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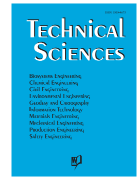

BASIC PHYSICAL PROPERTIES OF NORWAY SPRUCE (*PICEA ABIES* (L.) KARST.) SEEDS

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Key words: seeds, dimensions, seed mass, range of variations, correlation, separation.

Abstract

The range of variations in a given separation parameter and its relationships with other attributes have to be determined for designing seed cleaning and sorting processes. In this study, those relationships were determined for five batches of Norway spruce seeds supplied by a seed extraction plant in Jedwabno. The seeds were harvested from seed stands in northern Poland. The terminal velocity, length, width, thickness and mass of every seed were determined. The results were used to calculate the geometric mean diameter, aspect ratio, sphericity index and density of the evaluated seeds. Those parameters were compared by analysis of variance and linear correlation analysis. Similarities in the average values of all physical properties were noted only between seeds harvested in the same seed zone, from tree stands occupying the same habitat type. The analyzed seeds can be effectively separated into mass fractions with the use of traditional sorting devices such as pneumatic separators, mesh sieves with longitudinal or round openings, cylindrical graders, winnowing machines and pneumatic sieves, in order to achieve more uniform seedling emergence when each seed fraction is sown separately.

Symbols

D_g	– geometric mean diameter of a seed, mm,
m	– seed mass, mg,
R	– aspect ratio, %,
SD	– standard deviation of trait,
T, W, L	– seed thickness, width and length, mm,
v	– terminal velocity, m s^{-1},
x	– average value of trait,
ρ	– seed density, g cm^{-3},
Φ	– sphericity index, %.

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Introduction

The Norway spruce (*Picea abies* (L.) Karst.) is a tree that grows up to 50 m in height and 200 cm in diameter at breast height. Its geographic range covers mostly Central and Northern Europe where it adapts to various climate conditions. The Norway spruce requires a growing season of at least 60 days and a winter dormancy period of minimum 120 days with sub-zero temperatures. In optimal habitats, the Norway spruce is a shade-tolerant species, but it thrives under direct exposure to sunlight. The species has moderate soil requirements, but has a preference for soils with a relatively high moisture content. The Norway spruce thrives on fresh brown soils developed from sandy loam, characterized by a moderate nutrient content, relatively low acidity and a relatively low water table (MURAT 2002, JAWORSKI 2011).

The Norway spruce grows slowly in the first years of life, and its growth is accelerated at 30 to 50 years of age. Its growth rate decreases in old age, but the species continues to grow until the end of its life cycle (MURAT 2002, JAWORSKI 2011). The Norway spruce begins to produce seeds at 20–30 years of age in open spaces and at around 60 years of age in dense stands (*Nasiennictwo leśnych drzew*... 1995, MURAT 2002). Cones harvested at the turn of November and December are husked, and the extracted seeds are dewinged. Spruce seeds have a uniform dark reddish-brown color (Fig. 1), they reach 4–5 mm in length, they are rounded at one end and tapered to a point at the other end (*Nasiennictwo leśnych drzew*... 1995). Spruce seeds provide food for birds and small forest animals, including woodpeckers, squirrels and pygmy shrews (MURAT 2002).

Norway spruce seeds can be effectively preserved by drying. They are stored in air-tight containers at a temperature of 2–5°C, and their moisture content is reduced to approximately 6–7%. They can be stored in the above conditions for up to 6 years without significant loss of germination capacity. Seed vigor can be maintained for even 30 years by further reducing moisture content and storing seeds at sub-zero temperatures (MURAT 2002, ANIŚKO et al. 2006).

According to the literature (MIKOLA 1980, KHAN 2004, PARKER et al. 2006, SHANKAR 2006, UPADHAYA et al. 2007, WU, DU 2007, CASTRO et al. 2008, NORDEN et al. 2009, BURACZYK 2010, KALINIEWICZ 2012a), seed mass is one of the key determinants of germination and seedling growth. Plumper seeds generally germinate better due to a higher content of nutrient reserves which are required for seedling emergence. Depending on the species, germination rate can be proportional or inversely proportional to seed mass. The separation of seeds into mass fractions promotes uniform germination, which is a very important consideration in tree nurseries. However, seeds are difficult to sort

Fig. 1. Norway spruce seeds

based on mass as a separation parameter. For this reason, further research is needed to identify the relationships between the physical properties of seeds and use them to design seed separation process, in particular those that involve traditional sorting devices (pneumatic separators and mesh sieves).

The objective of this study was to determine the variations in and the correlations between the terminal velocity, basic dimensions (length, width and thickness), mass and density of Norway spruce seeds to select optimal parameters for seed separation processes.

Materials and Methods

The experimental material comprised five batches of Norway spruce seeds supplied by a seed extraction plant in Jedwabno in 2012. Three batches constituted seed propagation material from an identified source, and two batches contained selected and certified seeds. The seeds were extracted from cones harvested in three seed zones in northern Poland (Fig. 2). The analyzed batches were harvested from the following tree stands:

a) registration No. MP/1/46879/06, category of seed propagation material – from an identified source, type – tree stand, region of provenance – 205, municipality – Purda, geographic location – 53.39°N, 20.41°E, forest habitat – fresh mixed coniferous forest, age – 86 years (symbol: IS-1),

b) registration No. MP/1/46252/06, category of seed propagation material (deleted) – from an identified source, type – tree stand, region of provenance – 205, municipality – Szczytno, geographic location 53.33-53.40°N, 20.49-21.03°E, forest habitat – fresh mixed coniferous forest, age – 107 years (symbol: IS-2),

c) registration No. MP/1/45601/06, category of seed propagation material (deleted) – from an identified source, type – tree stand, region of provenance – 205, municipality – Szczytno, geographic location 53.29°N, 21.06°E, forest habitat – moist mixed coniferous forest, age – 131 years (symbol: IS-3),

d) registration No. MP/2/31324/05, category of seed propagation material (deleted) – selected seeds, type – tree stand, region of provenance – 451, municipality – Płośnica, geographic location 53.14°N, 20.04°E, forest habitat – fresh mixed forest, age – 113 years (symbol: SS),

e) registration No. MP/3/41105/05, category of seed propagation material – certified seeds, type – plantation, region of provenance – 103, municipality – Braniewo, geographic location 54.24°N, 19.50°E, forest habitat – moist mixed forest, age – 22 years (symbol: CS).

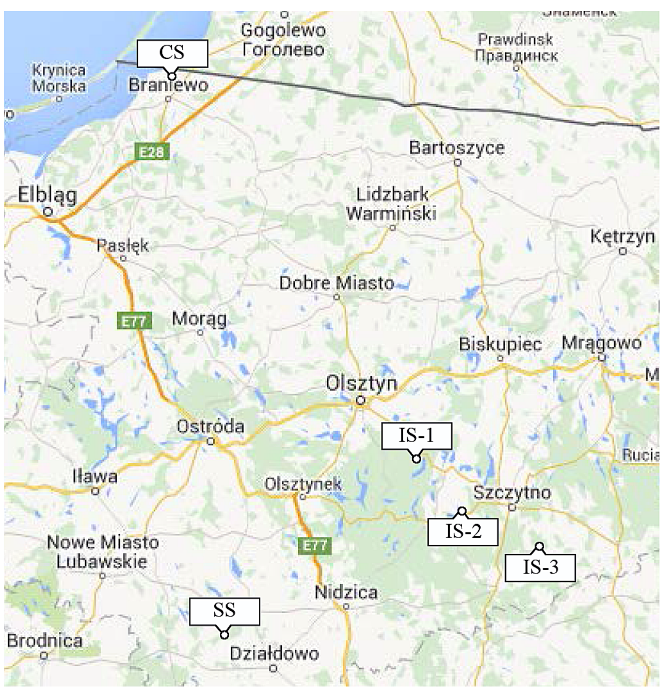

Fig. 2. Geographic location of Norway spruce stands

Analytical samples from every batch of seeds were collected by halving (*Nasiennictwo leśnych drzew*... 1995). Initial samples of approximately 0.5 kg were halved, and one half was randomly selected for successive halving. The above procedure was repeated to produce samples of around 100 seeds each. The ultimate sample size ranged from 85 (IS-3) to 116 (IS-2) seeds. The remaining seeds were sampled to determine their moisture content in the Radwag MAX 50/WH drying oven with a weighing scale (Radwag Radom, Poland). The analyzed seeds were characterized by a similar moisture content in the range of 6.8% to 7.3%.

In the first stage of the study, terminal velocity was determined in the Petkus K-293 pneumatic classifier (Petkus Technologie GmbH, Germany) with the resolution of 0.11 m s^{-1} (air flow rate – 1 m^3 h^{-1}). To facilitate the measurements, seeds were divided into fractions, and air stream velocity was changed every 0.55 m s^{-1}, which produced 7 to 9 fractions for every seed batch. Air stream velocity was adjusted within the range of variations corresponding to a given fraction, at 0.11 m s^{-1} intervals, and seeds were fed into the classifier. Seeds that fell to the bottom were fed back into the classifier and air stream speed was increased. The terminal velocity of a given seed was determined as the arithmetic mean of two air stream speeds calculated based on two consecutive measurements: the speed at which a seed fell to the bottom in the air stream and the speed at which a seed was lifted by the air stream.

The length and width of seeds were measured to the nearest 0.02 mm. Every seed was placed on a transparent slide and analyzed in the MWM 2325 workshop microscope (PZO Warszawa, Poland). The micrometric gauge was adjusted to move the stage to a position where the line on the eyepiece coincided with the contour of the beginning of the seed. The position was read from the gauge. The stage was then moved to a position where the line on the eyepiece coincided with the contour of the end of the seed, and the result was red from the gauge. The measured parameter was the difference between the first and the last reading. Seed width was measured with the use of the second micrometric gauge in an identical procedure. Seed thickness was determined with a dial thickness gauge to the nearest 0.01 mm. The thickness gauge was reset, the sensor plate was lifted, and individual seeds were placed inside the device, always on the same wall. The sensor plate was lowered and seed thickness was read from the dial.

Seed mass was determined on the WAA 100/C/2 weighing scale with 0.1 mg resolution (Radwag Radom, Poland).

In the second stage of the study, the measurements were used to determine:

a) geometric mean diameter D_g, aspect ratio R and sphericity index Φ (MOHSENIN 1986):

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

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

b) seed density ρ – based on the volumetric coefficient of proportionality determined experimentally by KALINIEWICZ et al. (2012b) with a liquid pycnometer:

$$\rho = \frac{m}{0.522 \cdot T \cdot W \cdot L} \tag{4}$$

Based on their mass, seeds were divided into three size categories: small seeds ($m < x$–SD), medium-sized seeds (x–SD ≤ m ≤ x+SD) and large seeds ($m > x$+SD). The results were rounded off to the next multiple of 1.

The results were processed in the Statistica v. 12.5 application with the use of popular statistical procedures such as one-way ANOVA and linear correlation analysis (RABIEJ 2012). The calculations were performed at a significance level of 0.05.

Results and Discussion

Based on the number of seeds in each sample and the standard deviations of the analyzed physical properties of Norway spruce seeds, the errors in the mean values of the evaluated properties did not exceed:

- for the terminal velocity – 0.2 m s^{-1},
- for the seed thickness – 0.04 mm,
- for the seed width – 0.07 mm,
- for the seed length – 0.1 mm,
- for the seed mass – 0.4 mg.

The physical properties of seeds are presented in Table 1. Statistically significant differences in the values of all analyzed properties and parameters were not noted only between seed batches IS-1 and IS-2. This could result from the fact that seeds of those batches were harvested from tree stands located in the same seed zone (with identical climatic and geomorphological conditions), occupying the same habitat type (fresh mixed coniferous forest). In the remaining cases, significant differences between the properties of the analyzed seeds were noted locally. This could be due to differences in habitat and soil type which, according to numerous authors (KLUCZYŃSKI 1992, *Nasiennictwo* *leśnych drzew...* 1995, KARLSSON, ÖRLANDER 2002, SIVACIOĞLU 2010), can considerably influence seed size. Seed size can also be determined by the age of the tree stand. KALINIEWICZ et al. (2013) demonstrated that the dimensions and mass of Scots pine seeds decreased with tree age. The largest number of the highest average values of the analyzed seed parameters was noted in seed batch IS-1 (terminal velocity, seed thickness, seed width, geometric mean diameter, aspect ratio and sphericity index), and the smallest number – in batch CS (seed thickness, seed width, seed length, geometric mean diameter). Seed density was the only parameter that was higher in batch CS, which indicates that those seeds were characterized by higher proportions of primary endosperm and germ than seeds from the other batches.

Table 1

Range of variations in the physical properties of Norway spruce seeds, with an indication of significant differences

Physical property/ indicator	Seed batch (sample size)				
	IS-1 (113) x±SD	IS-2 (116) x±SD	IS-3 (85) x±SD	SS (112) x±SD	CS (114) x±SD
v [m s^{-1}]	7.92±0.75^a	7.88±0.80^a	7.49±0.74^b	7.45±0.63^b	7.61±0.79^b
T [mm]	1.53±0.15^a	1.52±0.16^a	1.46±0.15^b	1.46±0.16^b	1.44±0.15^b
W [mm]	2.25±0.26^a	2.23±0.29^a	2.05±0.26^{bc}	2.12±0.31^b	2.04±0.25^c
L [mm]	4.15±0.44^a	4.22±0.45^a	4.15±0.43^a	4.11±0.44^{ab}	4.00±0.41^b
m [mg]	6.82±1.77^a	6.84±1.80^a	6.12±1.40^b	6.10±1.55^b	6.16±1.47^b
D_g [mm]	2.42±0.20^a	2.42±0.22^a	2.31±0.16^{bc}	2.33±0.23^b	2.27±0.17^c
R [%]	54.69±7.52^a	53.20±7.26^{ab}	50.10±8.51^c	51.91±7.01^{bc}	51.23±7.97^{bc}
Φ [%]	58.65±4.11^a	57.65±4.11^{ab}	55.97±5.05^c	56.93±4.16^{bc}	56.98±4.96^{bc}
ρ [g cm^{-3}]	0.91±0.11^c	0.91±0.12^c	0.95±0.18^b	0.91±0.14^c	1.01±0.17^a

$^{a, b, c}$ – different letters indicate statistically significant differences in the value of a given parameter (indicator).

The average terminal velocity was determined in the range of 7.45 to 7.92 m s^{-1}, and it was similar to that noted by KALINIEWICZ et al. (2012a), but approximately 20% higher than that reported by TYLEK (1999) in a study of seeds from southern Poland. Seeds harvested in southern Poland are larger and heavier (*Nasiennictwo leśnych drzew...* 1995) than those growing in the northern parts of the country. The above observations were confirmed by SZCZYGIEŁ (1981), CZERNIK (1983), TYLEK (1998) and OLEKSYN et al. (1998). Those results indicate that seed dimensions and seed mass decrease with an increase in the northern latitude of tree stands (MIKOLA 1980, OLEKSYN et al. 2001). Norway spruce seeds resemble Jack pine seeds in width, and shore pine and red pine seeds in length (CARRILLO-GAVILÁN et al. 2010). The analyzed seeds are similar to fenugreek seeds in thickness (ALTUNTAŞ et al. 2005) and to flaxseed in geometric mean diameter (PRADHAN et al. 2010). The aspect ratio of Norway spruce seeds was estimated at 52%, and it was only 4% lower than that reported by TYLEK (1998) despite significant differences in the dimensions of the compared seeds. The analyzed seeds were similar to wheat grain in terms of their aspect ratio and sphericity index (HEBDA, MICEK 2005, FRĄCZEK, WRÓBEL 2006, KALKAN, KARA 2011, MARKOWSKI et al. 2013).

A linear correlation analysis of selected physical properties of Norway spruce seeds (Table 2) revealed that most of them (excluding 18 cases) were strongly correlated at a significance level of 0.05. Practical significance, where the correlation coefficient was minimum 0.4, was noted in 43 out of 90 cases.

Table 2

Coefficients of linear correlation between selected physical properties of Norway spruce seeds

Seed batch	Physical property	*T*	*W*	*L*	*m*	*ρ*
IS-1	*v*	**0.421**	**0.314**	**0.324**	**0.569**	**0.302**
	T	1	**0.463**	**0.536**	**0.683**	**-0.247**
	W		1	**0.250**	**0.652**	**-0.214**
	L			1	**0.704**	-0.096
	m				1	**0.245**
IS-2	*v*	**0.522**	**0.306**	**0.273**	**0.639**	**0.328**
	T	1	**0.392**	**0.441**	**0.680**	-0.161
	W		1	**0.390**	**0.645**	**-0.299**
	L			1	**0.706**	-0.158
	m				1	**0.215**
IS-3	*v*	**0.528**	0.177	0.140	**0.743**	**0.421**
	T	1	0.199	0.115	**0.558**	-0.022
	W		1	-0.062	**0.285**	**-0.376**
	L			1	**0.376**	-0.198
	m				1	**0.487**
SS	*v*	**0.508**	**0.504**	**0.400**	**0.633**	-0.008
	T	1	**0.512**	**0.460**	**0.699**	**-0.326**
	W		1	**0.472**	**0.699**	**-0.470**
	L			1	**0.768**	-0.179
	m				1	0.029
CS	*v*	**0.511**	**0.249**	0.138	**0.736**	**0.514**
	T	1	**0.422**	0.164	**0.566**	-0.152
	W		1	0.155	**0.496**	**-0.296**
	L			1	**0.510**	-0.063
	m				1	**0.445**
Total	*v*	**0.518**	**0.352**	**0.265**	**0.675**	**0.279**
	T	1	**0.451**	**0.376**	**0.661**	**-0.212**
	W		1	**0.294**	**0.602**	**-0.371**
	L			1	**0.635**	**-0.164**
	m				1	**0.227**

Values in bold represent statistically significant correlations.

The highest value of the correlation coefficient (0.768) was observed between the length and mass of seeds in batch SS, and the lowest (0.022) – between the thickness and density of seeds in batch IS-3. The following seed parameters were most highly correlated with seed mass in each batch:

– terminal velocity (batches IS-3 and CS),
– thickness and width (batch SS),
– length (batches IS-1 and IS-2).

In view of the fact that the effects of the terminal velocity and basic dimensions of seeds on their mass are similar, it can be assumed that Norway spruce seeds can be separated into mass fractions with the use of traditional cleaning and sorting devices (pneumatic separators, separator buckets, graders and complex machines comprising separating elements).

In our study, the average mass of Norway spruce seeds was determined at 6.42±1.65 mg. The classification boundaries were rounded off, and seeds were divided into three size fractions: small seeds (m<5 mg), medium-sized seeds (m=5–8 mg) and large seeds (m>8 mg). The analyzed material contained 16.3% of small seeds, 70.2% of medium-sized seeds and 13.5% of large seeds. The distribution of terminal velocity, seed thickness, width and length values across size fractions is presented in Figure 3. The present results indicate that all four parameters can be used to sort Norway spruce seeds into fractions because they ensure maximum mass uniformity.

When air stream speed in two tunnels is set to 6.6 m s^{-1} and 8.8 m s^{-1}, seeds will be separated into three fractions, where the lightest fraction will comprise around 37% of small seeds and only 3% of medium-sized seeds, and the heaviest fraction will contain approximately 25% of large seeds and 2% of medium-sized seeds. TYLEK (1999) also observed that Norway spruce seeds can be effectively sorted with the use of pneumatic separators where viable (full) seeds are separated from non-viable (empty) seeds in a stream of air.

Mesh sieves with ≠1.4 mm and ≠1.6 mm longitudinal openings are recommended for sorting seeds based on their thickness. The sifted fraction will contain around 71% of small seeds and 26% of medium-sized seeds, and the retained fraction will be composed of around 6% small seeds, 15% of medium-sized seeds and 62% large seeds. Each fraction will have the following composition:

– fine-sized fraction (T≤1.4 mm) – 39% of small seeds and 61% of medium-sized seeds,

– medium-sized fraction (T=1.4-1.6 mm) – 7.6% of small seeds, 82.2% of medium-sized seeds and 10.2% of large seeds,

– coarse-sized fraction (T>1.6 mm) – 4.7% of small seeds, 52.8% of medium-sized seeds and 42.5% of large seeds.

Mesh sieves with ø2.0 mm and ø2.5 mm round openings are recommended for sorting seeds based on their width. The sifted fraction will contain approximately 69% of small seeds, 30% of medium-sized seeds and 1% of large seeds, and the retained fraction will be composed of around 1% of small seeds, 7% of medium-sized seeds and 48% of large seeds.

a

b

c

d

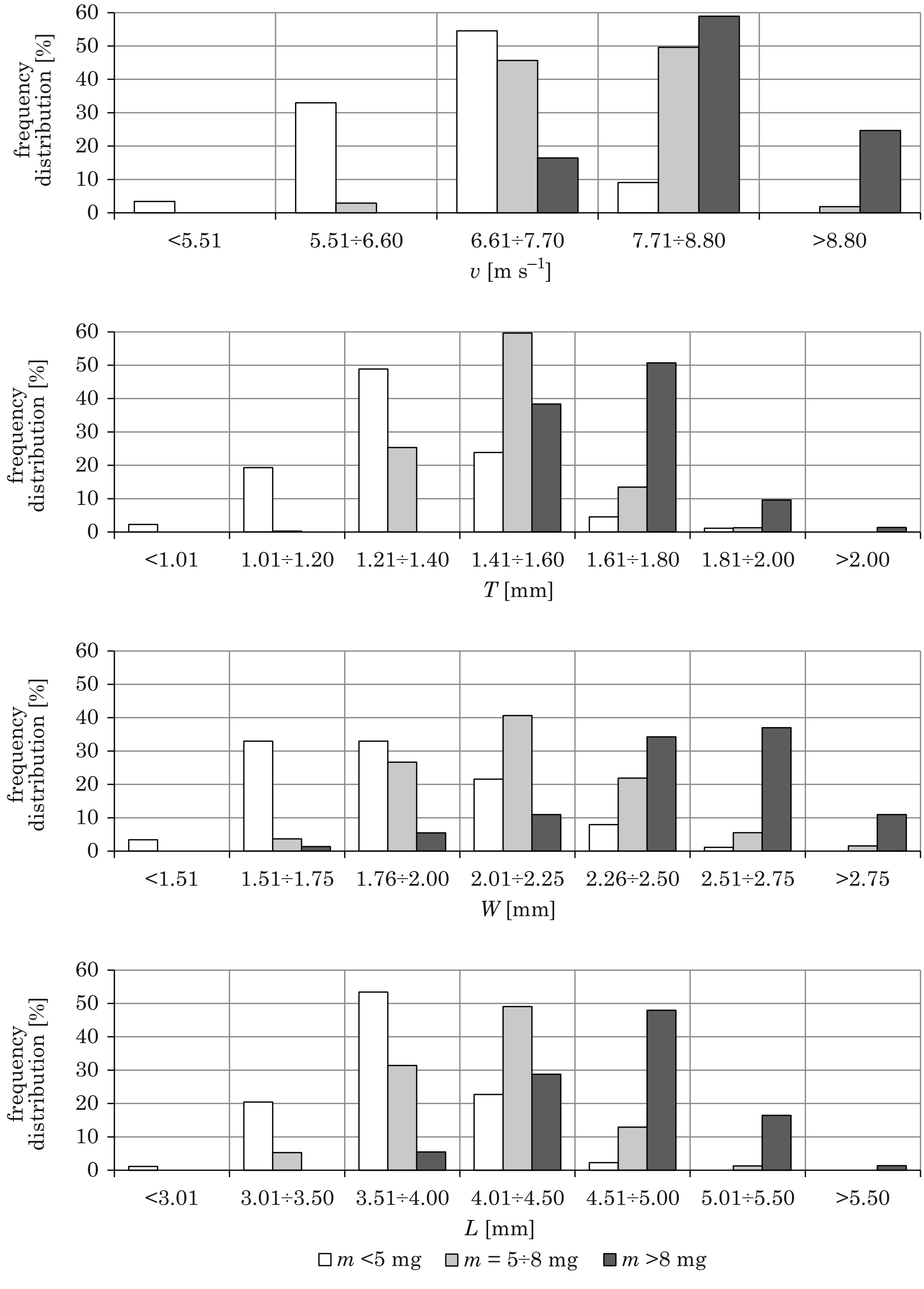

Fig. 3. Distribution of the terminal velocity (*a*), thickness (*b*), width (*c*) and length (*d*) of seeds in three mass fractions

When sorting seeds based on their length, two cylindrical graders with ø4.0 mm and ø4.5 mm indentations should be used. The fraction in the smaller trough will contain approximately 75% of small seeds, 37% of medium-sized seeds and 5.5% large seeds, whereas the fraction of the longest seeds (which are not carried to the trough in the grader with larger indentations) – around 2% of small seeds, 14% of medium-sized seeds and 65% of large seeds.

The results of the analysis (Table 3) indicate that the fractioning process classifies seeds into groups of similar size. The coefficient of variation of seed mass was determined at 26% before separation, and it was reduced in the resulting fractions. For example, in the medium-sized fraction, the above parameter was decreased by 20÷27% in comparison with unsorted seeds.

Table 3

Coefficient of variation (%) of seed mass in three seed fractions

Separation parameter	Seed fraction	Coefficient of variation of seed mass	
		fraction	total
v	I (v<6.6 m s^{-1})	24.21	25.67
	II (v=6.6÷8.8 m s^{-1})	20.56	
	III (v>8.8 m s^{-1})	20.94	
T	I (T<1.4 mm)	23.10	
	II (T=1.4÷1.6 mm)	19.12	
	III (T>1.6 mm)	22.31	
W	I (W<2.0 mm)	25.34	
	II (W=2.0÷2.5 mm)	18.78	
	III (W>2.5 mm)	23.68	
L	I (L<4.0 mm)	23.33	
	II (L=4.0÷4.5 mm)	18.75	
	III (L>4.5 mm)	22.05	

Conclusions

1. The results of this study confirmed the well-known fact the physical parameters of seeds, including Norway spruce seeds, are determined, among other factors, by habitat type and the geographical location of a seed stand. The average values of all physical properties of seeds from the analyzed batched did not differ significantly only in seeds harvested in the same seed zone, from tree stands occupying the same habitat type.

2. A linear correlation analysis revealed the strongest relationships between seed mass and terminal velocity or one of the basic seed dimensions (thickness, width, length). The degree of correlation was related to the specific characteristics of seeds in a given batch, but the values of correlation coefficients were generally similar. This indicates that Norway spruce seeds can be

effectively separated with the use of traditional cleaning and sorting machines and devices.

3. When Norway spruce seeds are sorted with a pneumatic separator, two speeds of the air stream should be set, i.e. around 6.6 m s^{-1} and 8.8 m s^{-1}. The separation process can also be performed using two mesh sieves with ≠1.4 mm and ≠1.6 mm longitudinal openings or two mesh sieves with ø2.0 mm and ø2.5 mm round openings. Another option is to use two cylindrical graders with ø4.0 mm and ø4.5 mm indentations. In each case, seeds will be separated into uniform mass fractions, thus improving seedling emergence uniformity.

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