they are replaced with new growth [1]. Young spruce shoots are abundant in vitamin C, and they are a popular folk remedy for cough, cold, respiratory ailments and pain. Spruce oil has antibacterial and antifungal properties [16–20]. In survival situations, spruce needles can be directly consumed or boiled into tea. Spruce needles have high water content, and they provide an alternative means of hydration. Spruce needles, young twigs and

essential oils are used to brew spruce beer. Spruce seeds and young plants are readily consumed by various forest animals which often cause substantial damage to spruce stands [21–25].

In spring, spruces produce cones that ripen 4 to 8 months later in autumn. Cones initially grow upright on the branches, but they begin to hang down in successive stages of maturation. Depending on the species, cones have the length of 2 to 20 cm, and they are yellow-green, red to dark purple in color [1]. Each scale covers two brown-black seeds which are usually released when the cone falls to the ground. Seeds have an average length of 2 to 7 mm, and the size and quality of spruce seeds is generally determined by genetic factors, climate and weather conditions [26–29].

Information about the variations and correlations between the physical properties of seeds is essential for designing and modeling seed cleaning, sorting, storing, sowing and processing operations [30,31]. Seed viability, germinative energy and germination capacity are the main determinants of seed quality [32]. According to many authors, germination efficiency is largely correlated with seed mass, but plumper seeds do not always germinate faster than small seeds [32–39]. In tree nurseries, seeds are sorted into different size fractions to promote even germination. This approach creates equal opportunities for seedling growth and decreases competition between seedlings [40]. Plants grown from sorted seeds are more uniform and are characterized by similar morphological parameters. However, in large production plants, seeds are difficult to sort based on their mass only, which is why 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 variations in the basic physical properties of seeds of selected spruce species and to identify the correlations between these attributes for the needs of the seed sorting processes.

2. Materials and Methods

2.1. Sample preparation

The basic physical properties of seeds of 11 spruce species were analyzed (Figure 1): blue spruce (*Picea pungens* Engelm.), Jezo spruce (*Picea jezoensis* Siebold & Zucc.), Lijiang spruce (*Picea likiangensis* Franch.), Meyer's spruce (*Picea meyeri* Rehd. & E.H.Wilson), Morinda spruce (*Picea smithiana* Wall.), Norway spruce (*Picea abies* L.), oriental spruce (*Picea orientalis* L.), red spruce (*Picea rubens* Sarg.), Schrenk's spruce (*Picea schrenkiana* Fish. & C.A.Mey.), Sitka spruce (*Picea sitchensis* Bong) and white spruce (*Picea glauca* Moench). Seeds were obtained in 2017 from Dendrona in Peciçe which produces tree, shrub, perennial plant and herbaceous plant seeds.

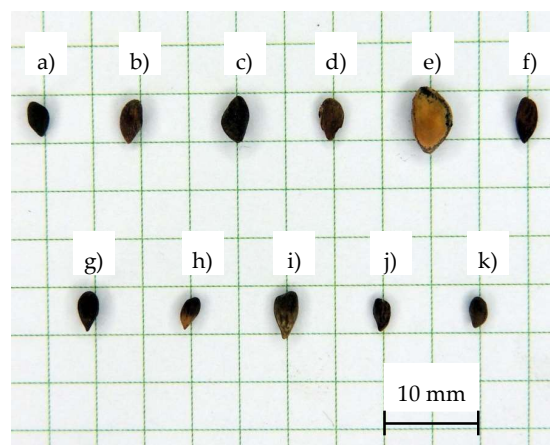


Figure 1. Seeds of: a) blue spruce, b) Jezo spruce, c) Lijiang spruce, d) Meyer's spruce, e) Morinda spruce, f) Norway spruce, g) oriental spruce, h) red spruce, i) Schrenk's spruce, j) Sitka spruce, k) white spruce

Seed samples for analysis were obtained by halving [32]. 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. The analyzed samples contained 93 to 116 seeds.

2.2. Physical properties

Terminal velocity (v) was determined in the Petkus K-293 pneumatic classifier to the nearest 0.11 m s^{-1} , and basic seed dimensions were measured under the MWM 2325 laboratory microscope (length L and width W) and with a thickness (T) gauge to the nearest 0.01 mm . The angle of external friction α was determined on a steel friction plate (surface roughness – $Ra=0.48 \text{ }\mu\text{m}$) positioned on a horizontal plane to the nearest 1° , and seed mass m – on the WAA 100/C/2 laboratory scale to the nearest 0.1 mg . The measurements were conducted based on the method described by Kaliniewicz et al. [41,42] and Kaliniewicz and Poznański [43]. 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 aspect ratios (T/W , T/L and W/L), geometric mean diameter D and sphericity index Φ were determined for each seed [44]:

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

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

Specific mass was determined for each seed [45]:

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

Seeds were divided into three roughly equal groups based on their thickness: fine seeds (group I – thinnest seeds), medium-sized seeds (group II – seeds with average thickness) and large seeds (group III – thickest seeds). Seed thickness was measured to the nearest 0.05 mm .

2.3. Statistical analysis

The measured physical parameters of seeds were processed in Statistica PL v. 12.5 at a significance level of $\alpha=0.05$. The differences between the measured properties 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. If the null hypothesis, which postulated that the average values of a given parameter in the analyzed seed species are equal, was rejected, the significance of differences was determined and homogenous groups were identified with the use of Duncan's test. A correlation analysis was performed to determine the strength and direction of the correlations between the analyzed seeds parameters. The degree of correlation was evaluated with the use of Pearson's correlation coefficient. The functions describing the correlations between the physical parameters of seeds were determined by regression analysis [46]. 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. A large number of statistically significant regression equations were obtained; therefore, only the equations with a minimum coefficient of determination of 0.8 were presented in the paper.

3. Results

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 93 to 116 seeds; therefore, the standard error of the estimate of the mean values of the evaluated physical properties of spruce seeds did not exceed:

- for terminal velocity – 0.25 m s⁻¹,
- for basic dimensions (thickness, width and length) – 0.1 mm,
- for the angle of external friction – 1.2°,
- for seed mass – 0.7 mg.

The physical properties of the analyzed seeds are presented in Table 1. The average terminal velocity ranged from 5.25 m s⁻¹ (Schrenk's spruce) to 8.34 m s⁻¹ (Morinda spruce). The following spruce species formed homogeneous groups in terms of terminal velocity: Jezo spruce, red spruce, white spruce, Lijiang spruce, Meyer's spruce and Schrenk's spruce.

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

Spruce species	Property					
	Terminal velocity <i>v</i> (m s ⁻¹)	Thickness <i>T</i> (mm)	Width <i>W</i> (mm)	Length <i>L</i> (mm)	Angle of external friction <i>α</i> (°)	Mass <i>m</i> (mg)
Blue spruce	6.09±0.54 ^c	1.44±0.13 ^c	1.77±0.18 ^c	3.70±0.34 ^d	27.33±4.40 ^c	4.22±0.93 ^c
Jezo spruce	5.79±1.14 ^b	1.49±0.18 ^d	1.98±0.27 ^d	3.91±0.41 ^e	29.02±5.74 ^{de}	4.78±1.97 ^d
Lijiang spruce	6.42±0.87 ^d	1.63±0.20 ^f	2.13±0.28 ^e	4.46±0.42 ^g	29.01±4.44 ^{de}	6.98±1.99 ^{fg}
Meyer's spruce	6.54±0.74 ^d	1.53±0.18 ^e	2.00±0.26 ^d	3.92±0.42 ^e	29.13±4.56 ^{de}	6.11±1.69 ^e
Morinda spruce	8.34±0.58 ^g	2.32±0.18 ^g	3.19±0.29 ^g	5.52±0.44 ^h	23.10±2.44 ^a	18.57±3.11 ^h
Norway spruce	7.61±0.85 ^f	1.54±0.20 ^e	2.19±0.26 ^f	4.23±0.48 ^f	29.41±4.75 ^e	6.92±2.33 ^{fg}
Oriental spruce	6.92±0.72 ^e	1.63±0.16 ^f	2.08±0.26 ^e	3.98±0.38 ^e	25.50±3.81 ^b	6.50±1.79 ^{ef}
Red spruce	5.71±0.65 ^b	1.21±0.12 ^b	1.61±0.20 ^b	3.15±0.29 ^c	28.99±5.05 ^{de}	2.95±0.83 ^b
Schrenk's spruce	6.60±0.86 ^d	1.63±0.16 ^f	2.24±0.27 ^f	4.54±0.42 ^g	28.11±4.88 ^{cd}	7.38±1.89 ^g
Sitka spruce	5.25±0.40 ^a	1.10±0.11 ^a	1.47±0.23 ^a	2.97±0.24 ^b	30.00±4.79 ^e	2.29±0.51 ^a
White spruce	5.69±0.56 ^b	1.21±0.14 ^b	1.43±0.17 ^a	2.76±0.22 ^a	28.87±4.70 ^{de}	2.36±0.63 ^a

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

The average seed thickness ranged from 1.10 mm (Sitka spruce) to 2.32 mm (Morinda spruce). Seed thickness was similar in the seeds of Meyer's spruce and Norway spruce, as well as in Lijiang spruce, oriental spruce and Schrenk's spruce. The following spruce species formed homogeneous pairs in terms of seed width: Sitka spruce and white spruce, Jezo spruce and Meyer's spruce, Lijiang spruce and oriental spruce, Norway spruce and Schrenk's spruce. The average seed width ranged from 1.43 mm (white spruce) to 3.19 mm (Morinda spruce), and the average seed length – from 2.76 mm (white spruce) to 5.52 (Morinda spruce). The following spruce species formed homogeneous groups in terms of seed length: Jezo spruce, Meyer's spruce and oriental spruce, as well as Lijiang spruce and Schrenk's spruce.

Only minor variations were noted in the average angle of external friction which ranged from 23.10° (Morinda spruce) to 30.00° (Sitka spruce). The smallest angle of external friction was noted in Morinda spruce and oriental spruce which differed from the remaining spruce species in this respect.

The average seed mass ranged from 2.29 mm (Sitka spruce) to 18.57 mg (Morinda spruce). The following spruce species formed homogeneous groups in terms of seed mass: Sitka spruce and white

spruce; Meyer's spruce and oriental spruce; Lijiang spruce, Norway spruce and oriental spruce: Lijiang spruce, Norway spruce and Schrenk's spruce.

Morinda spruce was characterized by the largest seeds (geometric mean diameter of 3.44 mm, Table 2), whereas Sitka spruce and white spruce had the smallest seeds (geometric mean diameter of 1.68 mm). Significant differences in geometric mean diameter were not observed in the following pairs of spruce species: Sitka spruce and white spruce, Jezo spruce and Meyer's spruce, Norway spruce and oriental spruce.

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

Spruce species	Indicator					
	Geometric mean diameter <i>D</i> (mm)	Aspect ratio <i>T/W</i> (%)	Aspect ratio <i>T/L</i> (%)	Aspect ratio <i>W/L</i> (%)	Sphericity index Φ (%)	Specific mass <i>m_D</i> (g m ⁻¹)
Blue spruce	2.11±0.15 ^c	81.81±8.50 ^f	39.17±3.93 ^c	48.24±5.74 ^{ab}	57.27±3.71 ^{bc}	1.99±0.37 ^c
Jezo spruce	2.25±0.20 ^d	76.16±11.29 ^{cd}	38.19±4.60 ^{bc}	50.84±7.17 ^{cd}	57.72±3.92 ^{bcd}	2.10±0.76 ^c
Lijiang spruce	2.48±0.23 ^f	77.52±10.98 ^{de}	36.72±4.71 ^a	47.79±5.63 ^a	55.83±3.76 ^a	2.77±0.62 ^{de}
Meyer's spruce	2.28±0.21 ^d	77.40±10.59 ^{de}	39.27±4.34 ^c	51.24±5.79 ^{cd}	58.46±3.41 ^d	2.64±0.53 ^d
Morinda spruce	3.44±0.21 ^h	73.06±7.59 ^{ab}	42.08±3.53 ^d	57.98±5.65 ^e	62.39±3.14 ^g	5.38±0.64 ^f
Norway spruce	2.42±0.26 ^e	70.60±7.79 ^a	36.44±2.75 ^a	51.98±4.53 ^d	57.35±2.31 ^{bc}	2.79±0.63 ^{de}
Oriental spruce	2.38±0.21 ^e	79.07±9.64 ^e	41.17±3.83 ^d	52.58±6.03 ^d	59.92±3.40 ^e	2.70±0.56 ^d
Red spruce	1.83±0.14 ^b	75.75±9.22 ^{bcd}	38.66±4.44 ^c	51.63±7.56 ^d	58.29±4.53 ^{cd}	1.61±0.39 ^b
Schrenk's spruce	2.54±0.19 ^g	73.49±10.74 ^{bc}	35.99±3.89 ^a	49.63±6.43 ^{bc}	56.17±3.50 ^a	2.89±0.64 ^e
Sitka spruce	1.68±0.12 ^a	76.12±11.20 ^{cd}	37.12±4.17 ^{ab}	49.62±8.11 ^{bc}	56.70±4.21 ^{ab}	1.36±0.25 ^a
White spruce	1.68±0.14 ^a	85.29±9.21 ^g	43.95±5.07 ^e	51.85±6.00 ^d	60.95±4.09 ^f	1.40±0.31 ^a

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

The average values of the calculated aspect ratios were determined in the following range: *T/W* ratio – from 70.60% (Norway spruce) to 85.29% (white spruce); *T/L* ratio – from 35.99% (Schrenk's spruce) to 43.95% (white spruce); *W/L* ratio – from 47.79% (Lijiang spruce) to 57.98% (Morinda spruce). The following spruce species differed considerably from the remaining species in terms of selected aspect ratios: blue spruce (*T/W* ratio), Morinda spruce (*W/L* ratio) and white spruce (*T/W* and *T/L* ratios).

The sphericity index was highest in the seeds of Morinda spruce (62.39%) and lowest in the seeds of Lijiang spruce (55.83%). The analyzed seeds formed 7 homogeneous groups in terms of the average values of the sphericity index. Morinda spruce, oriental spruce and white spruce seeds formed separate groups.

The average specific mass of spruce seeds varied widely from 1.36 g m⁻¹ (Sitka spruce) to 5.38 g m⁻¹ (Morinda spruce). The above species produced the smallest and the largest seeds, respectively, containing the largest and the smallest number of empty spaces, respectively, in parenchymal tissue. The seeds of Morinda spruce and red spruce differed most significantly from the remaining species in this respect.

3.2. Correlations between seed properties

As previously mentioned, germination efficiency is significantly influenced by seed mass, a trait that cannot be reliably used to sort seeds into fractions. For this reason, the correlations between seed mass and the remaining physical properties were determined in this study. A linear correlation analysis of the above parameters (Table 3) revealed that seed mass was least influenced by the angle of external friction. Seed mass was most highly correlated with terminal velocity (6 spruce species), seed length (Meyer's spruce, Morinda spruce and Norway spruce) and seed thickness (Sitka's spruce and white spruce). A strong correlation was also noted between seed mass and seed thickness, and the values of the relevant correlation coefficients were always higher than the coefficients of

correlation between seed mass and seed width. These results indicate that spruce seeds should be sorted with the use of mesh sieves with longitudinal rather than round openings.

Table 3. Coefficients of linear correlation between mass and the remaining physical properties of spruce seeds.

Spruce species	Coefficient of correlation between seed mass m and:				
	terminal velocity v	thickness T	width W	length L	angle of external friction α
Blue spruce	0.610*	0.538*	0.459*	0.516*	0.101
Jezo spruce	0.866*	0.573*	0.264*	0.455*	-0.594*
Lijiang spruce	0.765*	0.658*	0.653*	0.597*	-0.320*
Meyer's spruce	0.617*	0.747*	0.575*	0.798*	-0.488*
Morinda spruce	0.418*	0.688*	0.529*	0.753*	0.045
Norway spruce	0.654*	0.881*	0.759*	0.920*	-0.190*
Oriental spruce	0.782*	0.748*	0.640*	0.778*	-0.302*
Red spruce	0.533*	0.479*	0.354*	0.453*	-0.164
Schrenk's spruce	0.783*	0.503*	0.387*	0.434*	-0.167
Sitka spruce	0.515*	0.592*	0.349*	0.476*	-0.138
White spruce	0.374*	0.613*	0.443*	0.599*	-0.149

* – mean significant correlation at the 0.05.

Significant correlations (0.05) were observed in 49 out of 55 comparisons (pairs). The correlation coefficient was practically significant (higher than 0.4) in 41 cases. The highest value of the correlation coefficient (0.92) was noted between the mass and length of Norway spruce seeds.

In further analysis, the measured parameters of spruce seeds were pooled into a single experimental group. The correlations between the basic physical dimensions of seeds were determined by testing various regression functions (Figure 2). Quadratic functions best fit empirical data (equations with the highest coefficient of determination). An equation with the highest percentage of explained variation (0.88) was obtained for the correlation between seed mass and seed thickness. An increase in seed thickness from around 0.9 mm to around 2.8 mm was accompanied by an estimated 1800% increase in seed mass (from approx. 1.5 mg to approx. 28.3 mg). Seed mass significantly influences germination efficiency and germination rate; therefore, spruce seeds should be sorted into fractions based mainly on their thickness. The above approach is also dictated by the significant correlation between seed thickness and specific mass (coefficient of determination – 0.82). Seed length, seed width and terminal velocity could be used as secondary rather than primary distinguishing features in seed separation processes (the coefficient of determination for terminal velocity was determined at 0.70, and the relevant equation was not presented in the study).

The results of the analysis (Table 4) indicate that spruce seeds sorted based on seed thickness produce fractions with uniform seed mass. Before sorting, the coefficient of variation of seed mass ranged from around 17% (Morinda spruce) to around 41% (Jezo spruce), and it decreased in the sorted fractions. Medium-sized seeds (6 out of 11 cases) and large seeds (5 out of 11 cases) were least differentiated in terms of mass. In the analyzed seed groups, the coefficient of variation of seed mass differed across species and ranged from around 10% (group III, Morinda spruce) to around 39% (group I, Jezo spruce). After sorting, group II seeds of Norway spruce were most uniform in terms of seed mass (change of approx. 54.6%), whereas group I seeds of blue spruce were least uniform in terms of seed mass (change of approx. 3.5% relative to unsorted material). The following mesh sieves should be used to separate group I seeds of the analyzed spruce species: $\neq 1.05$ mm (Sitka spruce), $\neq 1.15$ mm (red and white spruce), $\neq 1.40$ mm (blue spruce, Jezo spruce, Meyer's spruce), $\neq 1.45$ mm (Norway spruce), $\neq 1.55$ mm (Lijiang spruce, oriental spruce, Schrenk's spruce) and $\neq 2.25$ mm (Morinda spruce). The following mesh sieves should be used to separate group III seeds: $\neq 1.15$ mm (Sitka spruce), $\neq 1.25$ mm (red and white spruce), $\neq 1.50$ mm (blue spruce), $\neq 1.55$ mm (Jezo spruce),

≈1.60 mm (Meyer's spruce and Norway spruce), ≈1.70 mm (oriental spruce and Schrenk's spruce), ≈1.75 mm (Lijiang spruce) and ≈2.40 mm (Morinda spruce).

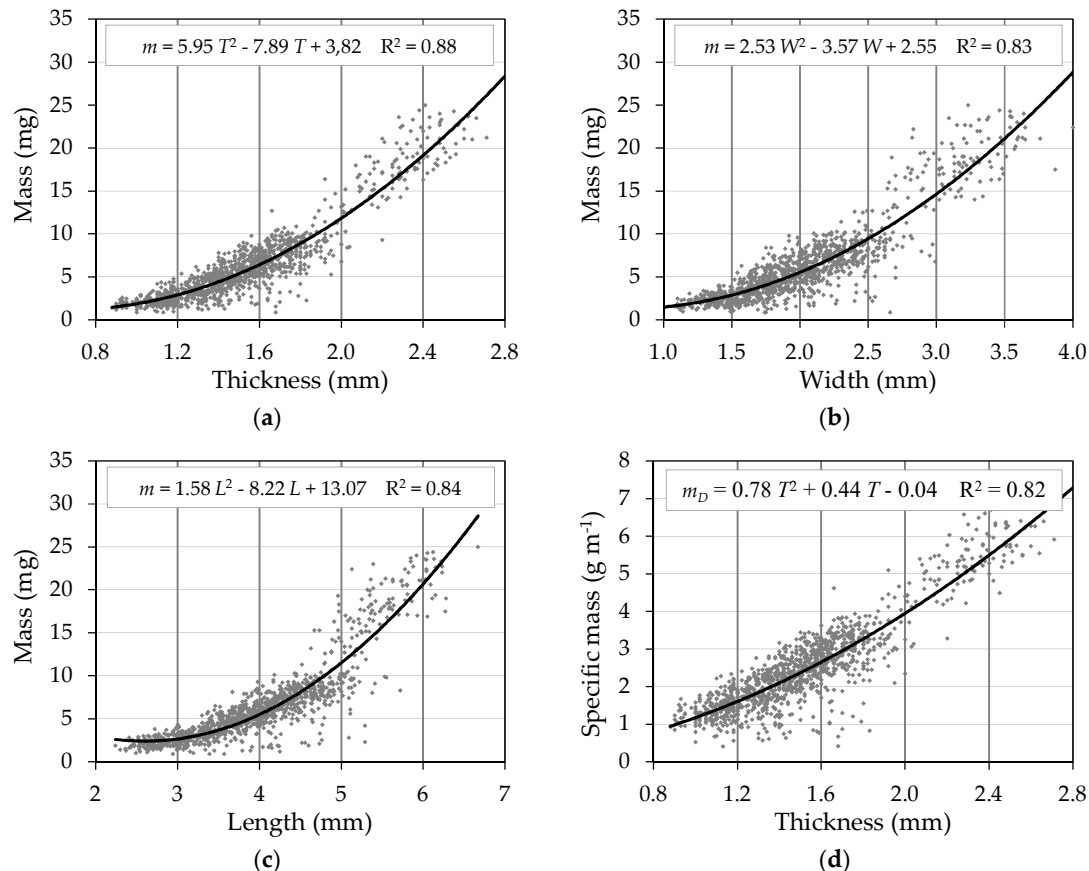


Figure 2. Relationships between the physical properties of spruce seeds: (a) Thickness and mass; (b) Width and mass; (c) Length and mass; (d) Thickness and specific mass

4. Discussion

According to the literature [26,32,47–50], seed plumpness, i.e. seed dimensions and seed mass, is largely influenced by genetic factors, the age of maternal trees and environmental conditions, mostly geographic location, habitat, distribution of fruit and seeds in the tree crown (height from the ground and orientation relative to the cardinal directions) and weather. Without taking the above considerations into account, the analyzed Norway spruce seeds were somewhat less plump than those studied by Oleksyn et al. [26], Tylek [51], Załęski [52] and Yehnjong et al. [53], they were similar to the seeds investigated by Kluczyński [47], and they were somewhat plumper than the seeds analyzed by Kaliniewicz et al. [42,54]. The above suggests that Norway spruce seeds evaluated in this study were characterized by average plumpness, and seed dimensions and seed mass were within the reference range for the species [26,32,55]. The remaining seed parameters and indices were similar to those noted by Kaliniewicz et al. [42,54,56]. The mass of the analyzed spruce seeds was similar to that of red spruce seeds from Ontario [27], Schrenk's spruce seeds from Tianshan Mountains [29], white spruce seeds from the Great Lakes region [57], and Morinda spruce seeds from Garhwal Himalaya [31]. White spruce seeds were similar to black spruce seeds [58] in terms of length and width. The seeds analyzed in the present study were characterized by average plumpness and could be regarded as representative of the studied spruce species. The aspect ratios and the sphericity index of the evaluated seeds were similar to those of wheat grains [59–61].

Pairs of spruce species characterized by significant similarities in all seed parameters were not identified in this study. The greatest similarities were observed between the seeds of Lijiang spruce

and Schrenk's spruce that did not differ significantly in terminal velocity, thickness, length, the angle of external friction, mass, T/L ratio, sphericity index or specific mass. In general, oriental spruce seeds differed most considerably from the remaining spruce species, whereas the seeds of Jezo spruce and Meyer's spruce were most similar to the remaining species. Therefore, the seeds of Jezo spruce and Meyer's spruce can be regarded as representative of the pine family and used to differentiate between the seeds of different spruce species. Aspect ratios T/L and W/L (5 homogeneous groups) were the least differentiating traits, whereas seed length, seed mass and geometric mean diameter (8 homogeneous groups) were the most differentiating attributes in the analyzed spruce seeds.

Table 4. Coefficient of variation of seed mass in three fractions of spruce seeds.

Spruce species	Seed fraction	Percentage (%)	Coefficient of variation (%) of seed mass	
			fraction	total
Blue spruce	I ($T \leq 1.40$ mm)	39.1	21.31	22.08
	II ($T = 1.41 \div 1.50$ mm)	33.9	14.43	
	III ($T > 1.50$ mm)	27.0	18.31	
Jezo spruce	I ($T \leq 1.40$ mm)	30.1	38.80	41.15
	II ($T = 1.41 \div 1.55$ mm)	34.4	30.93	
	III ($T > 1.55$ mm)	35.5	38.26	
Lijiang spruce	I ($T \leq 1.55$ mm)	30.4	26.53	28.46
	II ($T = 1.56 \div 1.75$ mm)	41.9	23.76	
	III ($T > 1.75$ mm)	27.7	20.11	
Meyer's spruce	I ($T \leq 1.40$ mm)	26.7	24.37	27.61
	II ($T = 1.41 \div 1.60$ mm)	40.6	18.61	
	III ($T > 1.60$ mm)	32.7	20.73	
Morinda spruce	I ($T \leq 2.25$ mm)	35.5	14.34	16.73
	II ($T = 2.26 \div 2.40$ mm)	34.6	13.11	
	III ($T > 2.40$ mm)	29.9	10.32	
Norway spruce	I ($T \leq 1.45$ mm)	34.5	19.73	33.61
	II ($T = 1.46 \div 1.60$ mm)	35.3	15.26	
	III ($T > 1.60$ mm)	30.2	23.54	
Oriental spruce	I ($T \leq 1.55$ mm)	26.6	26.01	27.55
	II ($T = 1.56 \div 1.70$ mm)	40.7	20.41	
	III ($T > 1.70$ mm)	32.7	16.02	
Red spruce	I ($T \leq 1.15$ mm)	33.6	26.13	28.00
	II ($T = 1.16 \div 1.25$ mm)	30.0	23.12	
	III ($T > 1.25$ mm)	36.4	23.37	
Schrenk's spruce	I ($T \leq 1.55$ mm)	29.1	23.12	25.59
	II ($T = 1.55 \div 1.70$ mm)	40.9	18.33	
	III ($T > 1.70$ mm)	30.0	23.39	
Sitka spruce	I ($T \leq 1.05$ mm)	35.8	19.94	22.40
	II ($T = 1.06 \div 1.15$ mm)	35.8	17.92	
	III ($T > 1.15$ mm)	28.4	16.63	
White spruce	I ($T \leq 1.15$ mm)	32.7	25.12	26.68
	II ($T = 1.16 \div 1.25$ mm)	32.7	22.08	
	III ($T > 1.25$ mm)	34.6	18.82	

The absolute value of the coefficient of correlation between the physical attributes of spruce seeds and seed mass ranged from 0.045 to 0.920, where the angle of external friction was least correlated with the remaining attributes. Our findings and the results reported by Tylek [62] in a study of European beech seeds and by Kaliniewicz et al. [63] in a study of fir seeds suggest that the frictional properties of the seeds of forest trees and shrubs can be used as secondary rather than primary distinguishing features in seed separation processes. Based on the calculated values of correlation coefficients, terminal velocity should be the main parameter for separating spruce seeds into fractions, in particular in Jezo spruce, Lijiang spruce and Schrenk's spruce seeds. This is

consistent with the general practice of sorting seeds of forest trees and shrubs where pneumatic separators are often deployed [32]. According to the literature [32,42,54,64–66], pneumatic separators can be effectively used to sort the seeds of European beech, European hornbeam, small-leaved lime, black locust, rowan, grey alder, European silver fir, Scotts pine, Norway spruce and European larch. However, a regression equation with the highest coefficient of determination (0.88) was obtained for the correlation between seed mass and seed thickness, which indicates that seed thickness (Figure 2) is the most reliable parameter for separating spruce seeds. The regression equation illustrating the correlation between seed thickness and specific mass (with a minimum coefficient of determination) also indicates that spruce seeds should be sorted with the use of mesh sieves with longitudinal openings. Separation processes that rely on seed thickness produce fractions that differ in the content of parenchymal tissue. Germination rates and germination efficiency can be improved when these seed fractions are sown separately. Seed thickness also proved to be a more reliable separation trait than terminal velocity in studies of European beech [66], Norway spruce [54] and European silver fir [63].

If a mesh sieve with longitudinal openings is not available, spruce seeds can also be sorted with a grain grader. A grain grader is particularly effective in sorting Meyer's spruce, Morinda spruce and Norway spruce seeds. According to Grochowicz [30], a grain grader has an indented cylinder for separating ellipsoidal seeds, such as the grain of the principal grain species. Grain graders are generally not used in tree nurseries, but they could be effective in sorting the seeds of the analyzed spruce species due to similarities in the aspect ratios of spruce seeds and wheat grain. The low popularity of grain graders in tree nurseries can be probably attributed to their low throughput as well as the fact that they separate seeds into only two fractions. A seed separator equipped with a grading deck with flat, differently sized and shaped mesh sieves offers a much quicker and more effective alternative. Mesh sieves with longitudinal (seeds sorted based on thickness) and round openings (seeds sorted based on width) can be used separately or together, but sieves with round openings should move in a vertical throwing motion for best results [30]. A pneumatic separator is generally less effective, but it is a useful device for sorting blue spruce, Jezo spruce, Lijiang spruce, oriental spruce, red spruce and Schrenk's spruce seeds.

As mentioned before, germination efficiency is largely affected by seed mass [32–39]. Heavier seeds are more likely to germinate and produce seedlings because plump seeds are more abundant in storage compounds that are essential for germination. Sorting procedures based on seed plumpness improve the evenness of germination, which is particularly important in tree nurseries because it facilitates the planning of nursery treatments. Seed sorting based on seed plumpness also eliminates empty seeds, which substantially improves the quality of seeding material [51]. The results of this study indicate that mesh sieves with longitudinal openings are more effective in producing seed fractions with uniform mass. The variations in seed mass decrease in every sorted fraction, from around 12.5% in Jezo spruce to around 41.9% in Norway spruce on average. Fine seeds (with potentially lowest germination capacity) and medium-sized seeds can be sown in rows or broadcast in conventional nurseries (by choosing the most appropriate seeding rate), whereas the plumpest seeds can be sown individually in beds or containers. The described approach will deliver the following benefits:

- effective seedling production through the rational use of space allocated to different seeds, which is a very important consideration in container nurseries,
- rational use of seeding material with minimal loss of potentially germinable seeds,
- environmental benefits – the genetic potential of seeding material is not depleted (some trees produce seeds whose size differs from the reference range for the species).

5. Conclusions

The average terminal velocity of the analyzed spruce seeds ranged from 5.25 to 8.34 m s⁻¹, average seed thickness – from 1.10 to 2.32 mm, average seed width – from 1.43 to 3.19 mm, average seed length – from 2.76 to 5.52 mm, the average angle of external friction – from 23.1 to 30.0°, and

average seed mass – from 2.29 to 18.57 mg. Sitka's spruce and white spruce produced the least plump seeds, whereas oriental spruce produced the plumpest seeds.

In the group of 11 evaluated spruce species, species pairs characterized by significant similarities in all analyzed parameters were not identified in this study. The seeds of Jezo spruce and Meyer's spruce were most similar to the seeds of other spruce species, whereas oriental spruce seeds differed most considerably from the remaining seeds. The largest homogeneous group of 6 spruce species was identified based on the values of the *W/L* ratio: Jezo spruce, Meyer's spruce, Norway spruce, oriental spruce, red spruce and white spruce. Spruce seeds were least differentiated in terms of the *W/L* ratio and the *T/L* ratio, and produced the smallest number of homogenous groups in this respect.

Spruce seeds should be sorted with the use of mesh sieves with longitudinal openings to produce fractions with similar seed mass. The separated seed fractions should be sown individually to improve germination efficiency and germination rate. Spruce seeds can also be sorted with grain graders, mesh sieves with round openings, pneumatic separators or complex separating systems that combine the above devices.

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