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Fine Dust Creation during Hardwood Machine Sanding

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Abstract: Wood dust generated during woodworking—particularly from hardwood species during sanding—poses a health and safety hazard to workers in the wood industry. This study aimed to determine the particle-size distribution of selected hardwood species and the content of fine particles in dust created during machine sanding, which pose the highest health and safety hazards in the woodworking industry. Six hardwood species were studied: black alder, European ash, common walnut, pedunculate oak, hornbeam, and European beech. The sieve analysis method was used to determine the particle-size distribution and article mean arithmetic particle diameter, and laser diffraction analysis was used to determine the finest particle content. Two size ranges were assumed: <2.5 µm and <10 µm. Beech dust had the smallest mean particle diameter. Dust from wood species used in the test had similar contents of fine fractions of particles. The average content of particles smaller than 2.5 µm in wood dust from the tested hardwood species did not exceed 1.9%. In terms of occupational exposure to wood dust, machine sanding conditions of hardwoods should be properly adjusted to limit the formation of large amounts of dust.

Keywords: hardwood; wood dust; particle-size distribution; sieve analysis; laser diffraction analysis

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1. Introduction

Mechanical woodworking is an essential part of wood-product manufacturing, e.g., furniture and flooring. Surface sanding is an important component of the process, producing smooth surfaces to ensure higher adhesion of applied impregnating agents, paints, and varnishes. The dust created during this process is deposited on floors, walls, and working surfaces in the production facilities and hinders the operation of rotating machine components [1–3]. Moreover, dust with particle sizes significantly smaller than 100 µm remains suspended in the air, posing health risks for workers and creating additional workplace risks by limiting visibility and increasing the risk of fire [4–9]. A considerable amount of heat is generated by woodworking machines, which may ignite settled dust [10]. The ignition of dust is strongly influenced by the particle size. Dust with small particles has a large specific surface area, which results in faster thermal decomposition compared with the same mass of dust with a larger particle size. The size of the airborne dust particles also affects their ignition temperature [11–16].

Despite equipping sanding stations with dust exhaust systems, air pollution by fine dust poses a serious health hazard for both position operators and other employees [17–21]. Prolonged exposure to air polluted with wood dust impairs the respiratory system and causes other related diseases such as allergies, occupational asthma, chronic obstructive pulmonary disease, skin problems (dermatitis), eye and nose irritation, and toxic effects, specific for particular wood species [22–24]. Markedly, the International Agency for Research on Cancer (IARC) has classified wood dust into substances with carcinogenic effects for humans (Group 1) (IARC 2012), and this has enhanced the scientific interest on wood dust [25–29]. According to the IARC, wood dust causes cancer of the paranasal sinuses, nasal cavity, and nasopharynx which have been observed mostly among workers exposed to hardwood dust. The risk of lung cancer has increased in workers who have been exposed to wood dust for more than 10 years and have taken more than 40 years of occupation since the first exposure [30].

Depending on the processing method, machining parameters, and the type of wood, wood dust may contain different amounts of fine particles. The hardness of wood influences the size of dust particles generated during sanding, and wood with a higher hardness tends to produce up to 10 times more dust particles with a size less than 100 μm than wood species with a lower hardness [31–33]. Hardwoods are more resistant to mechanical factors, e.g., the operation of a machining tool, which also creates smaller dust particles compared to softwoods, which are less resistant to processing due to their lower hardness and density [34–41]. Marková et al. [42] studied the particle-size distribution of dust created when various wood species were processed on orbital sanders. According to this study, the content of dust particles with a size less than 100 μm for all investigated species had similar values, ranging from 86% to 93% of the total mass of the dust created. Ockajova i Banski [36] obtained similar values for dust from European beech, Scots pine, and Norway spruce wood, but larger differences were observed for the particle fraction 32 μm which ranged from 50% for European beech to 78% for common alder. The high content of small particles makes the dust from these hardwood species particularly dangerous.

A comparative analysis of the content of dust particles with a size less than 80 μm from European beech, oak, and Norway spruce wood was performed by Očkajová et al. [28], who recorded the highest value of approximately 93% for beech, 87% for oak, and 77% for spruce, respectively. According to Očkajová et al. [43], the dust fraction with a particle size less than 125 μm obtained by belt and manual sanding was more than 97% of the total amount of waste generated for both oak and beech wood. In both cases, the finest dust fraction, i.e., particle sizes less than 32 μm, represented approximately 25% of the total waste generated. Studies carried out by Očkajová and Kučerka [44] showed that thermal modification did not significantly increase the content of small sized particles (<80 μm) during sanding. A different situation is in the case of the milling of thermally modified wood, where fine particle fractions increase when the temperature of modification rises [45–50].

Data related to the formation of dust, especially fine particles, during the machining of hardwood are diffuse and inconclusive. However, knowledge in this field is becoming more and more important because the limit of 5 mg.m^{-3} for the inhalable hardwood dust fraction according to the European Council Directive 1999/38/EC (1999) on the protection of workers from the risks related to exposure to carcinogens at work is no longer in force (Council Directive 1999/38/EC) [51]. The recent European Union (EU) legislation classified hardwood dust as carcinogenic to humans and set an occupational exposure limit of 2 mg.m^{-3} of inhalable hardwood dust fraction calculated or measured for a reference 8-h period, with a transitional limit value of 3 mg.m^{-3} until January 2023 (Directive (EU) 2017/2398) [52]. In addition, in 2002 the Scientific Committee for Occupational Exposure Limits (SCOEL) of the EU stated that wood dust exposure greater than 0.5 mg.m^{-3} can cause pulmonary effects and thus should be avoided (SCOEL 2002) [53]. The research is in line with the current scientific trend characterized by the reduction of the negative impact of woodworking and processing machines on the health and safety of machine operators [54–59].

The aim of this study was to perform a comparative analysis of the particle size of wood dust created during the machine sanding of hardwoods in order to determine the content of particles from selected fine fractions with a sieve size smaller than 63 μm, which pose the highest health and safety hazards in the woodworking industry.

2. Materials and Methods

2.1. Hardwood Species

The specimens used for sanding were prepared from six hardwood species commonly used in the wood industry (Table 1). The species were selected based on their industrial relevance and forest area related to this [60]. The walnut wood processed in Poland comes from plantations and imports and there are no ash forests. The ash wood comes from mixed forests. The wood was kiln-dried to 8% ± 1% moisture content, then specimens with a sanded surface of 150 mm × 80 mm were prepared. Six specimens of each species were prepared in order to obtain at least 500 g of test dust. To enable long-lasting sanding of wood specimens (until the wood is completely sanded), they were thickened by gluing to a particleboard spacer. The purpose of drying was to eliminate the influence of cohesion on the measurement results. Low moisture content reduces the cohesiveness of dust. An common method to measure the quantity related to dust cohesion is the angle of repose [61]. The angle of repose of wood dust and other lignocellulosic particles strongly depends on the moisture content [62,63].

Table 1. Density of the hardwood species used in this research work.

No.	Hardwood Species	Density [kg.m^{-3}]	Percentage of the Forest Area in Poland [%]
1.	Black alder (*Alnus glutinosa* Gaertn.)	446.3	5.6
2.	European ash (*Fraxinus excelsior* L.)	621.3	No data
3.	Common walnut (*Juglans regia* L.)	641.0	No data
4.	Pedunculate oak (*Quercus robur* L.)	686.4	7.9
5.	European beech (*Fagus sylvatica* L.)	686.6	6.1
6.	Hornbeam (*Carpinus betulus* L.)	753.6	1.5

2.2. Sanding

Sanding was performed using a prototype narrow belt sanding machine designed and made in the laboratory of the Department of Furniture Design (Faculty of Wood Technology, Poznań University of Life Sciences PULS). EKA 1000 F (Ekamant, Poland) sanding paper in the form of belts with dimensions 1000 mm × 80 mm was used. The grit of the paper was P120. A sanding belt speed of 14.5 m.s^{-1} and a sanding pressure of 0.65 N.cm^{-2} were applied. Dust created during sanding was collected using a multi-purpose vacuum cleaner of the type NT 30/1 Tact (Alfred Kärcher SE & Co. KG, Winnenden, Germany) connected to the working zone. This device ensured a near-total collection efficiency of dust. The principle of test sanding and the scheme of operation of the prototype sanding machine are shown in Figure 1.

2.3. Particle Size Determination

Particle size determination and calculation of the content of fine dust particles were carried out according to two complementary methods used in previous studies to determine dust particle size: sieving and laser light scattering described by [38,40,64]. Sieve analysis was carried out using an AS 200 (Retsch, Germany) sieving machine. A set of sieves with small apertures of 250 µm, 125 µm, and 63 µm was used due to the fineness of the wood dust. The dust fraction isolated during the sieve analysis in the bottom collector was taken for laser analysis. The results of the sieve analysis were used to calculate the mean arithmetic particle diameter as follows:

$$\overline{x} = \sum_{i=1}^{n} x_i \cdot q_{3_i} \quad (1)$$

where: q_3—particle distribution by mass, x—mean value of particle size class, and n—number of particle size classes.

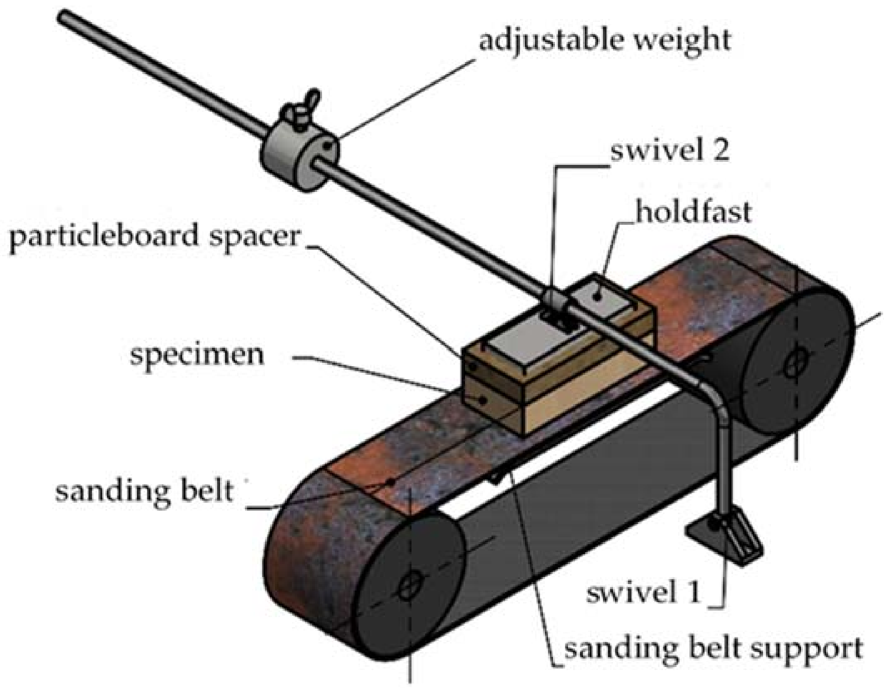

Figure 1. Scheme of the prototype sanding machine used in this work.

Particle-size distribution of the dust fraction with the sieve diameter smaller than 63 µm was determined by particle size analysis using an Analysette 22 Microtec Plus (Fritsch, Idar-Oberstein, Germany) laser particle sizer. The laser diffraction method generates a volume distribution of particle size. Assuming a constant density of wood matter, this is identical to the mass distribution [65]. Two particle size ranges were assumed: <2.5 µm and <10 µm. The mass content of particles <2.5 µm and <10 µm in this sieve dust fraction was calculated based on the results of laser particle size analysis using MaScontrol software (Fritsch, Idar-Oberstein, Germany). Particles in these size ranges were taken into consideration because they cause airborne dust pollution. The calculation of the content of particles <2.5 µm and <10 µm in the whole mass of dust created was performed as follows:

$$c_i = c_{S63} \cdot c_{Li} \tag{2}$$

where c_i—dust content in the assumed size range of the whole mass of dust created, c_{S63}—dust fraction isolated during the sieve analysis in the bottom collector, and c_{Li}—mass fractions of the dust in the assumed ranges determined using laser diffraction analysis in the c_{S63} fraction.

2.4. Statistical Analysis

The experimental data were statistically analyzed using STATISTICA 13.3 software (TIBCO Software Inc., Palo Alto, CA, USA). The post-hoc HSD Tukey's test was used to test the significance of the differences between the average values of the mean particle diameter and the content of <2.5 µm and <10 µm dust particles. Significance was established at $p < 0.05$.

3. Results and Discussion

The particle-size distribution of dust created during sanding is presented in Figure 2. The content of particles sized <2.5 µm and <10 µm was determined using the fraction 0–63 µm. Beech dust had the highest content of this fraction (56.6%). Different authors have observed a similarly high content of particles smaller than 63 µm in beech wood dust when P80 paper was used, ranging from 50% for a hand orbital sander [42] to approximately 90% for a hand belt sander [35]. A comparative study [5] of the performance of various sanders showed that when hand belt sanding was used, these particles accounted for 70% of total particles, 82% for a hand disc sander, and 56% for a narrow belt sander, respectively. This was due to the highly different operating characteristics of individual sanders, which significantly determined the particle size of the created dust. The machining parameters used in this work were different compared to hand sanders, i.e., a higher sanding speed and lower sanding pressure were applied, respectively.

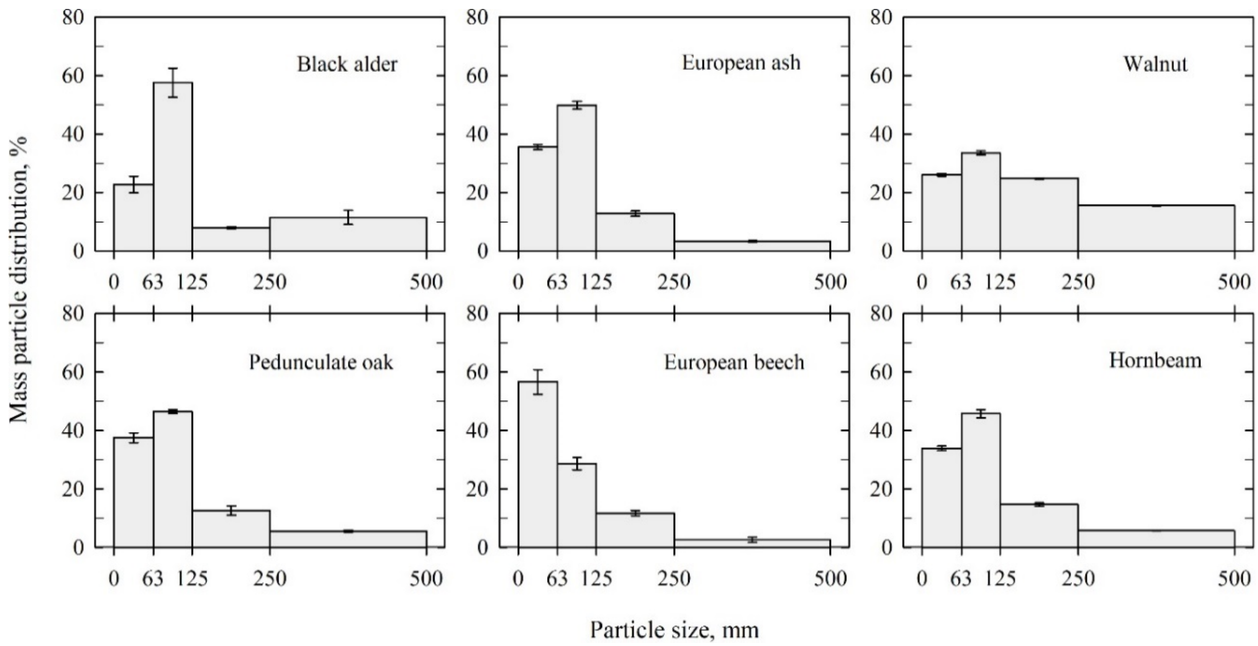

Figure 2. Particle-size distributions of investigated hardwood wood dust by sieving method (n = 3, error bars represent the standard deviation).

The mean particle diameters of the examined hardwood species and the content of the smallest wood dust fractions, i.e., <2.5 µm and <10 µm, are presented in Table 2.

Table 2. Particle mean diameter and content of the finest dust fraction of the investigated hardwood species (identical superscripts a, b, c, denote no significant difference for $p < 0.05$).

Wood Species	Particle Arithmetic Mean Diameter (µm)	Mass Content of Particles (%)	
		<10 µm	<2.5 µm
Black alder	$119.5^{c} \pm 4.65$	$5.8^{b} \pm 0.63$	$1.0^{abc} \pm 0.24$
European ash	$94.7^{b} \pm 3.45$	$7.5^{bc} \pm 2.03$	$1.6^{bc} \pm 1.49$
Common walnut	$144.7^{d} \pm 0.40$	$2.8^{a} \pm 0.46$	$0.4^{a} \pm 0.06$
Pedunculate oak	$100.1^{b} \pm 4.89$	$8.9^{c} \pm 0.43$	$0.4^{ab} \pm 0.23$
European beech	$76.5^{a} \pm 5.60$	$7.5^{bc} \pm 2.11$	$1.9^{c} \pm 0.66$
Hornbeam	$102.7^{b} \pm 0.09$	$7.3^{bc} \pm 0.26$	$1.3^{abc} \pm 0.32$

The extreme values of the average mean diameters of dust particles were 76.5 µm and 144.7 µm for beech and walnut, respectively. No statistical differences (p = 0.05) in the parameters were found for ash, oak, and hornbeam (Figure 3). The large differences between particle mean diameters result from the limitations of sieve analysis. A low number of particle size ranges is taken into account in the calculation of the results of this method (four ranges in this study). This method assumes that larger size ranges are used for coarser particles. Each subsequent sieve has an aperture twice larger than the previous one. This causes the rate of the coarsest particles to strongly influence the average particle size, and the values of the standard deviation are also high.

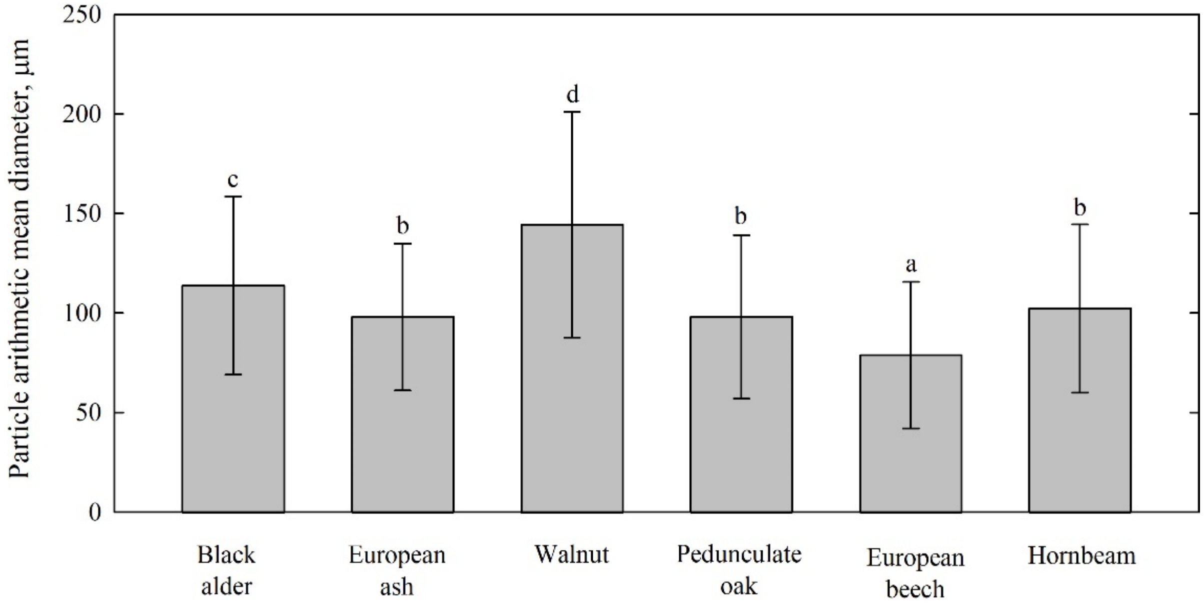

Figure 3. Particle mean diameter of the hardwood species investigated in this work (identical superscripts a, b, c, denote no significant difference for $p < 0.05$, error bars represent the standard deviation).

It seems that the equivalent sieve diameter of the particles does not strictly depend on the wood density. The average diameter of the walnut dust particles was statistically higher than that of alder, which has the lowest density in this study. It was also statistically significantly higher than the average diameter of the hornbeam dust particles, which had the highest density. Ratnasingam et al. [66] found that in six different Asian hardwoods, a high wood density causes the creation of dust particles with smaller sizes than a low wood density. Thorpe and Brown [67] studied 21 hardwood species and reported the same relationship. This was also confirmed by the results of research on the influence of thermal wood modification on the size of dust particles created during sanding [68–70]. The decrease in wood density due to modification produces coarser dust. In addition, Marková et al. [42] sanded alder, beech, and oak wood and showed that alder produced the smallest particles which had the lowest density. These studies were performed using sieve analysis only. The sieving of wood dust, which is not uniformly shaped, often having long and thin particles, may be inaccurate. These particles can clog the sieve mesh, so many of very small particles cannot pass through the fine sieve. It is unfortunately possible that the measurement method strongly influences the particle size estimation. The sieving method underestimates the results of the particle size analysis of coarse dust, but fine dust cannot pass through the small sieves. The laser diffraction method overestimates the results of the particle size measurement of wood dust due to the non-spherical shape of particles. Long and thin particles can be recognized as spheres with a diameter equal to the particle length [61,71]. Therefore, in order to avoid this error, many complementary measuring methods should be used.

The average mass content of particles smaller than 10 μm in dust from the tested wood species ranged from 2.8% to 8.9% for walnut and oak, respectively. No statistical differences ($p = 0.05$) of the average content of particles smaller than 10 μm were found in ash, beech, and hornbeam (Figure 4). A similar content of fine dust from the sanding of most hardwood species means that they should be treated with the same considerations to ensure the health and safety of wood industry workers [4].

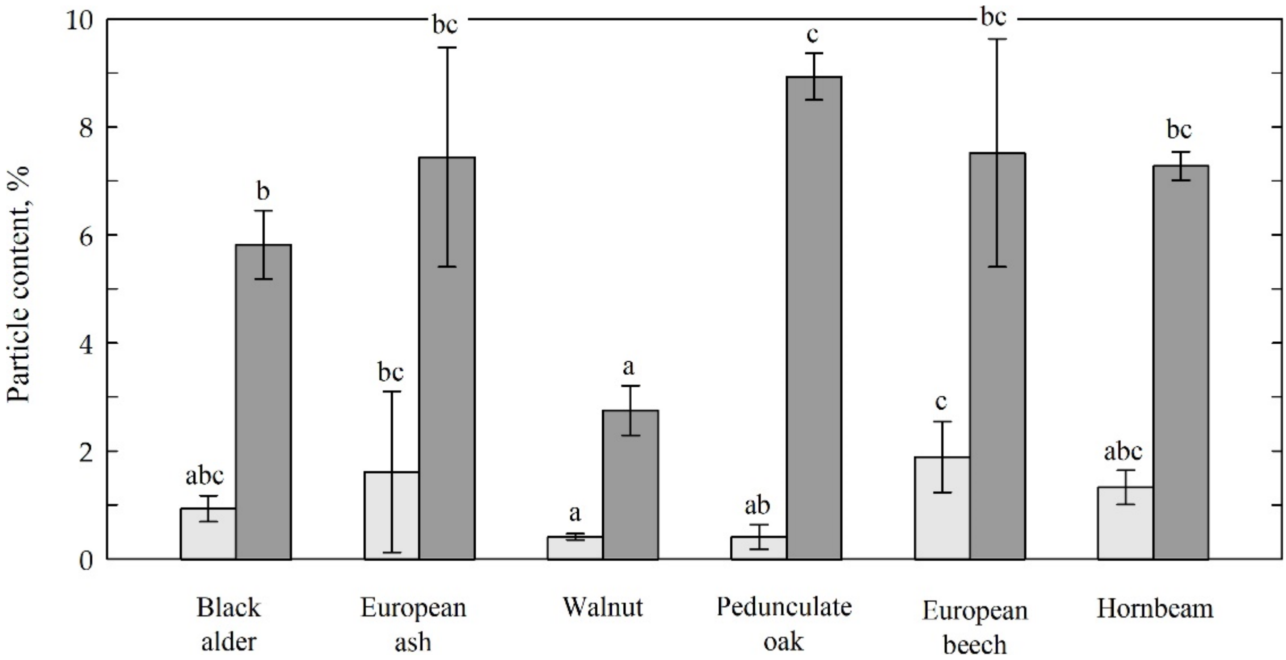

Figure 4. The mean content of particles <2.5 µm (**gray**) and <10 µm (**dark gray**); identical superscripts (a, b, c) denote no significant difference ($p < 0.05$), $n = 9$ ± standard deviation.

The average content of particles smaller than 2.5 µm in dust from tested species of wood did not exceed 1.9%, and the highest content was observed for beech wood. However, in terms of posing a health risk, the sanding conditions of beech wood should be adjusted to limit the formation of large amounts of dust because it contains a significantly higher content of particles that can penetrate the lower respiratory tract [1]. In other cases, the content of this dust fraction was significantly lower than in beech dust ($p = 0.05$), and the dust produced by sanding walnut wood had the smallest content of the fraction <2.5 µm, i.e., 0.4% (Figure 4).

Since wood dust is not homogeneous, further research should be carried out to characterize and reduce its formation. The selection of methods is very important, and it seems that sieving is not a good method for estimating the wood dust particle size, especially for very fine fractions, because they may not pass through fine sieves due to their non-spherical shape [44]. This results in a disproportionately high fraction of particles retained on these sieves; therefore, comprehensive and complementary methods, such as microscope image analysis or laser diffraction analysis, should be used to characterize fine wood dust [35,72,73]. Scanning electron microscopy and image analysis as well as energy-dispersive X-ray analysis allow us to take into account the shape identity of the particles when measuring the particle-size distribution [74,75]. Unfortunately, these methods have limitations that do not allow their common use in the industry, mainly associated with the sample representativeness. A relatively small number of particles can be recognized in an image. In addition, measurements are time-consuming and require experienced staff [61]. The only way to obtain reliable results of the content of fine dust fractions is to combine the advantages and eliminate the disadvantages of different particle size measurement methods. The sole use of the sieve analysis method to test the size of wood dust particles may result in a misinterpretation of the results, especially for very fine particles. Therefore, the research procedure should be supplemented with a method that allows for quick and accurate determination of the size of particles which are difficult to analyze with the use of fine mesh sieves. Such a method is the laser diffraction method, which, assuming a constant density of the wood matter, supplements the sieve analysis. Each study should be carried out using at least two methods: a rough one (sieving) to extract the fraction containing most of the fine particles, and the second for a thorough analysis of the tested dimensional ranges.

4. Conclusions

Two complementary methods, sieve analysis and laser diffraction analysis, were used to determination the particle-size distribution and content of very fine particles in dust generated during the machine sanding of six hardwood species. The particle-size distribution of the resulting dust was determined using sieve analysis, and the mean arithmetic particle diameter was calculated. Beech dust showed the smallest particle size, and the difference between the particle sizes of beech dust and other dust was statistically significant. Walnut wood dust had the largest particle size, and the dust from ash, oak, and hornbeam did not statistically differ in terms of the mean particle diameter.

Oak dust had the highest content of particles smaller 10 μm, but the results were not statistically significantly higher than the values obtained for beech, ash, or hornbeam wood dust. Noticeably, the highest content of particles smaller than 2.5 μm was found in beech wood dust; however, it was not statistically significantly higher than hornbeam, ash, or alder dust. Therefore, the exposure to wood dust generated during machine sanding of all studied hardwood species should be equally regarded as a source of serious occupational risk to woodworking employees.

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