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Analysis of the Physical Properties of Seeds of Selected *Viburnum* Species for the Needs of Seed Sorting Operations

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Abstract: *Viburnum* is a genus of colorful and ornamental plants popular in landscape design on account of their high esthetic appeal. The physical properties of viburnum seeds have not been investigated in the literature to date. Therefore, the aim of this study was to characterize the seeds of selected *Viburnum* species and to search for potential relationships between their physical attributes for the needs of seed sorting operations. The basic physical parameters of the seeds of six *Viburnum* species were measured, and the relationships between these attributes were determined in correlation and regression analyses. The average values of the evaluated parameters were determined in the following range: terminal velocity—from 5.6 to 7.9 m s^{-1}, thickness—from 1.39 to 1.87 mm, width—from 3.59 to 6.33 mm, length—from 5.58 to 7.44 mm, angle of external friction—from 36.7 to 43.8°, mass—from 16.7 to 35.0 mg. The seeds of *V. dasyanthum*, *V. lentago* and *V. sargentii* should be sorted in air separators, and the seeds of *V. lantana* and *V. opulus* should be processed with the use of mesh screens with round apertures to obtain uniform size fractions. The seeds of *V. rhytodophyllum* cannot be effectively sorted into batches with uniform seed mass, but they can be separated into groups with similar dimensions.

Keywords: *Viburnum* L.; physical attributes; variability; correlation; separation

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1. Introduction

According to estimates, shrub plants occupy 45% of land area on the surface of the Earth [1,2]. Shrubs are an important component of forest ecosystems; they promote the growth of other plants, stabilize biocenoses and contribute to the phytoremediation of forest soils. Shrubs protect tree stands against the damaging effects of strong winds, and their shoots, seeds and fruit are a source of food for many forest animals. Multicolored ornamental shrubs are used in landscape design on account of their high esthetic appeal, and they are often planted in parks, in green squares and along boulevards [1,3–6].

Ornamental shrubs include species of the genus *Viburnum*. The genus *Viburnum* consists of around 160–200 species, most of which are shrubs or small trees. Viburnum shrubs are widely distributed in the temperate climate of the northern hemisphere, and large clusters are also encountered in Asia and Central America. In the southern hemisphere, viburnum colonizes mostly mountain regions of Southeast Asia and South America [7–10].

Viburnum plants do not differ considerably in flower or fruit morphology, but significant differences are observed in fruit color and the morphology of leaves, buds and inflorescences [7,11–14]. Viburnum shrubs are often planted in gardens and used in landscape design on account of their colorful appearance, scented flowers, variations in plant size and growth habit, and highly ornamental red fruit [8,9,15,16].

Viburnum species produce fruit in the form of clusters containing 20–100 berries, which are yellow, orange, red, blue, purple or black in color when fully ripe, depending on the species [9,14]. Viburnum berries are drupes, where a single seed is surrounded by a layer of fleshy tissue. Berries are widely consumed by birds, which digest only the fleshy fruit and excrete seeds with feces, contributing to the spread of viburnum plants [14]. The seeds of many *Viburnum* species feature longitudinal grooves, and seed cross-sections have a wrinkled contour line [17]. Seeds are extracted from fruit by pressing on the flesh or by removing the flesh after fermentation treatment [4]. In most *Viburnum* species, long cold stratification is required to break seed dormancy [18–20]. In small nurseries, this is accomplished by sowing seeds in fall. Low temperatures and constant changes in temperature break seed dormancy, and seedlings emerge in spring [4,20].

One of the most important issues related to the planning and implementation of seed harvesting processes and further post-harvest and processing methods is the monitoring of seeds' physical properties, mainly their geometric features. These data are used to regulate the operating parameters of machines and devices used for the harvesting (threshing), cleaning, sorting, fractionating, hulling and grinding of -;these raw materials. Before sowing, seeds have to be separated to remove impurities and obtain uniformly germinating batches [21,22]. Seed batches are sown separately in nurseries to ensure that different treatments are performed at the appropriate stages of seedling growth. This approach also promotes uniform seedling growth, which is an important consideration when seeds are sown by single-seed mechanical drills. Based on the results of studies investigating different plant species [23–26], it was assumed that seed mass would exert the greatest influence on germination performance. However, the separation of seeds into batches with similar mass poses a challenge due to considerable variations in seed mass and basic seed dimensions [22,27–30]. For this reason, strong relationships between seed mass and other physical parameters should be identified to facilitate seed separation. To the best of the authors' knowledge, the range of changes in the physical attributes of viburnum seeds has not been investigated to date. The relevant information can be highly useful in various seed processing operations. Therefore, the aim of this study was to determine the relationships between the basic physical properties of seeds of selected *Viburnum* species for the needs of seed sorting operations.

2. Materials and Methods

2.1. Sample Preparation

The seeds of six *Viburnum* species were analyzed (Figure 1): *V. dasyanthum* Rehder, *V. lantana* L., *V. lentago* L., *V. opulus* L., *V. rhytodophyllum* Hemsl. and *V. sargentii* Koehne. Seeds for the experiment were supplied by two commercial distributors of seeds of forest trees and shrubs: Dendrona (Pęcice, Poland) and Florpak (Łomianki, Poland). Each seed sample weighed 200 g, and more than 100 seeds of each species were selected for analysis. Seeds were acquired by halving [31]. Every sample was divided into two batches, and one batch was randomly selected and halved. The process was repeated until the required number of seeds per sample was obtained. The analyzed samples consisted of 118 to 122 seeds each.

2.2. Physical Properties

The physical attributes of seeds were determined with the use of the procedures and at the measurement accuracy previously described by Kaliniewicz et al. [32]. The physical parameters of each seed were measured in the following order: terminal velocity (v), length (L), width (W), thickness (T), mass (m) and the angle of external friction (γ). The analyzed parameters were measured with the use of the Petkus K-293 air separator (Petkus Technologie GmbH, Wutha-Farnroda, Germany)—resolution 0.11 m s^{-1}, MWM 2325 workshop microscope (goniometric head, lenses with magnification $\times$10) (PZO, Warsaw, Poland)—resolution 0.01 mm, thickness gauge—resolution 0.01 mm, WAA 100/C/2 laboratory weighing scale (Radwag, Radom, Poland)—resolution 0.1 mg and an inclined steel friction plate with surface roughness Ra = 0.46 µm—resolution 1°.

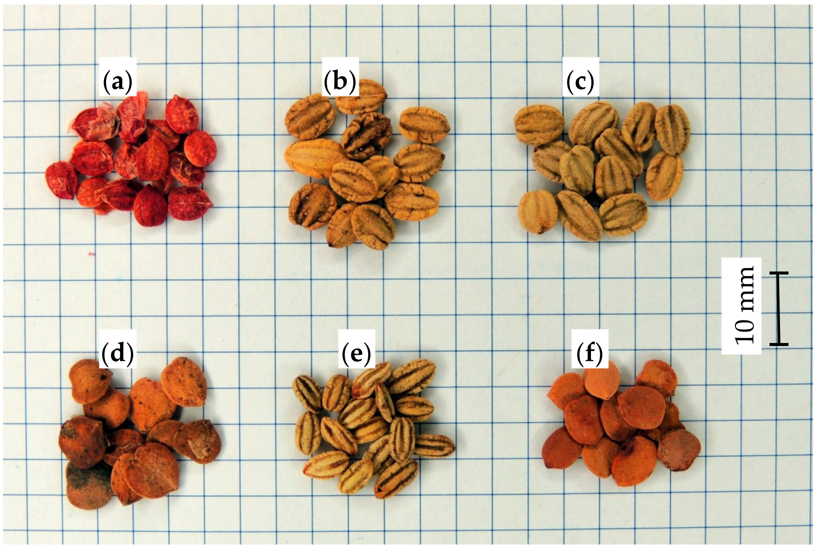

Figure 1. Seeds of (**a**) *Viburnum dasyanthum*, (**b**) *Viburnum lantana*, (**c**) *Viburnum lentago*, (**d**) *Viburnum opulus*, (**e**) *Viburnum rhytodophyllum* and (**f**) *Viburnum sargentii*.

The measured parameters were used to calculate the following indicators for each seed:

- geometric mean diameter (D) and sphericity index (Φ) [33]:

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

$$\Phi = \frac{D}{L}{\cdot}100 \tag{2}$$

where T—thickness, W—width, L—length;

- volume (V), based on an experimentally determined volumetric coefficient of proportionality (k):

$$V = k{\cdot}T{\cdot}W{\cdot}L \tag{3}$$

where the coefficient (k) of proportionality was determined with a 25 cm^3 liquid pycnometer based on the procedure described by Kaliniewicz et al. [34];

- density:

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

where m—mass;

- T/W, T/L, W/L, m/T, m/W, m/L and m/D aspect ratios.

The boundaries of each size class were determined by rounding off seed mass to the nearest 1 mg. It was assumed that in separation processes based on the terminal velocity or width of seeds, the seeds would be divided into three fractions, with a nearly identical number of seeds in each fraction.

2.3. Statistical Analysis

The results were processed statistically at a significance level of α = 0.05 in Statistica PL v. 13.3 (TIBCO Software Inc., Palo Alto, CA, USA). Descriptive statistics were applied to determine the mean, minimum and maximum values as well as the standard deviation of the analyzed parameters. The differences in the properties of seeds belonging to different *Viburnum* species were determined by one-way analysis of variance (ANOVA), and homogeneous groups were identified by Duncan's test. The relationships between the evaluated attributes were described by calculating linear correlation coefficients and deriving regression equations. Only the relationships with a minimum coefficient of determination of 0.4 are discussed in the article.

3. Results and Discussion

3.1. Experimental Material

An analysis of the standard deviation of the analyzed attributes, the size of seed samples, and the values of Student's t-distribution at a significance level of $\alpha = 0.05$ revealed that the standard error of the estimate did not exceed the following:

- 0.2 m s^{-1} for terminal velocity,
- 0.1 mm for seed thickness,
- 0.2 mm for seed width and length,
- 0.5° for the angle of external friction and
- 1.3 mg for seed mass.

The average value of the volumetric coefficient of proportionality *k* measured with a liquid pycnometer was determined at 0.527 in *V. dasyanthum* seeds, 0.467 in *V. lantana* seeds, 0.514 in *V. lentago* seeds, 0.465 in *V. opulus* seeds, 0.513 in *V. rhytodophyllum* seeds and 0.489 in *V. sargentii* seeds. The basic physical attributes of viburnum seeds are presented in Figure 2. Terminal velocity ranged from 4.1 m s^{-1} to 9.6 m s^{-1}, and the average value of this parameter was determined in the range of 5.6 m s^{-1} (*Viburnum sargentii*) to 7.9 m s^{-1} (*Viburnum lantana*). The following pairs of *Viburnum* species formed homogeneous groups in terms of terminal velocity: *Viburnum dasyanthum* and *Viburnum opulus; Viburnum lentago* and *Viburnum rhytodophyllum*. The terminal velocity noted in the first pair was similar to that reported in *Picea pungens* seeds [28] and *Abies procera* seeds [29], whereas the terminal velocity of the second pair approximated the values noted in *Juniperus communis* seeds [27]. In terms of terminal velocity, *Viburnum sargentii* seeds resembled *Picea rubens* and *Picea glaca* seeds [28] as well as *Abies lasiocarpa*, *Abies forrestii* and *Abies concolor* seeds [29], whereas *Viburnum lantana* seeds were similar to *Juniperus virginiana* seeds [27].

The basic physical attributes of seeds of the analyzed *Viburum* species were determined in the following range of values: thickness—from 0.95 mm (*Viburnum dasyanthum*) to 2.41 mm (*Viburnum rhytodophyllum*); width—from 2.47 mm (*Viburnum rhytodophyllum*) to 6.90 mm (*Viburnum lantana*); length—from 4.82 mm (*Viburnum dasyanthum*) to 9.89 mm (*Viburnum lantana*). Similar seed length was reported in many wheat cultivars [35–38], whereas similar seed width was observed in narrow-leaved lupin [39]. *Viburnum dasyanthum* and *Viburnum opulus* formed a homogeneous group based on seed thickness; *Viburnum lantana* and *Viburnum lentago*—based on seed width; and *Viburnum lantana* and *Viburnum opulus*—based on seed length. The seeds of *Viburnum dasyanthum* had a similar thickness to *Picea abies* and *Picea meyeri* seeds [28,34], similar width to *Pinus ponderosa* seeds [40], *Tilia cordata* seeds [41] and *Cornus controversa*, *Cornus florida* and *Cornus walteri* seeds [30], and similar length to *Pinus sylvestris* seeds [42]. *Viburnum lantana* seeds resembled *Pseudotsuga menziesii* seeds [34] and *Juniperus communis* seeds [27] in terms of thickness, *Abies forrestii* and *Abies concolor* seeds [29] and *Cornus mas* seeds [30] in terms of width, and *Pinus pinaster* seeds [40] and *Carpinus betulus* seeds [41] in terms of length. The seeds of *Viburnum lentago* had a similar length to *Pinus radiata* seeds [40], *Taxus baccata* seeds [34], *Carpinus orientalis* seeds [43] and *Abies lasiocarpa* seeds [29] and a similar thickness to *Juniperus virginiana* seeds [27]. *Viburnum rhytodophyllum* seeds were characterized by a similar thickness to *Robinia pseudoacacia* seeds [41] and *Abies balsamea* and *Abies koreana* seeds [29] and a similar width and length to *Pinus nigra* seeds [44]. *Viburnum sargentii* seeds were similar to *Pinus palustris* and *Pinus roxburghii* seeds [40] in terms of thickness and to *Pinus nigra* seeds [34] in terms of length.

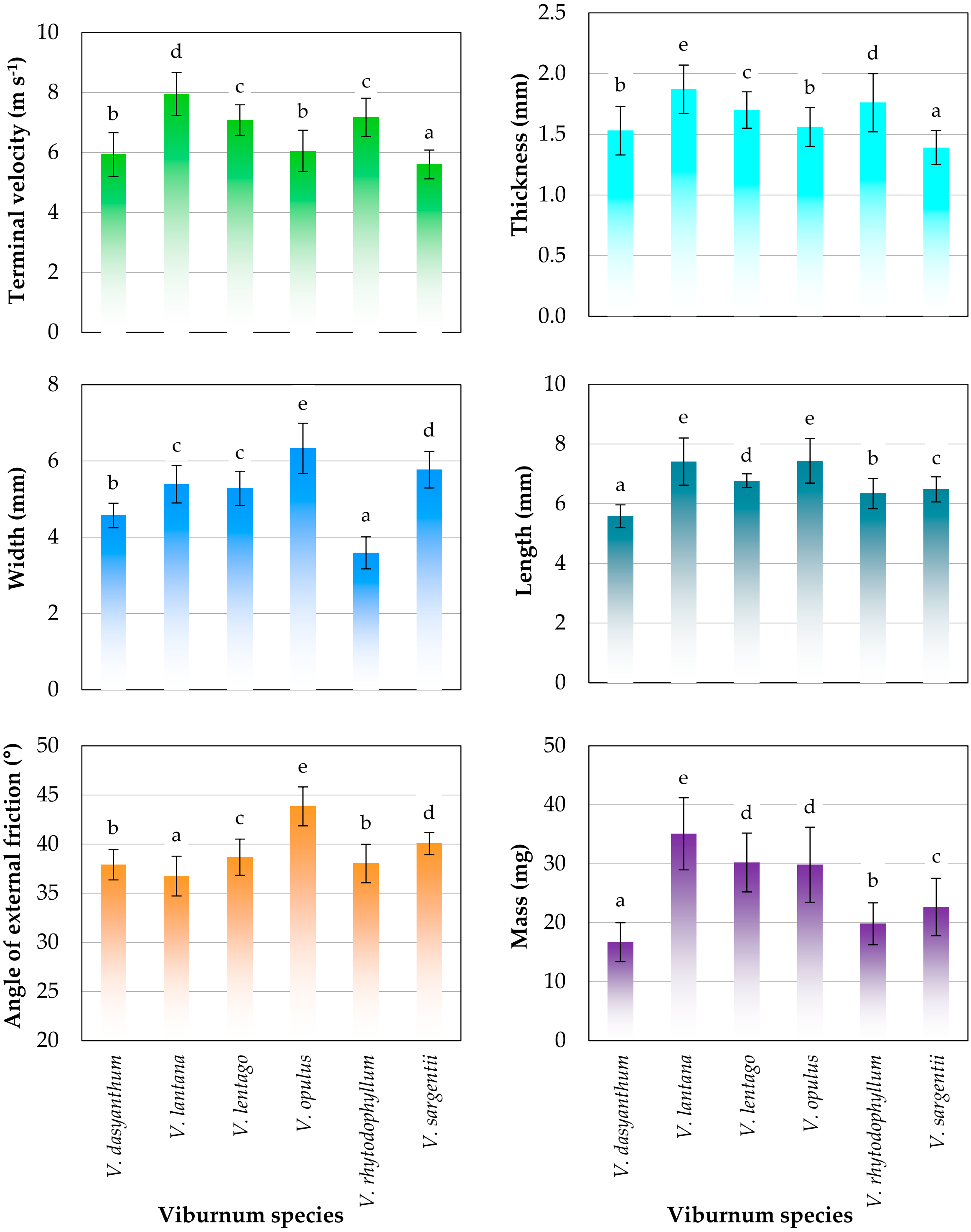

Figure 2. Physical attributes (mean value and standard deviation) of *Viburnum* seeds and significant differences between *Viburnum* species. Note: a, b, c, d, e—various letters denote significant differences at $p < 0.05$ (Duncan's test).

The angle of external friction was relatively large at 31° (*Viburnum lantana*) to 48° (*Viburnum opulus*), and its average values ranged from around 37° to around 44°. These findings can be attributed to the fact that viburnum seeds are relatively flat (thickness is significantly smaller than width and length), which results in a large contact area between the seed and the friction plate. The seeds of *Viburnum dasyanthum* and *Viburnum rhytodophyllum* formed a homogeneous group in terms of the angle of external friction.

The average seed mass ranged from 16.7 mg (*Viburnum dasyanthum*) to 35.1 mg (*Viburnum lantana*), and seeds with the lowest (7.1 mg) and the highest (54.0 mg) mass were noted in the above species, respectively. *Viburnum lentago* and *Viburnum opulus* formed a homogeneous group in terms of seed mass. The mass of *Viburnum dasyanthum* seeds was similar to that reported for the seeds of *Acer cissifolium* [45], *Pinus halepensis* [40], *Juniperus scopulorum* [27] and *Abies lasiocarpa* [29]. In turn, *Viburnum rhytodophyllum* seeds most closely resembled maple seeds [45], *Juniperus chinensis* seeds [27] and *Pinus nigra* seeds [22] in terms of mass. The mass of *Viburnum sargentii* seeds was similar to that noted for *Frangula alnus* seeds [46], and the mass of *Viburnum lentago* and *Viburnum opulus* seeds was similar to that reported for *Acer pseudoplatanus*, *Sorbus aria* and *Tilia cordata* seeds [46], *Pinus radiata* seeds [40] and *Abies concolor* seeds [29]. *Viburnum lantana* seeds were large, and they resembled the grain of selected wheat cultivars [36–38] as well as *Abies forrestii* seeds [29] in terms of mass.

Similarly to the classification based on seed mass, *Viburnum lentago* and *Viburnum opulus* seeds also formed a homogeneous group in terms of the geometric mean diameter (Table 1). Similar values of this parameter were reported in *Abies firma* seeds [29] and *Cornus macrophylla* seeds [30]. *Viburnum dasyanthum* and *Viburnum rhytodophyllum* seeds also formed a homogeneous group, and their geometric mean diameter was similar to that noted for *Juniperus chinensis* seeds [27] and *Picea smithiana* seeds [28]. Due to similarities in the average values of the measured parameters, the same *Viburnum* species also formed homogeneous groups in terms of seed volume.

Table 1. Physical attributes of seeds of selected *Viburnum* species (mean values ± standard deviation), with an indication of significant differences.

Indicator	*Viburnum* Species					
	V. Dasyanthum	*V. Lantana*	*V. Lentago*	*V. Opulus*	*V. Rhytodophyllum*	*V. Sargentii*
Geom. mean diameter (mm)	3.38 ± 0.20 ^{a}	4.20 ± 0.28 ^{d}	3.93 ± 0.18 ^{c}	4.17 ± 0.32 ^{d}	3.41 ± 0.23 ^{a}	3.72 ± 0.21 ^{b}
Sphericity index (%)	60.74 ± 4.36 ^{d}	57.04 ± 4.70 ^{bc}	58.00 ± 2.70 ^{c}	56.33 ± 3.48 ^{b}	53.94 ± 4.45 ^{a}	57.54 ± 3.13 ^{c}
Volume (mm^3)	20.51 ± 3.59 ^{a}	34.99 ± 7.13 ^{d}	31.28 ± 4.24 ^{c}	34.48 ± 8.19 ^{d}	20.57 ± 4.21 ^{a}	25.45 ± 4.18 ^{b}
Density (g·cm^{-3})	0.83 ± 0.19 ^{a}	1.01 ± 0.11 ^{c}	0.98 ± 0.17 ^{c}	0.88 ± 0.13 ^{ab}	1.00 ± 0.28 ^{c}	0.91 ± 0.26 ^{b}
Aspect ratio T/W (–)	0.33 ± 0.05 ^{b}	0.35 ± 0.04 ^{c}	0.32 ± 0.04 ^{b}	0.25 ± 0.03 ^{a}	0.50 ± 0.09 ^{d}	0.24 ± 0.03 ^{a}
Aspect ratio T/L (–)	0.27 ± 0.04 ^{c}	0.25 ± 0.04 ^{b}	0.25 ± 0.02 ^{b}	0.21 ± 0.03 ^{a}	0.28 ± 0.05 ^{c}	0.21 ± 0.02 ^{a}
Aspect ratio W/L (–)	0.82 ± 0.07 ^{d}	0.73 ± 0.09 ^{b}	0.78 ± 0.07 ^{c}	0.85 ± 0.08 ^{e}	0.57 ± 0.08 ^{a}	0.89 ± 0.08 ^{f}
Aspect ratio m/T (g m^{-1})	11.12 ± 2.56 ^{a}	18.79 ± 2.74 ^{d}	17.82 ± 2.92 ^{c}	19.17 ± 3.70 ^{d}	11.48 ± 2.62 ^{a}	16.51 ± 4.11 ^{b}
Aspect ratio m/W (g m^{-1})	3.65 ± 0.71 ^{a}	6.49 ± 0.88 ^{e}	5.75 ± 1.01 ^{d}	4.69 ± 0.74 ^{c}	5.60 ± 1.26 ^{d}	3.95 ± 0.90 ^{b}
Aspect ratio m/L (g m^{-1})	3.00 ± 0.60 ^{a}	4.74 ± 0.70 ^{e}	4.46 ± 0.74 ^{d}	4.00 ± 0.69 ^{c}	3.14 ± 0.60 ^{a}	3.51 ± 0.78 ^{b}
Aspect ratio m/D (g m^{-1})	4.94 ± 0.96 ^{a}	8.31 ± 1.01 ^{e}	7.69 ± 1.20 ^{d}	7.10 ± 1.15 ^{c}	5.84 ± 1.11 ^{b}	6.10 ± 1.37 ^{b}

T—thickness, W—width, L—length, m—mass, D—geometric mean diameter; a, b, c, d, e, f—superscript letters denote significant differences between the examined attributes.

The sphericity index of viburnum seeds ranged from 53.95% (*Viburnum rhytodophyllum*) to 60.74% (*Viburnum dasyanthum*), and homogeneous groups were formed by *Viburnum opulus* and *Viburnum lantana* seeds, and by *Viburnum lantana*, *Viburnum lentago* and *Viburnum rhytodophyllum* seeds. Similar values of the sphericity index were reported in *Picea* seeds [28], *Abies* seeds [29], wheat grain [35,36] and *Pinus nigra* seeds [22].

The density of viburnum seeds was in the range of 0.83 g cm^{-3} (*Viburnum dasyanthum*) to 1.01 g cm^{-3} (*Viburnum lantana*). In this respect, the evaluated species formed three homogeneous groups: (1) *Viburnum dasyanthum* and *Viburnum opulus*, (2) *Viburnum opulus* and *Viburnum sargentii* and (3) *Viburnum lantana*, *Viburnum lentago* and *Viburnum rhytodophyllum*.

The average values of the T/W aspect ratio ranged from 0.24 to 0.35, and homogeneous groups were formed by *Viburnum opulus* and *Viburnum sargentii* as well as by *Viburnum dasyanthum* and *Viburnum lentago*. The mean values of the T/L aspect ratio were in the range of 0.21 to 0.28, and three homogeneous groups were identified based on this trait. A similar T/L aspect ratio was reported in a large group of *Abies* seeds [29] and in *Cucurbita moschata* seeds [47]. The seeds of the analyzed *Viburnum* species differed significantly in the W/L aspect ratio, and *Viburnum rhytodophyllum* seeds differed most considerably from the remaining species in this respect. Similar values of the *W/L* aspect ratio (0.57 to 0.85) were noted in the seeds of many plant species, including most members of the genera *Juniperus* [27] and *Cornus* [30] as well as in *Coriandrum sativum* seeds [48] and *Cucurbita moschata* seeds [47]. Homogeneous groups were formed by *Viburnum dasyanthum* and *Viburnum rhytodophyllum* seeds in terms of *m/T* and *m/L* aspect ratios, by *Viburnum lantana* and *Viburnum opulus* seeds in terms of the *m/T* aspect ratio, by *Viburnum lentago* and *Viburnum rhytodophyllum* seeds in terms of the *m/W* aspect ratio, and by *Viburnum rhytodophyllum* and *Viburnum sargentii* seeds in terms of the *m/D* aspect ratio. An analysis of the average values of the *m/D* aspect ratio revealed similarities between *Viburnum dasyanthum* seeds and *Abies firma* seeds [29], between *Viburnum rhytodophyllum* seeds and *Juniperus chinensis* seeds [27], and between *Viburnum lantana* seeds and *Abies alba* seeds [29].

The results of the presented analysis revealed the highest number of similarities between *Viburnum dasyanthum* and *Viburnum rhytodophyllum* seeds (which formed homogeneous groups in terms of six attributes), whereas the following pairs of species were not similar in any of the examined parameters: *Viburnum dasyanthum* and *Viburnum lantana*, *Viburnum dasyanthum* and *Viburnum sargentii*, and *Viburnum opulus* and *Viburnum rhytodophyllum*. *Viburnum sargentii* seeds differed most considerably from the remaining species (six similarities), whereas *Viburnum opulus* seeds were most similar to the remaining *Viburnum* species (12 similarities).

3.2. Relationships between the Physical Properties of Seeds

The correlations between seed mass and the remaining physical properties in the analyzed *Viburnum* species are presented in Table 2. The absolute value of the correlation coefficient ranged from 0.016 (correlation with the angle of external friction in *Viburnum sargentii* seeds) to 0.688 (correlation with the width of *Viburnum opulus* seeds). Practical significance (>0.4) was noted in nine out of 30 comparisons.

Table 2. Coefficients of linear correlation between seed mass and the remaining physical properties of viburnum seeds.

***Viburnum* Species**	**Coefficient of Correlation between Seed Mass and**				
	Terminal Velocity	**Thickness**	**Width**	**Length**	**Angle of External Friction**
V. dasyanthum	0.506 *	0.145	0.269 *	0.129	−0.181 *
V. lantana	0.323 *	0.528 *	0.632 *	0.554 *	−0.201 *
V. lentago	0.418 *	0.318 *	0.173	0.134	0.038
V. opulus	0.281 *	0.428 *	0.688 *	0.587 *	−0.227 *
V. rhytodophyllum	0.107	0.055	0.071	0.103	0.073
V. sargentii	0.428 *	−0.038	0.061	0.057	−0.016

* Denotes significant correlations at 0.05.

In four species (*V. dasyanthum*, *V. lentago*, *V. rhytodophyllum* and *V. sargentii*), seed mass was most strongly correlated with terminal velocity. In the remaining species (*V. lantana* and *V. opulus*), the strongest correlations were noted between seed mass and seed width. The second highest value of the correlation coefficient was observed in the relationship between seed mass and seed length. These results indicate that viburnum seeds would be most effectively separated with the use of air separators, mesh screens with round apertures, or cylindrical graders. In previous studies, terminal velocity was suggested as the key parameter for sorting the seeds of *Carpinus betulus*, *Tilia cordata* and *Alnus incana* [41]; *Juniperus chinensis* and *Juniperus virginiana* [27]; *Picea pungens*, *Picea Jezoensis*, *Picea likiangensis*, *Picea orientalis*, *Picea rubens* and *Picea schrenkiana* [28]; *Abies balsamea*, *Abies forrestii*, *Abies grandis*, *Abies firma*, *Abies procera*, *Abies concolor* and *Abies lasiocarpa* [29]; and *Pinus nigra* [22]. Seed width was proposed as the key criterion for separating the seeds of *Sorbus aucuparia* [41], *Cornus sanguinea* and *Cornus walteri* [30], whereas seed length was regarded as the most important parameter for sorting the seeds of *Fagus silvatica atropurpurea* and *Robinia pseudoacacia* [41]; *Picea meyeri*, *Picea smithiana* and *Picea abies* [28]; *Abies concolor* [29]; and *Cornus amonum*, *Cornus macrophylla* and *Cornus obliqua* [30].

A comparison of the measured values in all *Viburnum* species (Table 3) revealed the strongest correlations between seed mass and seed length (R = 0.700) and between terminal velocity and seed thickness (R = 0.645). Practical significance was noted in six out of 15 comparisons. The angle of external friction and seed mass were bound by the weakest correlation, which indicates that these parameters should not be used as critical traits in the separation of viburnum seeds. Similar observations were made in studies of other plant species [27–29,41,49].

Table 3. Coefficients of linear correlation between the basic physical properties of viburnum seeds.

Attribute	Terminal Velocity	Thickness	Width	Length	Angle of External Friction
Thickness	0.645 *	1			
Width	−0.206 *	−0.158 *	1		
Length	0.208 *	0.218 *	0.511 *	1	
Angle of ext. friction	−0.380 *	−0.325 *	0.449 *	0.196 *	1
Mass	0.476 *	0.385 *	0.529 *	0.700 *	0.032

* Denotes significant correlations at 0.05.

The coefficient of determination reached 0.4 in two linear regression equations (Figure 3), and it was highest for the correlation between seed mass and seed length. Seed mass increased from around 12 mg to around 48 mg (by 300%) with a rise in seed length from around 4.8 mm to around 9.9 mm. These findings indicate that viburnum seeds could be effectively separated in cylindrical graders. Mesh sieves with round apertures could also be used in the separation of viburnum seeds, in particular in processes where high sorting performance is required.

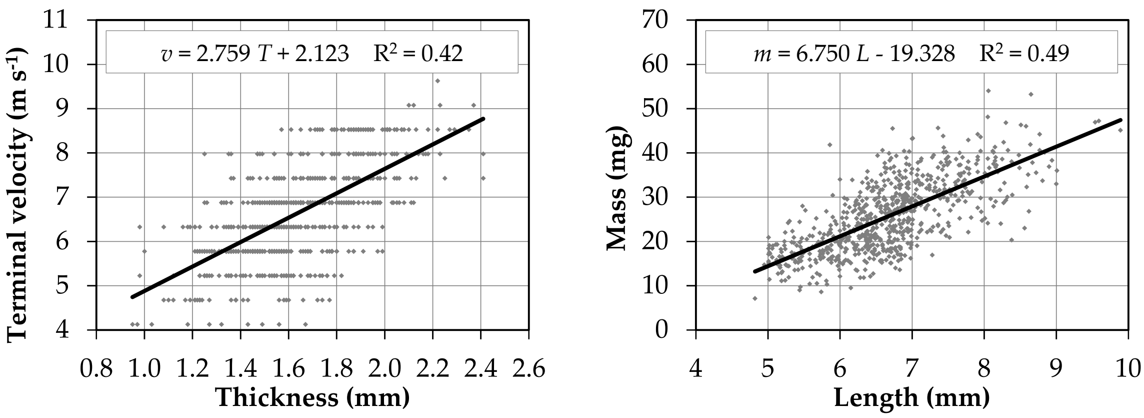

Figure 3. Relationships between the physical properties of seeds.

3.3. Recommendations for Seed Sorting

Based on the identified differences in seed mass and seed dimensions, the analyzed *Viburnum* species were divided into three size classes, where the boundary values differed for each class (Table 4). Class 1 (smallest seeds) was composed of seeds weighing less than 15 mg (*V. dasyanthum*), 18 mg (*V. rhytodophyllum*), 20 mg (*V. sargentii*), 27 mg (*V. lentago* and *V. opulus*) and 32 mg (*V. lantana*). Class 3 (largest seeds) contained seeds with a mass greater than 18 mg, 21 mg, 25 mg, 32 mg and 37 mg. In all *Viburnum* species, the percentage distribution of seeds from different size classes ranged from 24.8% (class 1, *V. dasyanthum*) to 37.7% (class 3, *V. sargentii*).

Table 4. Seed mass classes in the analyzed *Viburnum* species.

Viburnum Species	Seed Class	Percentage (%)
V. dasyanthum	1 (m < 15 mg)	24.8
	2 (m = 15–18 mg)	35.5
	3 (m > 18 mg)	39.7
V. lantana	1 (m < 32 mg)	29.8
	2 (m = 32–37 mg)	34.7
	3 (m > 37 mg)	35.5
V. lentago	1 (m < 27 mg)	28.8
	2 (m = 27–32 mg)	37.3
	3 (m > 32 mg)	33.9
V. opulus	1 (m < 27 mg)	32.8
	2 (m = 27–32 mg)	33.6
	3 (m > 32 mg)	33.6
V. rhytodophyllum	1 (m < 18 mg)	30.6
	2 (m = 18–21 mg)	34.7
	3 (m > 21 mg)	34.7
V. sargentii	1 (m < 20 mg)	30.3
	2 (m = 20–25 mg)	37.7
	3 (m > 25 mg)	32.0

m—mass.

The strongest correlations were noted between seed mass and two basic seed dimensions (length and width), which suggests that viburnum seeds should be separated in cylindrical graders and/or mesh sieves with round apertures. In most cases (24 of 36 analyzed variants), the division of seeds of each *Viburnum* species into three fractions based on seed length or seed width (Table 5) decreased the values of the coefficient of variation of seed mass in each fraction. This implies that individual seeds in each fraction would have similar mass, and the greatest similarities in seed mass could be expected in fractions containing the largest seeds. In these fractions, the coefficient of variation of seed mass was lower than in the entire seed batch, ranging from 0.9% (longest *V. opulus* seeds) to 18.3% (longest *V. lantana* seeds), and the greatest improvement in seed mass uniformity (approx. 33%) was observed in the fraction of medium-long *V. lantana* seeds. A comparison of the coefficients of variation of seed mass in different fractions revealed that a more desirable ratio (10:8) was achieved when seeds were divided into three fractions based on width rather than length. These findings suggest that viburnum seeds would be most effectively separated with the use of mesh sieves with round apertures. The following aperture size is recommended for the seeds of the examined *Viburnum* species: ø 3.8 mm for *V. rhytodophyllum*, ø 4.7 mm for *V. dasyanthum*, ø 5.5 mm for *V. lentago*, ø 5.6 mm for *V. lantana*, ø 6.0 mm for *V. sargentii* and ø 6.6 mm for *V. opulus*. Mesh sieves with round apertures should also be applied to separate seeds with the smallest width, but aperture size should be reduced to ø 3.3 mm for *V. rhytodophyllum*, ø 4.3 mm for *V. dasyanthum*, ø 5.1 mm for *V. lentago* and *V. lantana*, ø 5.5 mm for *V. sargentii* and ø 6.0 mm for *V. opulus*. As a result, fraction III seeds, accounting for around 31% (*V. rhytodophyllum*) to around 37% (*V. dasyanthum*) of the processed material, would be separated by the top screen, whereas fraction I seeds, accounting for around 26% (*V. rhytodophyllum*) to around 34% of the processed material, would be separated by the bottom screen. Fraction II seeds, accounting for around 32% (*V. lentago*) to around 38% (*V. rhytodophyllum*) of the processed batch, would be captured on the bottom screen. Mesh sieves have round apertures, and the hopper should vibrate vertically to enable seeds to pass through the screen or, if seed width exceeds aperture diameter, to be captured and propelled along the inclined screen.

Table 5. Coefficient of variation of seed mass in three seed fractions.

Viburnum Species	Seed Fraction	Percentage (%)	Coefficient of Variation (%) of Seed Mass	
			Fraction	Total
V. dasyanthum	I ($L \leq 5.30$ mm)	28.9	19.7	19.8
	II (L = 5.31–5.80 mm)	38.0	20.9	
	III ($L > 5.80$ mm)	33.1	18.1	
	I ($W \leq 4.30$ mm)	26.4	24.4	
	II (W = 4.31–4.70 mm)	36.4	18.2	
	III ($W > 4.70$ mm)	37.2	16.8	
V. lantana	I ($L \leq 7.00$ mm)	34.7	17.4	17.5
	II (L = 7.01–7.80 mm)	35.5	11.7	
	III ($L > 7.80$ mm)	29.8	14.3	
	I ($W \leq 5.10$ mm)	29.8	14.8	
	II (W = 5.11–5.60 mm)	36.4	12.2	
	III ($W > 5.60$ mm)	33.8	15.8	
V. lentago	I ($L \leq 6.70$ mm)	35.6	18.6	16.5
	II (L = 6.71–6.90 mm)	36.4	13.9	
	III ($L > 6.90$ mm)	28.0	16.3	
	I ($W \leq 5.10$ mm)	33.9	16.8	
	II (W = 5.11–5.50 mm)	32.2	17.5	
	III ($W > 5.50$ mm)	33.9	14.4	
V. opulus	I ($L \leq 7.10$ mm)	32.0	20.0	21.3
	II (L = 7.11–7.70 mm)	36.9	14.6	
	III ($L > 7.70$ mm)	31.1	21.1	
	I ($W \leq 6.00$ mm)	29.6	15.4	
	II (W = 6.01–6.60 mm)	35.2	15.3	
	III ($W > 6.60$ mm)	35.2	18.5	
V. rhytodophyllum	I ($L \leq 6.20$ mm)	31.4	20.4	17.9
	II (L = 6.21–6.60 mm)	37.2	18.2	
	III ($L > 6.60$ mm)	31.4	15.3	
	I ($W \leq 3.30$ mm)	28.9	20.1	
	II (W = 3.31–3.80 mm)	38.0	18.3	
	III ($W > 3.80$ mm)	33.1	14.8	
V. sargentii	I ($L \leq 6.30$ mm)	32.0	21.6	21.5
	II (L = 6.31–6.70 mm)	37.7	23.8	
	III ($L > 6.70$ mm)	30.3	18.8	
	I ($W \leq 5.50$ mm)	32.0	24.4	
	II (W = 5.51–6.00 mm)	33.6	20.7	
	III ($W > 6.00$ mm)	34.4	19.8	

L—length, *W*—width.

The histograms depicting the distribution of seed size classes in each *Viburnum* species having seed width as the key separation criterion are presented in Figure 4. A combination of two mesh screens with the described dimensions should be applied to separate viburnum seeds into the following fractions:

- fraction III (widest seeds), containing around 33% to around 37% of seeds from the entire batch of a given *Viburnum* species—from around 8% (*V. opulus*) to around 38% (*V. sargentii*) of class 1 seeds, from around 26% (*V. sargentii*) to around 39% (*V. rhytodophyllum*) of class 2 seeds, and from around 38% (*V. lentago*) to around 66% (*V. opulus*) of class 3 seeds;
- fraction II (medium-wide seeds), containing around 32% to around 38% of seeds from the entire batch of a given *Viburnum* species—from around 20% (*V. opulus*) to around 51% (*V. rhytodophyllum*) of small seeds, from around 23% (*V. lentago*) to around 51% (*V.

opulus) of medium-sized seeds, and from around 28% (*V. rhytodophyllum*) to around 43% (*V. lentago*) of large seeds;

- fraction I (narrowest seeds), containing around 26% to around 34% of seeds from the entire batch of a given *Viburnum* species—from around 32% (*V. sargentii*) to around 72% (*V. opulus*) of class 1 seeds, from around 17% (*V. opulus*) to around 41% (*V. lentago*) of class 2 seeds, and from 0% (*V. opulus*) to around 27% (*V. rhytodophyllum*) of class 3 seeds.

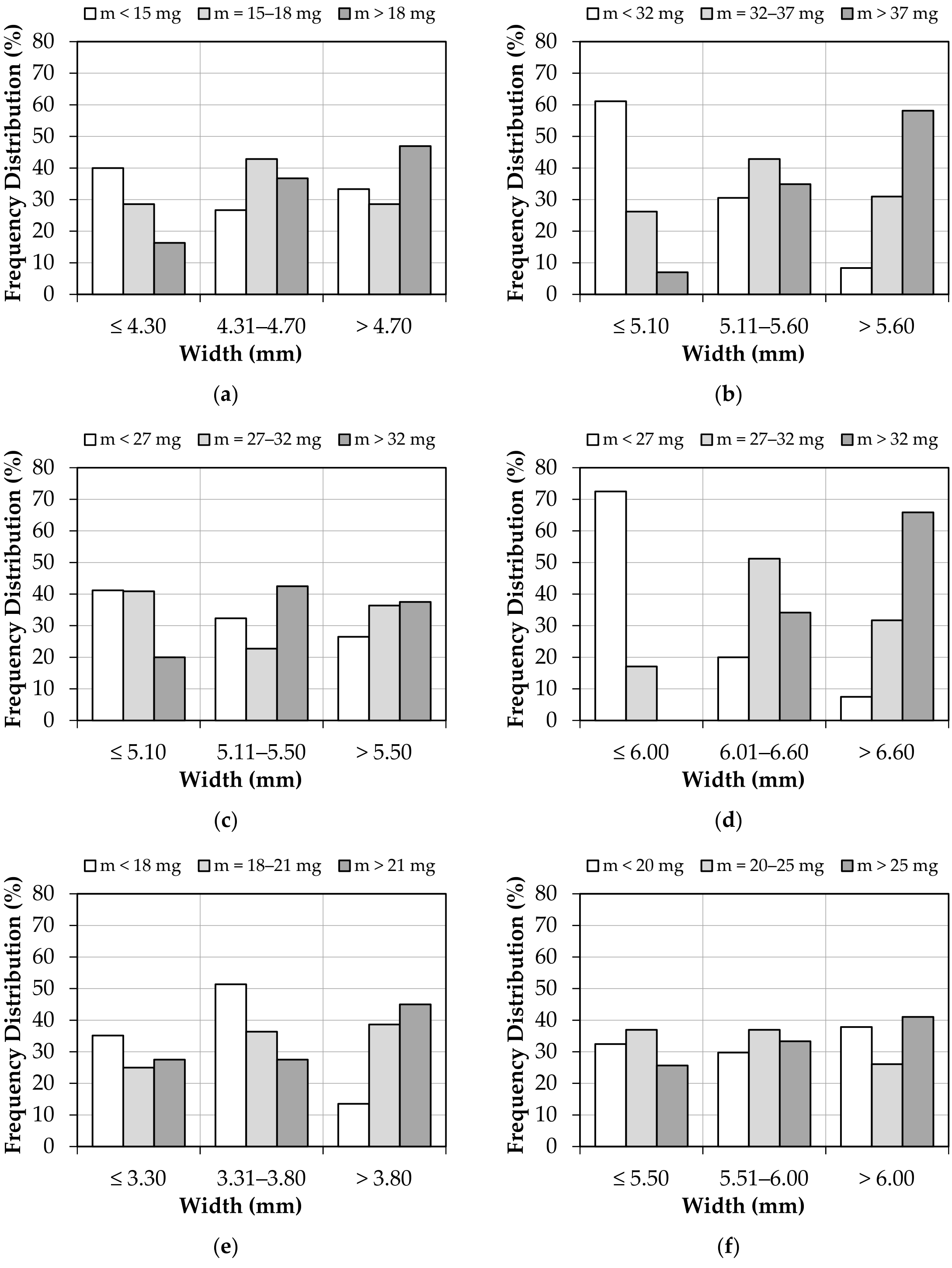

Figure 4. Distribution of seed width in the analyzed *Viburnum* species: (**a**) *V. dasyanthum*; (**b**) *V. lantana*; (**c**) *V. lentago*; (**d**) *V. opulus*; (**e**) *V. rhytodophyllum*; (**f**) *V. sargentii*.

In the obtained fractions, uniform mass distribution of individual seeds was observed only in *V. lantana* and *V. opulus*, where each fraction contained seeds of the corresponding size classes. The seeds of the remaining *Viburnum* species can be sorted into fractions with similar dimensions to accurately set the operating parameters of single-seed mechanical drills.

Similar results were noted when seed batches were divided into three fractions based on seed length; however, this approach proved to be somewhat less effective in *V. lantana* and *V. opulus.* Therefore, the results of this analysis were not presented in the article. An analysis of the data in Table 2 suggests that in *V. dasyanthum*, *V. lentago* and *V. sargentii* an air separator could also be used to increase the mass uniformity of individual seeds in each fraction.

4. Conclusions

In the analyzed group of six *Viburnum* species, the greatest similarities in the basic physical properties of seeds were noted in *Viburnum dasyanthum* and *Viburnum rhytodophyllum*. The seeds of *Viburnum sargentii* differed most considerably from the remaining species, whereas the seeds of *Viburnum opulus* were most similar to those of other species.

The mass of viburnum seeds was most frequently correlated with terminal velocity, followed by seed width. These relationships were characterized by the highest values of correlation coefficients. To obtain seed fractions with uniform parameters, *V. dasyanthum*, *V. lentago* and *V. sargentii* seeds should be processed in air separators, whereas *V. lantana* and *V. opulus* seeds should be separated on mesh sieves with round apertures. The mass of *V. rhytodophyllum* seeds was not significantly correlated with other physical attributes, which suggests that seeds of this *Viburnum* species should not be sorted before sowing.

In general, seed mass was bound by the strongest correlation with seed length, followed by terminal velocity and seed thickness. The coefficient of determination describing the two latter correlations was determined at 0.49 and 0.42, respectively.

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