

## Article

# Evaluation of Mechanical Wood Properties of Silver Birch (*Betula pendula* L. Roth.) of Half-Sib Genetic Families

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**Abstract:** Silver birch, a widely distributed deciduous tree native to Europe, is valued for its wood applications in construction, furniture making, and paper production. In Lithuania, silver birch ranks as the third most common forest-tree species, comprising 22% of the forested areas, and is an important species for tree breeding due to its potential and adaptability. This study was focused on assessing the mechanical properties of wood (sample and log hardness, wood density, dynamic modulus of elasticity (MOEdyn), static modulus of elasticity (MOE) and bending strength (MOR)) in silver birch (*Betula pendula* L. Roth.) trees from different half-sibling families. Two experimental plantations of the progenies of Lithuanian populations (half-sib families) of silver birch from different regions were analysed. From these plantations, four genetic families were selected for mechanical properties evaluation. The study findings revealed significant variability in various wood properties among different genetic families, although the static modulus of elasticity did not exhibit significant differences between the chosen genetic families. All measured wood properties decreased from the bottom to the top of the model trees. Wood hardness displayed a moderately negative correlation for wood density and weak correlations for MOE and MOR. Given the weak correlations between wood hardness and other wood mechanical properties, it is suggested that MOEdyn would be a more suitable trait for genetic studies.



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**Keywords:** silver birch; wood hardness; half-sib families; modulus of elasticity; wood density

## 1. Introduction

Silver birch (*Betula pendula* Roth.) is a deciduous tree species native to Europe and parts of Asia. It is widely distributed and valued for its wood, which has various applications in construction, furniture making, paper production, and more. Understanding the mechanical properties of silver birch wood is essential for optimising its utilization in different industries [1].

Silver birch is the third most spread forest-tree species in Lithuania, after Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) H. Karst.). Birch stands comprise 22% of the area occupied by forests [2]. Silver birch is the most common and prospective tree species for tree breeding in Lithuania [1]. From 2006, in the Lithuanian field-trial test for genetic half-sib families and wood-properties evaluation, wood hardness was added as a trait measured by a Pilodyn 6J Forest device. Earlier studies selected the Pilodyn device for non-destructive testing and to achieve a good negative correlation with basic wood density [3]. Even though wood hardness is used as a trait for genetic studies, the main parameters used for measuring wood quality in the industry are wood density, modulus of elasticity, and bending strength [4,5]. Wood density is an important indicator of wood quality and is closely related to its mechanical properties [6,7]. The density of silver birch

wood ranged from approximately 550 to 650 kg/m<sup>3</sup> [8]. The elastic modulus, also known as the modulus of elasticity, reflects the stiffness of wood and its ability to withstand deformation under load. The previous studies showed that the elastic modulus of silver birch wood was in a range of 10 to 15 GPa [8,9].

The studies in Sweden analysed wood quality for the genetic trials of silver birch [10,11]. Other studies focused on wood quality distribution by site conditions [12,13]. Overall, silver birch exhibits remarkable ecological plasticity and can adapt to diverse environmental conditions. Genetic studies have revealed local adaptation in silver birch populations, with certain genotypes displaying superior performance in specific habitats [14,15]. Understanding the genetic basis of local tree-species adaptations is crucial for conservation efforts and forest management practices, particularly with climate change. Several studies were focused specifically on the wood quality parameters of conifer species and the influence of forest management on wood density, modulus of elasticity, and stiffness [16–19]. As emphasised in the European Green Course and the EU Forest Strategy for 2030, it is appropriate to pay more attention to other tree species and their wood parameters, especially in the context of climate change [20,21].

This study aimed to evaluate the mechanical wood properties of silver birch (*Betula pendula* Roth) trees of different half-sib families.

## 2. Materials and Methods

The study objects were selected in the experimental plantations of the progenies of Lithuanian populations (half-sib families) of silver birch from different regions of origin (Table 1). All selected plantations were established in 1999.

**Table 1.** Description of experimental plantations of the progenies of birch populations in Lithuania.

No.	Plantation	Area, ha	North Latitude	East Longitude	Altitude, m	Region of Provenance	Climate/Continental Index	Forest Site Type *	Number of Population Families
1	Šiauliai, Lukšiai	1.4	55°58′	23°09′	120	1	Intermediate/27	Nb	24/111
2	Kaunas, Dubrava	1.5	54°55′	23°27′	75	2	Intermediate/27	Ld	24/109

\* Nb: mineral low-fertility soil of normal moisture regime; Ld: temporary over-moisture mineral very fertile soil according to the Lithuanian classification of forest-site types [22].

Each of the 24 populations in the experimental plantations was represented by 5 progeny families, for a total of 101 families. The experimental design included 6 blocks, and trees of each family were grown in one row of 10 trees located randomly within the block. Tree seedlings were planted in rows every 2.0–2.3 m, leaving a distance of 1.5 m between seedlings in the rows by strips using a mill (on the Dubrava plantation) or a soil plough (on the Šiauliai plantation).

All standing trees for wood hardness were measured with a Pilodyn 6J device (Proceq, Switzerland) in the experimental plantations (Table 2). The Pilodyn 6J device measured the penetration depth of a steel needle, shooting it into the wood with a constant energy (6 J). The penetration depth was used to evaluate the wood hardness. The hardest wood showed higher resistance to penetration, and the penetration depth was lower. Wood hardness was considered the representative trait for wood quality in tree genetic plasticity studies. Phenotypic plasticity was evaluated by the Shukla [23] method and by calculating the ecoalences of the families and their statistical significance.

**Table 2.** Distribution of silver birch genetic families by wood hardness measured by Pilodyn 6J. Different letters mean the significant difference between parameters by ANOVA Duncan multiple ranges at a significance level  $p < 0.05$ .

Family No.	Mean of Pilodyn	Std. Dev	Std. Error	Duncan Multiple Range Test	Family No.	Mean of Pilodyn	Std. Dev.	Std. Error	Duncan Multiple Range Test
52-172	22.44	1.54	0.24	T	60-76	23.29	1.34	0.21	LFKNJQIRHOPGM
52-169	22.49	1.44	0.18	ST	15-132	23.31	1.12	0.15	LFKNJQIRHOPGM
20-125	22.50	1.34	0.17	ST	49-74	23.35	1.57	0.17	LFKNJQIEHOPGM
45-99	22.56	1.11	0.18	SRT	18-50	23.39	1.45	0.21	LFKNJQIEHOPGM
01-113	22.57	1.30	0.23	SRT	52-171	23.39	1.11	0.15	LFKNJQIRHOPGM
20-128	22.70	1.74	0.24	SQRT	49-72	23.40	1.31	0.22	LFKNJQIEHOPGM
52-173	22.77	1.58	0.25	SQRPT	45-98	23.41	1.52	0.26	LFKNJQIEHOPGM
16-162	22.79	1.57	0.24	SQRPT	54-83	23.43	1.13	0.15	LFKNJQIRHOPGM
54-84	22.80	1.26	0.20	SQROPT	51-86	23.45	1.18	0.13	LFKNJQIEHOPGM
47-92	22.85	1.63	0.24	SNQROPT	37-56	23.47	1.51	0.20	LFKNJQIEHOPGM
40-118	22.94	1.34	0.19	SNQROPTM	47-91	23.53	1.61	0.27	LFKNJDIEHOPGM
34-63	22.96	1.60	0.22	SNQROPTM	43-65	23.56	1.16	0.20	LFKNJDIEHOGM
34-59	23.00	1.08	0.17	LSNQROPTM	18-21	23.57	1.81	0.25	LFKNJDIEHGM
49-71	23.00	1.43	0.21	LSNQROPTM	43-PL	23.60	1.71	0.29	LFKNJDIEHCGM
54-81	23.00	1.29	0.21	LSNQROPTM	51-89	23.66	1.37	0.20	LFKBJDIEHCGM
S-43	23.00	1.20	0.19	LSNQROPTM	20-124	23.74	1.34	0.20	LFKBJDIEHCG
45-100	23.03	1.17	0.20	LSKNQROPTM	40-119	23.75	1.58	0.23	LFKBJDIEHCG
49-73	23.04	1.64	0.22	LSKNQROPTM	37-54	23.76	0.99	0.13	LFKBJDIEHCG
01-111	23.07	1.46	0.26	LSKNQROPTM	18-48	23.76	1.20	0.17	LFKBJDIEHCG
40-120	23.09	1.51	0.26	LSKNQROPTM	43-64	23.79	1.62	0.22	FKBJDIEHCG
43-68	23.09	1.14	0.17	LSKNQROPTM	37-55	23.88	1.14	0.17	FBJDIEHCG
60-75	23.12	1.43	0.22	LSKNJQROPTM	51-87	23.89	1.37	0.17	FBJDIEHCG
19-142	23.12	1.63	0.25	LSKNJQROPTM	S-39	23.90	0.98	0.17	FBDIEHCG
47-93	23.14	1.35	0.22	LSKNJQIROPTM	43-BSM	23.91	1.53	0.27	FBDIEHCG
49-69	23.14	1.45	0.24	LSKNJQIROPTM	51-90	23.95	1.23	0.16	FBDEHCG
43-66	23.15	1.33	0.21	LSKNJQIROPTM	39-155	24.00	0.97	0.16	FBDECG
60-77	23.17	1.37	0.16	LSKNJQIROPTM	37-57	24.04	1.08	0.14	FBDEC
33-175	23.17	1.27	0.18	LSKNJQIROPTM	18-47	24.06	1.10	0.19	BDEC
34-60	23.21	1.28	0.18	LSKNJQIRHOPM	37-53	24.08	1.68	0.27	BDEC
38-143	23.23	1.38	0.24	LSKNJQIRHOPM	66-150	24.09	1.17	0.19	BDEC
01-112	23.23	1.41	0.18	LSKNJQIRHOPM	60-78	24.21	1.36	0.21	BDAC
16-130	23.25	1.26	0.16	LSKNJQIRHOPGM	47-94	24.21	1.56	0.23	BDAC
16-163	23.27	1.50	0.18	LKNJQIRHOPGM	39-154	24.32	1.06	0.18	BAC
16-161	23.27	1.41	0.17	LKNJQIRHOPGM	34-58	24.36	1.38	0.20	BA
51-88	23.29	1.51	0.20	LFKNJQIRHOPGM	60-79	24.78	1.08	0.16	A
18-52	23.29	1.82	0.32	LFKNJQIEHOPGM					

The number of measured trees per family per test was calculated to determine the average number of trees per genetic family. The adjusted sum of the mean squares of a feature was calculated for each family using the SAS procedure MEANS. The total sum of mean squares was also calculated. The Shukla ecovalence coefficient was calculated using the following Equation (1).

$$\text{shukla} = (n_{\text{fam}} * (n_{\text{fam}} - 1) * ss - sss) / ((n_{\text{site}} - 1) * (n_{\text{fam}} - 1) * (n_{\text{fam}} - 2)) \quad (1)$$

where  $n_{\text{fam}}$  is the number of families,  $ss$  is the sum of mean squares of the trait,  $sss$  is the total sum of mean squares of the trait, and  $n_{\text{site}}$  is the number of tests.

For the evaluation of wood mechanical properties, four representative half-sib families were selected by the wood hardness trait of the standing trees. The genetic families with not less than 30 remaining standing trees were selected. The ANOVA Duncan multiple range test was used for all selected families to ensure the significant differences between the genetic families with the hardest and softest wood. Two genetic families were selected following such principles. (1) One family with the lowest mean values of wood hardness represented the hardest wood, and one family with the highest wood-hardness values represented the softest wood. (2) One family was chosen to represent the non-plastic genetic family, and one family represented the plastic genetic family, calculated by the Shukla ecovalence coefficient (Table 2).

The genetic family 52–172 was identified as the family with the hardest wood, and the family 60–79—with the softest wood (Table 2). Genetic family 51–88 was selected as representative of the non-plastic family, and family 49–69 as representative of the plastic genetic family. According to the mentioned parameters, three model trees were selected per genetic family in the experimental plot. The selected trees were cut and transported to the laboratory. Altogether, 24 trees were cut; 12 were sampled in the Kaunas and 12 in the Šiauliai experimental areas. The model tree stems were sorted into 3 m logs across the length of the stem. Three to four representative sections were taken from each tree stem for wood mechanical properties determination. In the laboratory, 3 m logs were divided into 1 m sections (A, B, C), as shown in Figure 1.

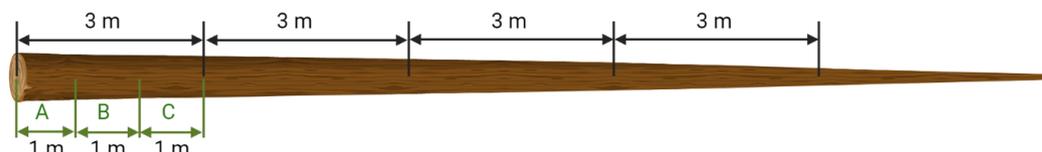


Figure 1. Model tree sampling.

For each 1 m section, the wood hardness was measured at three points with a Pilodyn 6J device (Figure 2).

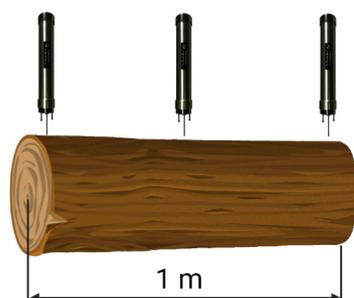
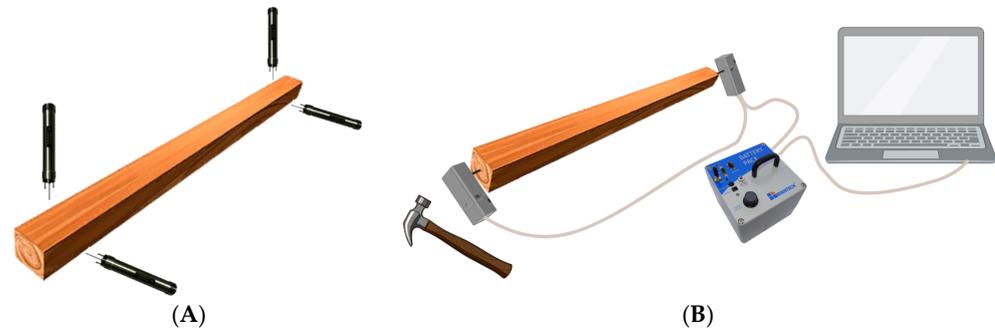


Figure 2. Scheme for wood-hardness measurement places on log samples.

Wood samples of 50 mm × 50 mm × 1000 mm were cut from the logs. Altogether, 520 wood samples were prepared. The samples were prepared and tested without measuring the amount of sapwood and heartwood. For wood samples, wood hardness at four points, dynamic modulus of elasticity ( $MOEdyn$ ), static modulus of elasticity ( $MOE$ ), and bending strength ( $MOR$ ) were measured. The wood hardness and  $MOEdyn$  test schemes are shown in Figure 3.



**Figure 3.** Wood-hardness test scheme for wood samples (A) and wood propagation speed measurement by ARBOTOM 3D (B).

Wood-hardness tests for the wood samples were performed with a Pildoy 6J device. The  $MOEdyn$  was measured by multiplying wood density and sound propagation speed according to Equation (2). The sound propagation speed was measured by ARBOTOM 3D acoustic tomography.

$$MOEdyn = V^2 \rho \quad (2)$$

where  $MOEdyn$  is the dynamic modulus of elasticity ( $N\ mm^{-2}$ ),  $\rho$  is the wood density ( $kg\ m^{-3}$ ); and  $V$  is the wave propagation speed ( $m\ s^{-1}$ ).

In the laboratory, all wood samples were tested with a Bending Testing Machine 500 kN (FORM + TEST Seidner & Co. GmbH, Riedlingen, Germany). The tests were conducted following the methodology given in Standard EN 408:2006 [24]. The samples were tested in a four-point bending test. The  $MOE$  and  $MOR$  were evaluated and calculated at 12% moisture content according to Standard EN: 384:2016 [25]. The static modulus of elasticity was calculated according to Equation (3).

$$MOE = \frac{l^3(F_2 - F_1)}{bh^3(w_2 - w_1)} \left[ \left( \frac{3a}{4l} \right) - \left( \frac{a}{l} \right)^3 \right] \quad (3)$$

where  $F_1, F_2$  is an increment of load on the straight-line portion of the load-deformation curve,  $0.2 F_{max}$  ( $F_2$ ) or  $0.4 F_{max}$  ( $F_1$ ), N;  $w_2, w_1$  is the increment of deformation corresponding to  $F_2, F_1$ , mm;  $l$ —span, mm;  $a$  is the distance between a loading position and the nearest support, mm;  $b$  is the width of the cross-section, mm; and  $h$  is the depth of cross-section, mm.

A random wood sample was cut from each broken specimen to determine the wood density, which was determined using Equation (4).

$$\rho_w = \frac{m_w}{a_w b_w l_w} \quad (4)$$

where  $\rho_w$  is wood density,  $kg\ m^{-3}$ ;  $m_w$  is the mass of the sample, kg;  $a_w, b_w$  are the cross-section dimensions of the sample, m; and  $l_w$  is the length of the sample, m.

To determine the wood density, the samples were cut near the breakage point immediately after the bending test. The moisture content was determined by the oven-dry method according to Standard EN: 13183-1:2002 [26]. The wood density was calculated using the

mass–volume ratio according to Equation (5). The values at 12% moisture content were calculated according to Standard EN 384:2016 [25].

$$W = \frac{m - m_0}{m_0} \times 100\% \quad (5)$$

where  $W$  is the moisture content, %;  $m$  is the wet sample mass, g; and  $m_0$  is the dry sample mass, g.

The statistical analysis of ANOVA and correlations was performed with the SAS 9.4. (SAS Institute Inc., Cary, NC, USA) statistical program.

### 3. Results

The main values of the tree diameter at breast height (DBH), tree height, log hardness, sample hardness, wood moisture, wood density, dynamic modulus of elasticity (MOEdyn), static modulus of elasticity (MOE), and bending strength (MOR) of silver birch of different genetic families are summarised in Table 3. The mean tree DBH of model trees varied from 16.2 cm in the birch genetic family representing the softwood to 18.5 cm in the non-plastic genetic family. The mean height of the model trees ranged from 17.0 m to 20.0 m. The tree with the largest height of 22.3 m was found in the genetic family with hardwood, and the lowest height tree of 14.5 m was found in the non-plastic genetic family. The mean log hardness values between genetic families varied slightly from 17.0 mm to 18.7 mm.

**Table 3.** Summary of the descriptive statistics of the main parameters by different genetic families.

Parameter	Units	Mean	Std Dev	Std Error	Minimum	Maximum	Probability
Hard							
Tree DBH	cm	18.20	2.10	0.16	12.90	20.70	
Tree Height	m	20.04	1.94	0.15	15.10	22.30	
Log hardness	mm	18.61	1.26	0.10	15.67	21.67	
Sample hardness	mm	10.15	1.26	0.10	7.00	14.25	
Moisture	%	9.68	1.22	0.09	7.32	19.52	<0.0001
Density	kg/m <sup>3</sup>	545	37.04	2.81	487	661	
MOEdyn	N/mm <sup>2</sup>	12,489	1773.58	134.45	7637	17,267	
MOR	N/mm <sup>2</sup>	52.71	9.83	0.75	22.14	81.96	
MOE	N/mm <sup>2</sup>	11,386	2239.75	169.79	4608	17,571	
Non-Plastic							
Tree DBH	cm	18.50	1.87	0.17	14.50	20.75	
Tree Height	m	18.13	1.69	0.15	14.50	20.20	
Log hardness	mm	17.65	1.38	0.13	15.33	21.00	
Sample hardness	mm	10.07	1.71	0.16	7.00	15.25	
Moisture	%	9.83	1.11	0.10	8.09	13.15	<0.0001
Density	kg/m <sup>3</sup>	568	52.45	4.81	470	712	
MOEdyn	N/mm <sup>2</sup>	12,028	1967.27	180.34	8213	18,316	
MOR	N/mm <sup>2</sup>	51.00	10.85	0.99	15.26	78.43	
MOE	N/mm <sup>2</sup>	10,916	2493.07	228.54	3428	16,777	
Plastic							
Tree DBH	cm	17.48	2.85	0.26	14.85	22.35	
Tree Height	m	18.67	1.44	0.13	16.20	20.10	
Log hardness	mm	17.52	1.16	0.11	14.67	20.33	
Sample hardness	mm	9.61	1.26	0.11	6.75	15.50	
Moisture	%	9.36	0.74	0.07	7.60	11.02	<0.0001
Density	kg/m <sup>3</sup>	578	39.99	3.64	513	705	
MOEdyn	N/mm <sup>2</sup>	12,776	1923.60	174.87	8221	18,616	
MOR	N/mm <sup>2</sup>	54.67	9.71	0.88	30.34	76.12	
MOE	N/mm <sup>2</sup>	11,255	2318.79	210.80	5742	17,166	

Table 3. Cont.

Parameter	Units	Mean	Std Dev	Std Error	Minimum	Maximum	Probability
			Soft				
Tree DBH	cm	16.16	2.02	0.20	13.30	18.55	
Tree Height	m	17.04	0.94	0.09	15.50	18.20	
Log hardness	mm	17.00	1.01	0.10	14.00	19.00	
Sample hardness	mm	9.94	1.38	0.14	6.75	14.00	
Moisture	%	9.49	0.95	0.09	7.45	12.75	<0.0001
Density	kg/m <sup>3</sup>	571	44.32	4.33	499	704	
MOEdyn	N/mm <sup>2</sup>	12,423	1776.47	173.37	7351	16,267	
MOR	N/mm <sup>2</sup>	54.34	9.61	0.94	30.69	73.17	
MOE	N/mm <sup>2</sup>	11,222	2209.71	215.65	4406	16,961	

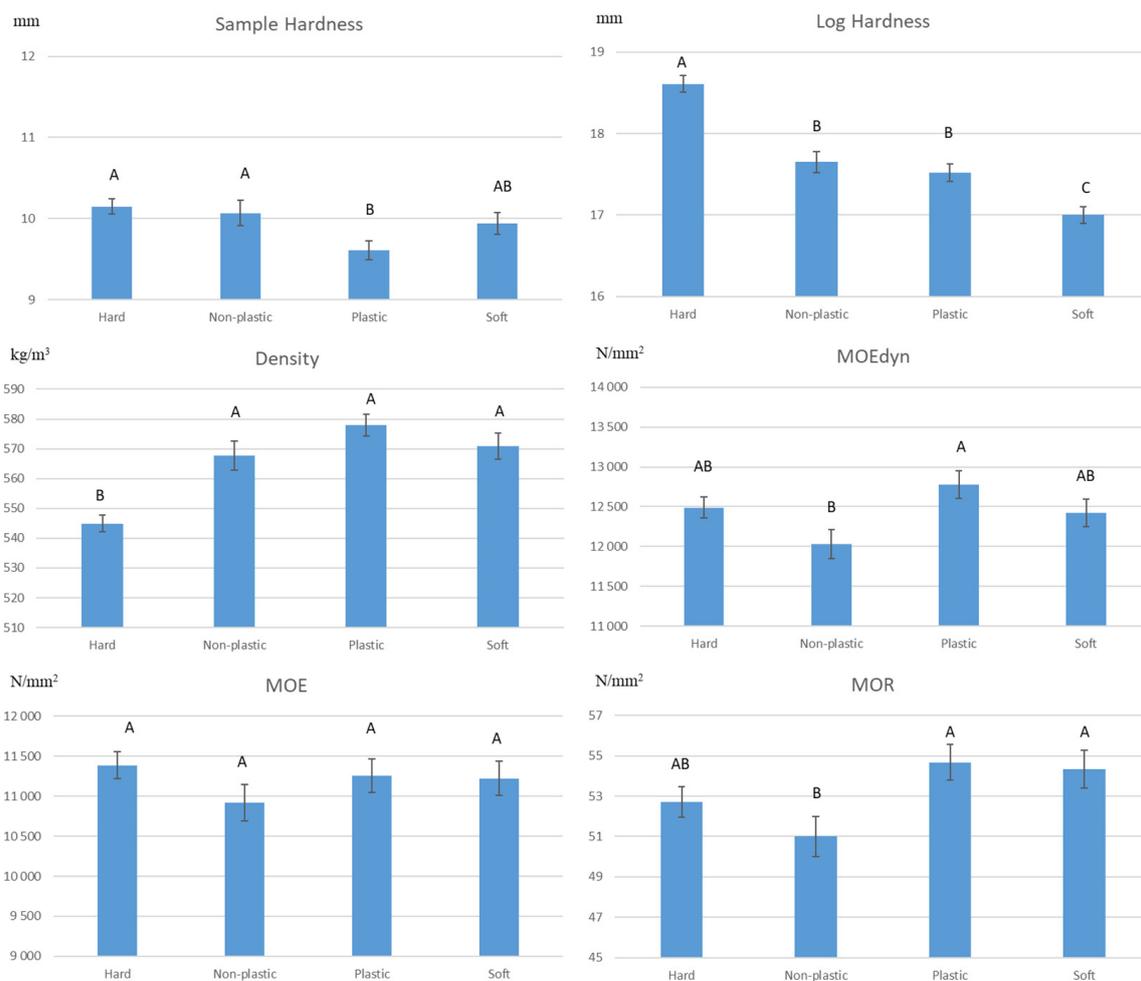
The variation of sample hardness, wood density, MOEdyn, MOE, and MOR in relation to the genetic families is given in Table 3 and Figure 4. The highest sample hardness value was found in the plastic genetic family (15.5 mm), and the lowest value of sample hardness was found in the genetic family with the softwood (14.0 mm). The mean values of the wood hardness of the samples were similar for all genetic families and varied from 9.6 mm to 10.2 mm. The mean moisture content of the samples was 9.6%. The mean wood density ranged between 545 and 578 kg/m<sup>3</sup>. The differences between the mean MOEdyn in the studied genetic families varied in a narrow range from 12,028 N/mm<sup>2</sup> (for non-plastic family) to 12,776 N/mm<sup>2</sup> (for plastic family). The highest mean values of MOR were found for the plastic family, and the lowest were found for the non-plastic family, with a 6.7% difference between the genetic families. The mean MOE ranged from 10,916 N/mm<sup>2</sup> to 11,386 N/mm<sup>2</sup> between the genetic families.

The significantly lowest mean sample hardness was found for the plastic genetic family compared to other genetic families (Figure 4). For the log hardness, the genetic families representing the soft-wood and hard-wood significantly differed by 9%. The lowest mean wood density was found for the genetic family representing the hardwood, and this value significantly differed from other genetic families. The MOEdyn significantly differed between the plastic and non-plastic genetic families. The MOE was similar in all the studied genetic families, and the MOR in the non-plastic genetic family was significantly lower than in other genetic families (Figure 4).

The wood mechanical properties of different tree-stem sections are shown in Figure 5. Analysis of the wood sample hardness showed a large difference between the stem sections. The hardest wood samples were in the first stem section. This parameter decreased significantly from the stem bottom to the top, and the difference between stem sections I and IV was about 18%. The log hardness differed significantly between the stem sections I–III and IV. The highest mean wood density was found in the stem bottom section. There were no significant differences in wood density between the other stem sections. The highest mean MOEdyn was found in the II stem section. The MOE and MOR showed a decreased trend from section I to section IV, with 11% for MOE and 13% for MOR.

To compare the relations between tree and wood parameters, the Pearson correlations were analysed (Table 4).

The strongest correlation was found between the MOE and MOR parameters ( $r = 0.86$ ) (Table 4). The wood density significantly correlated with all selected parameters. The MOEdyn correlated with the MOE ( $r = 0.48$ ) and the MOR ( $r = 0.41$ ). The sample hardness strongly correlated with the wood density ( $r = -0.67$ ). The Tree DBH correlated with the log hardness ( $r = 0.36$ ) and the sample hardness ( $r = -0.15$ ). However, the wood density had weak correlations with MOEdyn ( $r = 0.19$ ), MOE ( $r = 0.18$ ) and MOR ( $r = 0.09$ ). Most of the evaluated parameters showed low or moderate correlations.

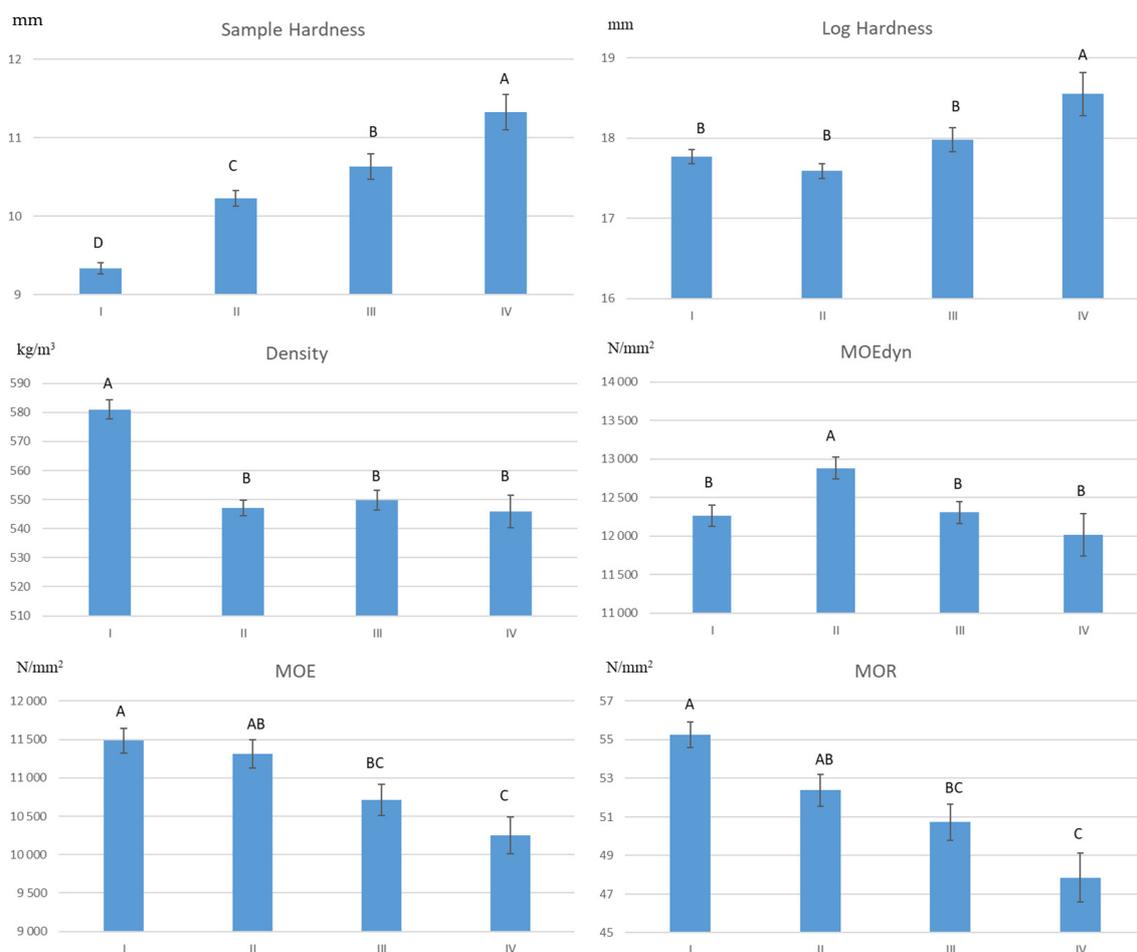


**Figure 4.** The main birch wood parameters—sample and log hardness, wood density, dynamic modulus of elasticity (MOEdyn), static modulus of elasticity (MOE) and bending strength (MOR)—in different genetic families. Different capital letters above the columns show significant differences between the wood from selected genetic families by ANOVA Duncan multiple range test at a significance level of  $p < 0.05$ .

**Table 4.** The relationship between main wood parameters and the tree parameters by Pearson correlations. Bold values mean statistically significant correlations at a significance level of  $p < 0.05$ . The right side of the matrix shows correlations, and the left side shows probability.

Parameter	Tree DBH *	Tree Height	Log Hardness	Sample Hardness	Wood Density	MOEdyn	MOR	MOE
Tree DBH		−0.0727	<b>0.3553</b>	−0.1506	<b>0.1279</b>	0.0070	−0.0703	−0.0138
Tree Height	0.0979		−0.0377	0.0669	− <b>0.3337</b>	0.0839	−0.0337	<b>0.0907</b>
Log hardness	<b>&lt;0.0001</b>	0.391		<b>0.2516</b>	−0.1728	− <b>0.2003</b>	− <b>0.0873</b>	− <b>0.1005</b>
Sample hardness	<b>0.0006</b>	0.1281	<b>&lt;0.0001</b>		−0.670	− <b>0.2505</b>	− <b>0.2010</b>	− <b>0.1760</b>
Wood Density	<b>0.0035</b>	<b>&lt;0.0001</b>	<b>&lt;0.0001</b>	<b>&lt;0.0001</b>		<b>0.1901</b>	<b>0.1801</b>	<b>0.0917</b>
MOEdyn	0.8731	0.056	<b>&lt;0.0001</b>	<b>&lt;0.0001</b>	<b>&lt;0.0001</b>		<b>0.4059</b>	<b>0.4848</b>
MOR	0.1098	0.444	<b>0.0468</b>	<b>&lt;0.0001</b>	<b>&lt;0.0001</b>	<b>&lt;0.0001</b>		<b>0.8646</b>
MOE	0.7531	<b>0.0388</b>	<b>0.0221</b>	<b>&lt;0.0001</b>	<b>0.0368</b>	<b>&lt;0.0001</b>	<b>&lt;0.0001</b>	

\* DBH—tree diameter at breast height/1.3 m above ground level; MOEdyn—dynamic modulus of elasticity, MOE—static modulus of elasticity, and MOR—bending strength.



**Figure 5.** The differences in the main birch wood parameters—sample and log hardness, wood density, dynamic modulus of elasticity (MOEdyn), static modulus of elasticity (MOE) and bending strength (MOR)—in different stem sections (obtained from the tree bottom to the tree top). Different capital letters above the columns show significant differences between stem sections by ANOVA Duncan multiple range test at a significance level  $p < 0.05$ .

#### 4. Discussion

The study results demonstrated a genetic effect on the wood quality parameters of the samples for log hardness, wood density, dynamic modulus of elasticity (MOEdyn), static modulus of elasticity (MOE), and bending strength (MOR). The findings of this study showed that different half-sib families caused various responses to the wood quality characteristics of silver birch trees. Previous studies, for example, conducted in Sweden, also showed high variation in wood hardness—from 8.3 to 24.1 mm—for silver birch standing trees [10]. This is an even larger variation in wood hardness compared to the log hardness parameters in this study. These differences may be due to different tree ages and specific growing conditions. Another study in Sweden showed similar mean wood-hardness parameters to this study (17.4 mm) for standing trees obtained with a Pilodyn instrument for silver birch [11].

The genetic progeny test plots showed a wide range of wood-density parameters, as shown in the Swedish studies, where the average wood-density values ranged from 408 to 444 kg/m<sup>3</sup> [10,11]. The wood density determined during the genetic studies in Sweden was 21%–28% lower than the data from the genetic research in Lithuania. These differences could be caused by the different genetic materials of trees and specific growing conditions. Other studies conducted in the 30-year-old silver birch stands in different regions of Poland showed higher mean wood-density values, which were 512 kg/m<sup>3</sup>.

Mean values of wood density have been found to increase with age, and 70-year-old trees have higher wood density than 30-year-old trees [12]. The results in Poland reflect the wood-density distribution between different tree parts in this study. Previous studies in Wales and Scotland (UK) also showed a significant effect of wood density on the silver birch growth rate, with faster-growing trees having significantly lower wood density than slow-growing trees [27]. The relationship between wood hardness and the non-destructive wood quality parameter—acoustic velocity—was different in different Swedish studies. The Jones et al. [10] study found a positive, relatively weak relationship, with  $r$  values of 0.09 and 0.16. Later studies by Jones et al. [11] showed a negative correlation between acoustic velocity and wood hardness ( $r = -0.18$ ). This study showed a negative correlation between MOEdyn calculated by acoustic velocity and wood-density values, with a log of ( $r = -0.20$ ) and a sample hardness of ( $r = -0.25$ ). Correlation in both Sweden studies showed a moderate relationship between wood hardness and wood density [10,11]. Similar trends were found in this study of Lithuanian genetic trials. The relationship between different locations and stand age in Sweden varied from  $r = -0.36$  to  $r = -0.62$ .

In analysing the MOE and MOR parameters for silver birch in Finland, the MOE was 13,620 N/mm<sup>2</sup>, and the MOR was 43,9 N/mm<sup>2</sup> for the wood samples with knots. Higher values were found for wood samples without knots, where the MOE was 16,530 N/mm<sup>2</sup> and the MOR 52.7 N/mm<sup>2</sup> [28]. The mentioned study found a strong correlation between MOE and MOR for all tested samples ( $r = 0.87$ ). Compared to the Finland study, our results showed lower mean values for the MOE and MOR of silver birch but a similar correlation between these two parameters. The lower MOE and MOR mean values in Lithuania could be caused by young tree age and measured samples from full tree height because of the high variation of wood parameters within the tree. From this study's results, the MOE and MOR values decreased from tree bottom to tree top. The decrease in MOE values was found in the silver birch stands with different growing rates in Wales and Scotland [27]. This study showed that the mean MOE in the slow-growing stand was 12,668 N/mm<sup>2</sup> and in the fast-growing stand, 8108 N/mm<sup>2</sup>.

The wood density—one of the main wood quality parameters—moderately strongly correlated with the MOE ( $r = 0.67$ ) and the MOR ( $r = 0.66$ ) parameters in the Finland study [27]. An earlier study in Sweden shows stronger correlations between wood density and MOE ( $r = 0.85$ ) [29]. Another study from China and the USA found a strong correlation between the wood density and the MOE obtained using SilviScan [30]. The authors found that the relationship between the wood density and MOE was  $r = 0.85$  for 10 different hardwood species [30]. This study showed a weak correlation between the wood density with MOE and MOR. The relations between the mentioned parameters could be improved by increasing the number of model trees and a more diverse tree age of the samples. The different results of this study may have been due to some limitations. One of which is the limited selection of model trees, as genetic trials are very valuable for genetic selection and genetic studies. A strictly regulated selection of only specific trees was allowed to be used for this study. Due to the limited selection of the model trees, all tree parts (sections) were taken in this study. Under these conditions, some wood quality parameters may be lower due to a certain proportion of samples from the tree top containing a larger amount of juvenile wood, which may decrease the wood quality parameters. Different site conditions in the silver birch's genetic trials in Lithuania could also be considered a limitation of this study. Additional research is needed in the future, and it is necessary to measure more model trees and more half-sib families after next-generation genetic trials for silver birch are established in Lithuania.

## 5. Conclusions

This investigation aimed to assess the wood mechanical properties between half-sib families of silver birch and analyse the relationship between the wood-hardness parameter and other wood properties. This study has identified a high variability of different wood properties between different genetic families, although the static modulus of elasticity did

not show significant differences between the selected genetic families. All measured wood properties decreased from the bottom to the top of the model trees.

Wood hardness showed a moderately negative correlation with wood density and weak correlations with the static modulus of elasticity and bending strength. Due to weak correlations between wood hardness and other wood mechanical properties, a dynamic modulus of elasticity would likely be a more appropriate trait for genetic studies. Further efforts are needed to obtain more accurate results by studying more model trees.

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