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Among-site differences in wood properties and decay resistance of wood in *Pinus sylvestris* naturally growing in Mongolia

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Abstract

The wood properties (basic density and compressive strength parallel to the grain under green conditions), chemical components (lignin content, total polyphenol [as equivalent with tannic acid], monosaccharides [as equivalent with glucose], and ethanol-toluene extracts), and decay resistance were investigated in the heartwood of 50 naturally growing *Pinus sylvestris* L. trees from five different sites (Sites 1 to 5) in Ulaanbaatar, Mongolia. A mixed-effects model was developed to evaluate the among-site differences in measured properties. In addition, principal component analysis was applied to characterize the wood properties of sample trees in each site. The mean values of lignin content, polyphenol content, monosaccharide content, and mass loss caused by *Trametes versicolor* and *Fomitopsis palustris* were 30.3%, 95.3 mg/g, 38.9%, 34.4%, and 4.2%, respectively. Mass loss caused by *T. versicolor* was negatively correlated with lignin content but not with monosaccharide content. In contrast, mass loss caused by *F. palustris* showed a significant negative correlation with monosaccharide content but not with lignin content. Among-site differences were observed in polyphenol content, mass loss by *T. versicolor*, and physical and mechanical properties of wood. The principal component analysis results showed that trees from Site 4 showed higher mechanical properties and excellent decay resistance compared to other Sites. Based on these results, it is concluded that site selection is important to control the quality of the final products. In addition, improvement of wood quality can be achieved by selecting mother trees in the appropriate tree breeding program for establishing plantations.

Keywords Basic density, Compressive strength, Polyphenol content, Chemical components, *Trametes versicolor*, *Fomitopsis palustris*

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Introduction

The *Pinus* genus is mainly found in the northern hemisphere. Its natural range includes the boreal and temperate forest zones of most of Eurasia [1]. Of *Pinus* species, *Pinus sylvestris* L. (Scots pine in English) is the most widely distributed species [1]. The species is one of the most commercially important forestry species for timber production [2]. The wood is highly workable and distinguished by its excellent strength-to-weight ratio, making it one of the strongest softwoods [3]. Due to these characteristics, *P. sylvestris* is extensively used in construction and in the production of furniture, pulp, and paper [1, 4, 5]. In Central and Northeastern Asia, *P. sylvestris* commonly grows in forest-steppe transition zones, particularly in the northern regions of Kazakhstan, Mongolia, and China [6].

In Mongolia, natural forests dominated by *P. sylvestris* were 4.3% of the total forested area and accounted for approximately 5% of the wood stock in the country [7]. Although the wood stock of *P. sylvestris* is lower than other coniferous species, *Larix sibirica* (62.2% of the total forested area and 79.3% of the wood stock), it is an important species for the Mongolian wood industry [6]. Recently, the plantation of *P. sylvestris* has been established in Mongolia to sustainably produce wood resources. Therefore, to effectively utilize the wood obtained from the natural forests and plantations of this species, its wood properties and chemical components have been studied by several researchers [8–10].

The durability and resistance of wood are important factors when wood is used for a building material. Thus, mechanical and physical properties [9, 10], decay resistance [8, 11, 12], and chemical properties related to decay resistance [13–20] and their relationships has been investigated for heartwood of *P. sylvestris*. A significant negative correlation was found between the total polyphenol concentration and mass loss caused by *Coniophora puteana* (brown-rot fungus) in the heartwood of *P. sylvestris* from Finland [16, 21]. In addition, ethanol-toluene extracts negatively correlated with mass loss by *T. versicolor* and *F. palustris* in Mongolian softwoods, *P. sylvestris*, *Pinus sibirica*, *Picea obovata*, and *L. sibirica* [8].

Geographic and climatic conditions are important factors that affect wood properties and durability [22, 23]. Tumenjargal et al. [23] investigated the wood properties of *L. sibirica* naturally grown in five different provenances in Mongolia. They found the geographic variations in the physical and mechanical properties of wood in *L. sibirica*. Accordingly, among-site variations in wood properties and decay resistance of wood should be also examined for other important Mongolian forestry species.

In the present study, the wood properties (basic density and compressive strength parallel to the

grain under green conditions), chemical components (amounts of lignin, total polyphenol [as equivalent with tannic acid], monosaccharides [as equivalent with glucose], and ethanol-toluene extracts), and decay resistance (mass loss by white- and brown-rot fungi) were investigated for the *P. sylvestris* heartwood collected from five different natural forests in Ulaanbaatar, Mongolia. Among-site differences in the measured properties were determined. Based on the results, the implementation of tree breeding to improve the natural decay resistance of this species was also discussed.

Materials and methods

Experimental sites

The experimental forest sites were located around Ulaanbaatar, Mongolia (48° 07′ – 12′ N, 106° 78′ – 89′ E, ca. 1481 m above the sea level, Fig. 1). In the present study, five different sites (Sites 1 to 5) were selected for sampling of wood of *Pinus sylvestris* L. There were no substantial differences in geography, climatic conditions, or soil among the five selected sites, but the sites were at least 3 km apart in horizontal distance. All sites are naturally regenerated forests mixed with *P. sibirica* and *L. sibirica*. Healthy ten trees with 20 to 25 cm stem diameter at 1.3 m above the ground were selected in each site (Table 1). The exact tree age was unknown because the sample trees were naturally regenerated.

Growth characteristics and stress-wave velocity of stems

Growth characteristics, including stem diameter and tree height, as well as the stress-wave velocity of the stem, were evaluated for 50 trees across five different sites. Stem diameter was recorded at 1.3 m above the ground using a measuring tape, while tree height was determined with an ultrasonic height meter (Vertex IV, Haglöf, Långsele, Sweden). Stress-wave propagation time was measured using a handheld stress-wave timer (Fakopp Microsecond Timer, Fakopp Enterprise, Sopron, Hungary) following the procedure described by Ishiguri et al. [24]. The start and stop sensors were positioned at 1.5 and 0.5 m above the ground to assess stress-wave velocity along the longitudinal direction. A small hammer was used to hit the start sensor, generating a stress wave. The stress-wave propagation time between the two sensors was recorded, with six measurements taken at the same position for each tree. The stress-wave velocity was then calculated by dividing the distance between the sensors by the average stress-wave propagation time. The stress-wave velocity of the stems is closely related to the Young's modulus of wood [24].

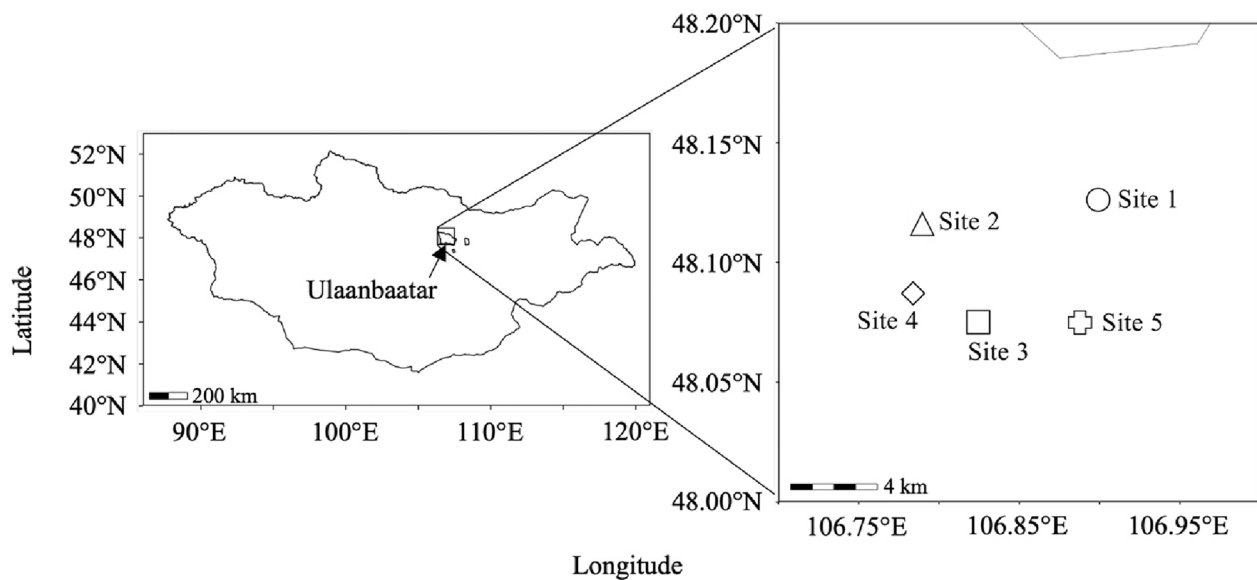


Fig. 1 Sampling location

Table 1 Growth characteristics, stress-wave velocity of stems, annual ring number, basic density, and compressive strength of *Pinus sylvestris* trees from five sites

Site	D (cm)	TH (m)	SWV (km/s)	ARN	BD (g/cm ³)	CS (MPa)
1	27.2 ± 1.6	17.7 ± 1.0	4.17 ± 0.30	109 ± 12	0.40 ± 0.05	19.0 ± 2.9
2	24.9 ± 4.0	12.4 ± 1.8	3.89 ± 0.25	52 ± 5	0.36 ± 0.02	16.5 ± 1.7
3	29.0 ± 5.6	17.7 ± 1.4	3.90 ± 0.39	56 ± 5	0.38 ± 0.03	16.3 ± 1.1
4	24.6 ± 3.8	14.7 ± 1.0	4.08 ± 0.33	47 ± 8	0.43 ± 0.06	19.4 ± 2.9
5	28.2 ± 3.8	20.5 ± 2.2	4.21 ± 0.20	73 ± 5	0.37 ± 0.04	16.3 ± 1.3
Mean	26.8 ± 3.8	16.6 ± 1.5	4.05 ± 0.29	–	0.39 ± 0.04	17.5 ± 2.0

Number of trees in each site = 10. D, stem diameter at 1.3 m above the ground; TH, tree height; SWV, stress-wave velocity of stems; ARN, annual ring number; BD, basic density; CS, compressive strength under green conditions. Values after mean indicate standard deviation

Wood properties

After measuring the growth characteristics and stress-wave velocity, pith-to-bark increment core samples with a diameter of 5 mm (at least five core samples in each tree) were obtained by a core borer (Haglöf, Långsele, Sweden) at 1.3 m above ground level to evaluate wood properties, chemical components of wood, and decay resistance. Each core was visually inspected for severe damage. To export the core samples from Mongolia to Japan, all core samples were once oven-dried at 60 °C for 2 days.

Basic density and compressive strength parallel to the grain under green conditions were measured as wood properties using the core sample. The samples for measuring the basic density and compressive strength were collected within 3 cm from the pith, suggesting that all samples were heartwood and juvenile wood. The samples were dipped into tap water for one week to recover

green conditions (moisture content of the samples did not measure). Basic density was determined at 1 cm intervals from the pith to the bark by dividing the oven-dried weight (at 105 °C) by the green volume, which was measured using the water displacement method [25]. Compressive strength parallel to the grain in the green condition was evaluated using 5 mm samples prepared near basic density samples. Testing was conducted using a core-sample strength equipment (Fractometer II, IML, Wiesloch, Germany), following the procedures described by Matsumoto et al. [26].

Chemical components of wood

Wood meal for chemical analysis was prepared from small core specimens, each 3 cm in length, taken from the pith side (heartwood and juvenile wood) of the core samples. The specimens were initially sectioned using

a disposable knife and then further processed into a wood meal using a small blender (Crush Millser, Iwata, Osaka, Japan). In the present study, amounts of lignin, total polyphenol (as equivalent to tannic acid), and ethanol-toluene extracts were determined as chemical components of wood. In addition to these chemical components, monosaccharides (as equivalent to glucose) were also determined.

The lignin content was determined by the acetyl bromide method (modified method described by Iiyama and Wallis [27]). The wood meals were extracted with 120 mL mixture of 95% ethanol (40 mL; Kanto Chemical Co., Tokyo, Japan) and toluene (80 mL; Kanto Chemical Co., Tokyo, Japan) using a Soxhlet extractor for six hours. After extraction, the organic solvent was evaporated off by a rotary evaporator (N-1100, EYELA, Tokyo, Japan). The extracts in the flask were air-dried in a fume hood for a day before being dried in the oven at 105 ± 3 °C overnight. The amount of the ethanol-toluene extracts was determined gravimetrically. Furthermore, five mg of extracted wood powder in each tree was used as the sample for lignin content measurement. The lignin content was calculated by the following equation (Eq. 1):

$$\text{Lignin (\%)} = \frac{100(A_s - A_b)V}{aW} \quad (1)$$

where A_s and A_b are the absorbance of the sample and blank at 280 nm, V is the volume of solution, a is the absorptivity of lignin standard (20.09 L/(g cm)), and W is the weight of the extracted sample (mg).

To determine the total polyphenol content, 50 mg of oven-dried wood powder with 2 mL of 80% (v/v) aqueous acetone was sonicated at room temperature for 30 min, following the method described by Kainulainen et al. [28]. The total polyphenol content (as equivalent to tannic acid) was quantified using the Folin-Ciocalteu method described by Julkunen-Tiitto [29]. To determine polyphenol content (as equivalent to tannic acid), the Folin-Ciocalteu reagent (diluted tenfold, MP Biomedical, Illkirch, France) was used. The absorbance was measured at 735 nm using a spectrophotometer (V-650, JASCO, Tokyo, Japan). Calibration curves were prepared using tannic acid (Kanto Chemical, Tokyo, Japan) at concentrations of 0.20, 0.10, 0.05, and 0.02 mg/mL. The total polyphenol content was expressed as milligrams of tannic acid equivalents per gram of dry weight of the sample.

Monosaccharide content was determined by the phenol-sulfuric acid method [30]. The wood powder (0.2 mg) was reacted with 500 μ L of 5% phenol (Wako Pure Chemical Industries, Osaka, Japan) in distilled water and mixed thoroughly. To the solution, 2.5 mL of concentrated sulfuric acid (95%, FUJIFILM Wako Pure Chemical Corporation, Osaka, Japan) was added using

a dispenser (PROSPENSER, Sartorius, Göttingen, Germany) to run down the wall of the test tube. The sample absorbance was measured at 490 nm for hexose within 2 h using a spectrophotometer (V-650, JASCO, Tokyo, Japan). Calibration curves were prepared using concentrations of D(+)-glucose (FUJIFILM Wako Pure Chemical Corporation, Osaka, Japan) at 10, 20, 50, 100, and 200 μ g/mL ($y = 0.0065x - 0.048$; $R^2 = 0.999$) for hexose sugar. The monosaccharide content was expressed as a percentage of the dried wood sample [31].

Decay test

The decay test was carried out according to the method described by Matsumoto et al. [32] using two fungal species, *Trametes versicolor* (FFPRI1030) as a white-rot fungus and *Fomitopsis palustris* (FFPRI0507) as a brown-rot fungus. A total of 50 specimens were used for the decay test for each fungus. Increment cores were cut from the pith side into about 3 cm lengths, dried at 60 °C for one day, and then weighed. Since only the innermost 3 cm of heartwood was used, these specimens also primarily represented juvenile wood. All the specimens were sterilized with propylene oxide (FUJIFILM Wako Pure Chemical Corporation, Osaka, Japan) for two days in a desiccator. Each fungus was precultured on a Potato Dextrose Agar (Difco Laboratories, MI, USA) medium in a glass tube (2.5 cm in diameter and 12.0 cm in length). After mycelium had spread on the medium, specimens were put onto the medium in the glass tube and then incubated at 26 ± 2 °C with 70% relative humidity for one month. After the incubation, mycelium was carefully removed from the specimens using a small brush and tweezers. The decayed specimens were oven-dried at 60 ± 2 °C for one day to determine their weight after the decay test. Using the weight before and after the day test, the percentage of mass loss was determined.

Statistical analysis

Statistical analysis was conducted using R software (version 4.3.1, [33]). To evaluate among-site differences in each property, the following linear mixed-effects model with sites as a random effect (Eq. 2) was developed using the lmer function in the lme4 package [34]:

$$y_{ij} = \mu + \text{Site}_j + e_{ij} \quad (2)$$

where y_{ij} is the measured value for the i th individual tree of the j th sites; μ is the general mean value, Site_j is the random effect of j th site, and e_{ij} is residual. The variance component ratio of site in each property was calculated as a percentage of the total variance components in the model [35]. In this model, the higher the variance component ratio of the site in a property indicates that the property has the larger among-site variations. In addition,

the obtained random-effect parameter estimates (Site, in Eq. 2) represent differences in each site from the general mean (μ in Eq. 2). In addition to the modeling, the Tukey–Kramer test was also applied to assess whether the measured properties with higher variance component ratios (20% or more) differed significantly among sites or not.

To clarify the relationship between the measured traits, Pearson's correlation coefficients were determined for data from all trees ($n=50$). Principal component analysis was conducted to characterize the trees in each site. The analysis was performed using the mean values of several wood properties with higher variance component ratio among measured properties in each tree. In addition, principal component scores were calculated to represent the contribution of these properties to each principal component.

Results

Growth characteristics and stress-wave velocity of the stem

Table 1 shows mean values and standard deviations of stem diameter, tree height, and stress-wave velocity of stems in five sites in Mongolia. Stem diameter ranged from 24.6 cm (Site 4) to 29.0 cm (Site 3) across the sites. For the tree height, the highest and lowest mean values were recorded in Site 5 (20.5 m) and Site 2 (12.4 m). Stress-wave velocity of stems ranged from 3.89 km/s (Site 2) to 4.21 km/s (Site 5). The overall mean values of stem diameter, tree height, and stress-wave velocity of stems were 26.8 cm, 16.6 m, and 4.05 km/s, respectively.

Wood properties, chemical components, and decay resistance

The means and standard deviations of annual ring number, basic density, and compressive strength are listed in Table 1. The mean annual ring number ranged from 47 (Site 4) to 109 (Site 1). Basic density ranged from 0.36 g/cm³ (Site 2) to 0.43 g/cm³ (Site 4). In compressive strength, the highest value was found in Site 4 (19.4 MPa), while the lowest value was recorded in Sites

3 and 5 (16.3 MPa). The overall mean values were 0.39 g/cm³ for basic density and 17.5 MPa for compressive strength.

The amounts of lignin, polyphenol (as equivalent to tannic acid), monosaccharide contents (as equivalent to glucose), and ethanol-toluene extracts are shown in Table 2. The lignin content ranged from 28.1% (Site 3) to 32.2% (Site 2), with an overall mean of 30.3%. Among all sites, Site 1 exhibited the lowest polyphenol content (56.4 mg/g), while the highest value (136.4 mg/g) was observed in Site 3. The mean values of monosaccharide content in all sites were 38.9%. The means of monosaccharide content at site level ranged from 34.2% (Site 3) to 42.1% (Site 1). The highest ethanol-toluene extract content was recorded at Site 3 (10.0%), whereas the lowest was found at Site 4 (6.0%), with an overall mean of 8.0%.

The mean mass loss due to *T. versicolor* ranged from 23.3% (Site 4) to 46.0% (Site 1) (Table 2). Similarly, the mean mass loss caused by *F. palustris* ranged from 3.6% (Site 1) to 5.1% (Site 5) (Table 2). The overall mean mass loss for *T. versicolor* and *F. palustris* was 34.4% and 4.2%, respectively. Mass loss caused by *T. versicolor* was higher than that caused by *F. palustris*.

Relationships among measured properties

Correlation coefficients between measured properties are listed in Table 3. Stem diameter was positively correlated with tree height ($r=0.319$) and negatively correlated with the stress-wave velocity of stems ($r=-0.394$). Basic density showed moderate positive correlations with compressive strength ($r=0.533$), and a lower positive correlation with lignin content ($r=0.280$). Monosaccharide content was negatively correlated with polyphenol content ($r=-0.365$). Conversely, monosaccharide content was positively correlated with compressive strength ($r=0.293$). Mass loss caused by *F. palustris* was negatively correlated with compressive strength ($r=-0.310$), and monosaccharide content ($r=-0.400$). Mass loss caused by *T. versicolor* negatively correlated with basic density

Table 2 Amounts of chemical components and mass loss by white- and brown-rot fungi

Site	LC (%)	PC (mg/g)	MC (%)	ETH (%)	ML _w (%)	ML _b (%)
1	29.1±4.7	56.4±40.3	42.1±5.8	7.6±2.4	46.0±13.2	3.6±1.2
2	32.2±4.2	84.0±25.3	39.8±6.2	8.9±2.9	30.1±11.1	4.1±1.7
3	28.1±4.8	136.4±56.1	34.2±6.7	10.0±2.8	34.9±14.8	4.1±1.3
4	31.3±6.5	105.3±50.3	40.3±5.1	6.0±1.7	23.3±18.3	4.4±1.5
5	30.9±4.9	94.3±43.7	38.2±4.8	7.7±1.6	37.5±10.7	5.1±1.5
Mean	30.3±5.0	95.3±43.1	38.9±5.7	8.0±2.3	34.4±13.6	4.2±1.4

Number of trees each site = 10. LC, lignin content; PC, polyphenol content (as equivalent with tannic acid); MC, monosaccharide content (as equivalent with glucose); ETH, ethanol-toluene extracts; ML_w, mass loss by *T. versicolor*; ML_b, mass loss by *F. palustris*. Values after mean indicate standard deviation

Table 3 Correlation coefficients (*r*) between measured properties

Factor 1	Factor 2	<i>r</i>		Factor 1	Factor 2	<i>r</i>	
<i>D</i>	TH	0.319	*	BD	LC	0.280	*
	SWV	− 0.394	**		PC	0.019	
	BD	− 0.117			MS	− 0.053	
	CS	− 0.180			ETH	− 0.177	
	LC	− 0.138			ML _w	− 0.359	*
	PC	0.264			ML _b	0.059	
	MS	− 0.160			LC	− 0.042	
	ETH	0.100			PC	− 0.166	
	ML _w	0.072			MS	0.293	*
TH	ML _b	0.165		CS	ETH	− 0.263	
	SWV	0.313	*		ML _w	− 0.069	
	BD	− 0.078			ML _b	− 0.310	*
	CS	− 0.037			PC	− 0.260	
	LC	− 0.105			MS	0.043	
	PC	− 0.025			ETH	− 0.059	
	MS	− 0.151			ML _w	− 0.412	**
	ETH	0.026			ML _b	0.041	
	ML _w	0.212			MS	− 0.365	**
SWV	ML _b	0.071		PC	ETH	0.084	
	BD	0.081			ML _w	− 0.138	
	CS	0.251			ML _b	0.092	
	LC	0.013			ETH	− 0.191	
	PC	− 0.234			ML _w	0.221	
	MS	0.125			ML _b	− 0.400	**
	ETH	− 0.178			ML _w	0.088	
	ML _w	0.212			ML _b	0.071	
	ML _b	− 0.171			ML _b	− 0.169	
BD	CS	0.533	***	ML _w	ML _b		

Number of trees = 50. *D*, stem diameter; TH, tree height; SWV, stress-wave velocity; BD, basic density; CS, compressive strength; LC, lignin content; PC, polyphenol content (as equivalent with tannic acid); MS, monosaccharide content (as equivalent with glucose); ETH, ethanol-toluene extracts; ML_w, mass loss by *T. versicolor*; ML_b, mass loss by *F. palustris*; ***, significant correlation ($p < 0.001$); **, significant correlation ($p < 0.01$); *, significant correlation ($p < 0.05$)

($r = -0.359$) and lignin content ($r = -0.412$), but not monosaccharide content.

Among-site differences in measured properties

Table 4 shows the variance components of linear mixed-effects model for explaining among-site differences in measured properties. All fixed-effect parameters had *p*-values below 0.05. Among the measured properties, lignin content showed the lowest variance component ratio (1.0%), while the highest variance component ratio of site was observed in tree height (79.7%). Among measured properties, the variance component ratio of the sites in tree height, basic density, compressive strength, polyphenol content, ethanol-toluene extracts, and mass loss by *T. versicolor* exceeded 20% (Table 4). Results of Tukey–Kramer test revealed statistically significant differences among five sites in these six properties (Fig. 2).

The loading values of principal components 1 and 2 are presented in supplementary Table S1, and the principal component scores are illustrated in Fig. 3. The total percentage of variance explained by principal components 1 and 2 was 34.3% and 29.2%, respectively. High loading values in principle component 1 were observed for basic density (0.642) and compressive strength (0.641), whereas stress-wave velocity (0.559) and mass loss (0.589) showed high loading values in principle component 2 (Table S1). Polyphenol content had a negative loading value in principle component 2 (− 0.516) (Table S1), indicating an inverse relationship with stress-wave velocity and polyphenol content in this component.

Table 4 Fixed-effect parameter estimates, random-effect parameters, and variance component ratio obtained from linear-mixed effect models for explaining site differences in the measured properties

Property	Fixed-effect parameter				Random-effect parameter					Variance component		
	Estimate	SE	t-value	p-value	Site 1	Site 2	Site 3	Site 4	Site 5	δs	δe	VCs (%)
D (cm)	26.813	0.886	30.260	<0.001	0.328	-1.163	1.346	-1.356	0.844	2.391	15.637	13.3
TH (m)	16.588	1.398	11.860	<0.001	1.104	-4.113	1.065	-1.861	3.805	9.536	2.434	79.7
SWV (km/s)	4.053	0.067	60.580	<0.001	0.077	-0.099	-0.090	0.015	0.096	0.014	0.089	13.3
BD (g/cm ³)	0.389	0.012	32.960	<0.001	0.007	-0.019	-0.006	0.030	-0.012	0.001	0.002	20.5
CS (MPa)	17.484	0.715	24.440	<0.001	1.307	-0.852	-1.016	1.577	-1.016	2.114	4.535	31.8
LC (%)	30.297	0.747	40.540	<0.001	-0.121	0.179	-0.204	0.094	0.052	0.264	25.783	1.0
PC (mg/g)	95.120	13.160	7.227	0.002	-30.621	-8.588	31.960	7.891	-0.643	673.700	1962.300	25.6
MC (%)	38.942	1.326	29.360	<0.001	2.038	0.530	-2.934	0.830	-0.464	5.538	33.186	14.3
ETH (%)	8.036	0.666	12.070	<0.001	-0.329	0.613	1.494	-1.510	-0.268	1.675	5.500	23.3
ML _w (%)	34.433	3.807	9.044	<0.001	8.742	-3.204	0.325	-8.158	2.293	53.570	192.610	21.8
ML _b (%)	4.236	0.247	17.120	<0.001	-0.223	-0.052	-0.039	0.042	0.272	0.103	2.066	4.8

Number of trees = 50. D, stem diameter; TH, tree height; SWV, stress-wave velocity; BD, basic density; CS, compressive strength; LC, lignin content; PC, polyphenol content (as equivalent with tannic acid); MC, monosaccharide content (as equivalent with glucose); ETH, ethanol-toluene extracts; ML_w, mass loss by *T. versicolor*; ML_b, mass loss by *F. palustris*; SE, standard error; δs , variance component of site; δe , residual variance; VCs, variance component ratio of site

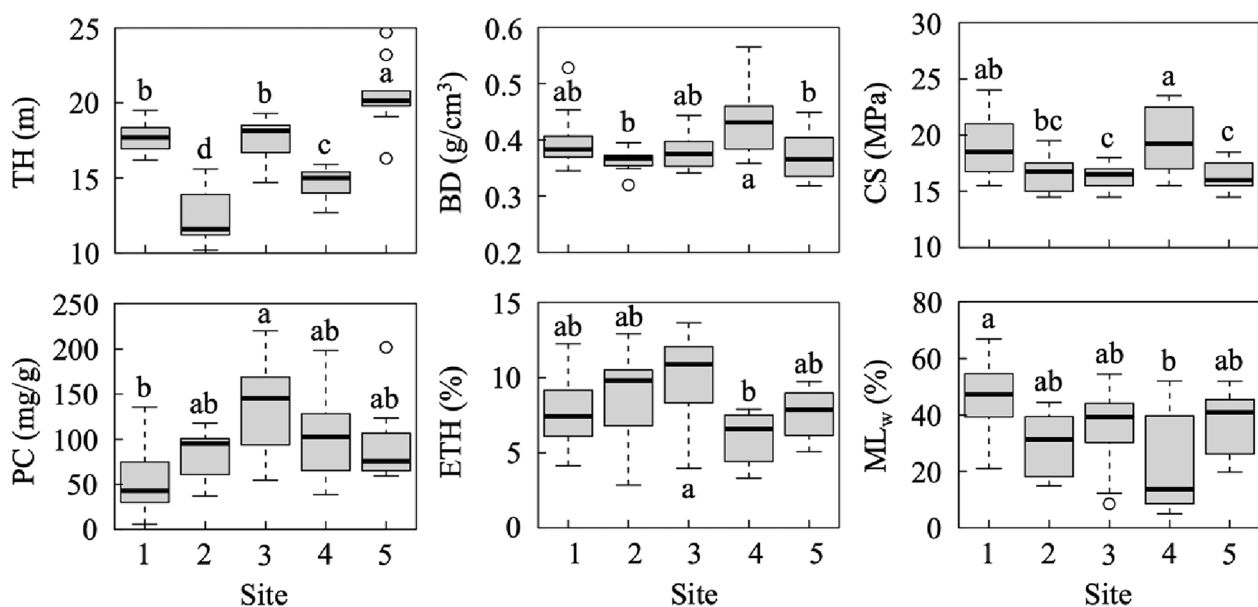


Fig. 2 Boxplots of measured properties with a variance component ratio exceeding 20% in the linear mixed effect model accounting for site differences. Note: TH, tree height; BD, basic density; CS, compressive strength; PC, polyphenol content; ETH, ethanol-toluene extracts; ML_w, mass loss by white-rot *T. versicolor*. The variance component ratio is listed in Table 4. The same alphabet letters indicate no significant differences ($p < 0.05$) among the sites by the Tukey–Kramer test

Discussion

Wood properties, chemical components, and decay resistance

The wood properties [9, 10] and chemical properties [14–20] of *Pinus sylvestris* and its decay resistance [8, 11, 13] have been widely studied by several researchers. Comparable results for basic density, compressive

strength, and chemical components of *P. sylvestris* are shown in Table 5. Considering sampling position (juvenile vs. mature wood) and moisture content at testing, the compressive strength values in this study might be similar to those reported by previous researchers. Amounts of lignin, glucose, and ethanol-toluene extracts were also similar to those reported to the

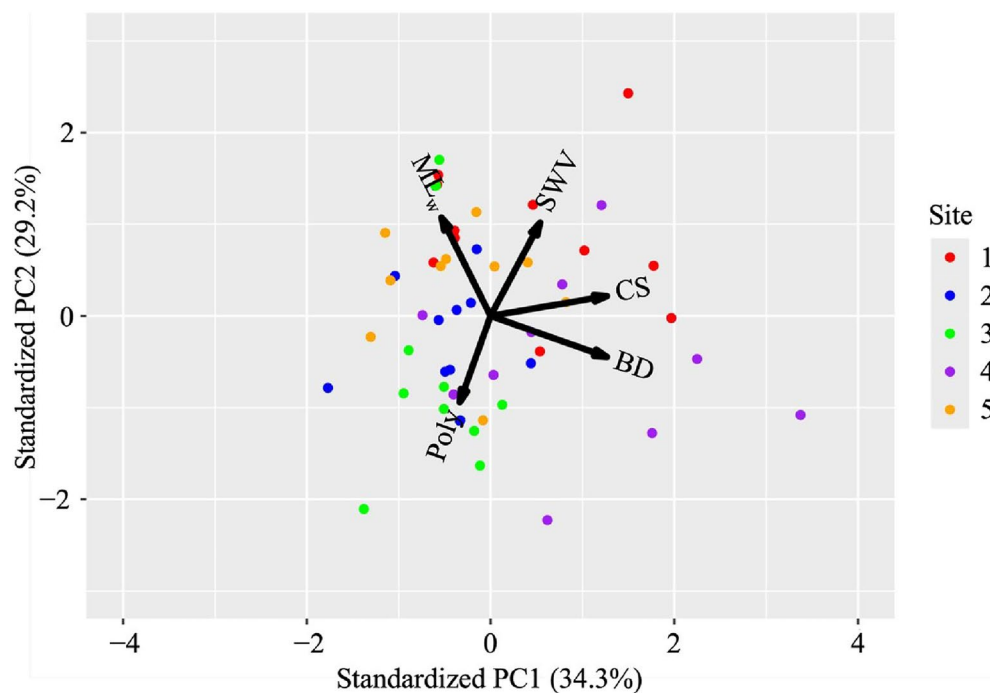


Fig. 3 Principal component analysis score of the measured traits. Note: SWV, stress-wave velocity of stems; BD, basic density; CS, compressive strength parallel to the grain under green conditions; Poly, polyphenol contents; $ML_{\text{versicolor}}$ mass loss by *T. versicolor*

Table 5 Basic density, compressive strength, and amounts of chemical components in the heartwood or juvenile wood of *Pinus sylvestris*

BD (g/cm ³)	CS (MPa)	LC (%)	PC (mg/g)	MC (%)	ETH (%)	Origin	References
0.39	17.5	30.3	95.3	38.9	8.0	Mongolia	This study
0.39	25.6 ^{*1}	–	–	–	–	Mongolia	[10]
0.40	36.8 ^{*1}	–	–	–	–	Mongolia	[9]
–	–	28.0	–	–	–	Finland	[17]
–	–	27.7	–	47.1 ^{*2}	11.6	Sweden	[18]
–	–	36.3	–	–	–	Sweden	[20]
–	–	–	4.6	–	–	Finland	[13]
–	–	–	1.79	–	–	Finland	[14]
–	–	–	13.6	–	–	Finland	[15]
–	–	–	10.5	–	–	Finland	[12]
–	–	–	–	35.3 ^{*2}	–	Sweden	[19]
–	–	–	–	–	5.8	Mongolia	[8]

BD, basic density; CS, compressive strength; LC, lignin content; PC, polyphenol content (as equivalent with tannic acid); MC, monosaccharide content (as equivalent with glucose); ETH, ethanol-toluene extracts; ^{*1}, values at air-dry condition; ^{*2}, glucose content

previous reports [8, 17–20]. In contrast, a particularly notable result was the much higher polyphenol content (tannic acid equivalent) observed in samples, compared to values reported for *P. sylvestris* from Finland [13–16]. This elevated polyphenol content in heartwood might be a distinguishing feature of *P. sylvestris* growing in Mongolia. In addition, the large standard

deviation in polyphenol content might reflect natural variation among individual trees. Although the results of the decay test cannot be directly compared with other studies due to differences in testing methods, mass loss values in the present study showed higher values in *T. versicolor* and lower values in *F. palustris*, which was also reported by Sarkhad et al. [8].

Relationships among growth characteristics and wood properties

In coniferous species, a weak negative correlation was found between stem diameter and stress-wave velocity of stems [24]. This fact suggests that trees with a faster radial growth rate have a relatively lower Young's modulus of wood. In the present study, a weak negative correlation ($r = -0.394$) was found between stem diameter and stress-wave velocity of stems (Table 3), suggesting that larger *P. sylvestris* trees grown in natural forests in Mongolia might have slightly lower Young's modulus of wood. On the other hand, tree height was positively related to stem diameter ($r = 0.319$) and stress-wave velocity of stems ($r = 0.313$) (Table 3). Thus, relationships between stem diameter, tree height, and stress-wave velocity were contradictory. The contradictory results might be related to the tree age of samples: sample trees in the present study were naturally regenerated trees with different ages (Table 1). Further research is needed to clarify the relationships between stem diameter, tree height, and stress-wave velocity in trees naturally growing in Mongolia.

Basic density was positively correlated with compressive strength ($r = 0.533$) (Table 3). The positive relationship between basic density and compressive strength was reported by previous researchers [9, 25]. Thus, the compressive strength might be estimated by basic density in juvenile wood of this species. In addition to compressive strength, a weak positive correlation ($r = 0.280$) was found between basic density and lignin content (Table 3), suggesting that an increase in lignin content of wood might be an increase in wood density in this species. A weak positive correlation ($r = 0.293$) was found between compressive strength and monosaccharide contents (Table 3). The contents of the monosaccharide in this study might be mainly derived from cell wall components (cellulose and hemicellulose). Thus, trees with higher compressive strength might have higher contents of cell wall components. However, further detailed research is needed to clarify the effect of amounts of cell wall components (cellulose, hemicellulose, and lignin) on the physical and mechanical properties of *P. sylvestris* wood.

Factors influencing decay resistance

The quantity and composition of wood extractives and other chemical components play the most significant role in determining the natural durability of wood [36, 37]. For example, polyphenols and terpenoids are known to contribute to decay resistance in *P. sylvestris* [13]. Harju and Venäläinen [13] reported the total polyphenol content was significantly negatively correlated with mass loss caused by *C. puteana* (a brown-rot fungus) in the heartwood of *P. sylvestris* from Finland. In the present study, polyphenol content in the heartwood did not show

significant correlations with mass loss by white- and brown-rot fungi (Table 3). However, it was significantly negatively correlated with monosaccharides (Table 3). This result suggests that a higher allocation of resources to polyphenol production may reduce carbohydrate availability for cellulose and hemicellulose synthesis, leading to an alteration in metabolic balance [38].

In general, brown-rot fungi degrade only structural carbohydrates (cellulose and hemicellulose), leaving lignin essentially undigested, whereas white-rot fungi utilize all wood constituents, including carbohydrates and lignin [39]. In the present study, mass loss caused by *T. versicolor* was significantly negatively correlated with lignin content but not monosaccharide content (Table 3). In contrast, mass loss caused by *F. palustris* showed a significant negative correlation with monosaccharide content but not with lignin content (Table 3). These findings suggest that lignin in *P. sylvestris* heartwood plays a crucial role in resistance to white-rot decay, while monosaccharides are more influential in brown-rot resistance. However, the average value of mass loss by *F. palustris* was quite lower than that by *T. versicolor* (Table 2). The reasons are still unknown, but a significant negative correlation between mass loss by *F. palustris* and monosaccharide contents might be affected by the lower mass loss value. Additional experiments are needed to evaluate mass loss by *F. palustris* of the heartwood of *P. sylvestris* naturally grown in Mongolia.

Although ethanol-toluene extractive content was measured in this study, no chemical composition analysis of these extracts was conducted. Among the chemical components in the ethanol-toluene extractives, terpenoids which enhance the durability of conifer heartwood are considered as major constituents of ethanol-toluene extracts [18]. Heijari et al. [18] reported that resin acids such as abietic, neoabietic, and pimaric acids were abundant in *P. sylvestris* heartwood, and their concentrations were negatively correlated with mass loss caused by the *C. puteana*, indicating a protective role in decay resistance. Thus, further investigation for identify the chemical components with antifungal activity are needed for *P. sylvestris* grown in Mongolia.

Among-site differences

It is well known that wood properties and decay resistance in a tree species vary among provenances of natural forests and clones or families selected in tree breeding programs [11, 23, 40]. Tumenjargal et al. [23] examined the wood properties of *L. sibirica* trees from natural forests in the five Mongolian provenances. They found significant differences in the physical and mechanical properties of *L. sibirica* wood among the five provenances, indicating existence of a geographic variation

of wood properties in *L. sibirica* grown in natural populations in Mongolia. In addition, medium narrow-sense heritability was found in mass loss by *F. palustris* and polyphenol content (as taxifolin equivalent) in heartwood from 15 full-sib families of *Larix kaempferi* created under the tree breeding program in Japan [40]. Harju and Venäläinen [11] determined wood properties and decay resistance against a brown-rot fungus, *C. puteana*, in the heartwood of 33-year-old *P. sylvestris* half-sib families from Korpilahti in central Finland. They reported that genetic variation in decay resistance of wood was higher than that in wood properties [11]. As shown in Table 4, relatively larger variance components of the random effect of the site differences were found in basic density (20.5%), compressive strength (31.8%), polyphenol content (25.6%), ethanol-toluene extract contents (23.3%), and mass loss by *T. versicolor* (21.8%). In the present study, core samples were collected from natural stands. The five sites were located near Ulaanbaatar, Mongolia, with distances of at least 3 km between sites, and there were no marked differences in geography and climatic conditions. Therefore, the higher variance components ratio of the site in the developed mixed-effect model (Eq. 2) might mainly reflect the larger among-site variations due to genetic differences of trees, suggesting that these five properties might be genetically controlled and differ among sites. For example, relatively larger values of the random-effect parameter were found in basic density and compressive strength in Sites 1 and 4, but the lowest value was observed in Site 5. These results indicated that trees with higher basic density and compressive strength might exist at the site level. In addition, relatively high polyphenol contents and mass loss caused by *T. versicolor* was found in Sites 3 and 4, respectively, whereas Site 1 showed the lowest values. This suggests a negative correlation at the site level between polyphenol content and mass loss, although the correlation was not statistically significant (Table 3). This result also indicates that selecting *P. sylvestris* trees that naturally grow in these five sites with higher polyphenol content could enhance the natural decay resistance of this species [13]. These tendencies of differences among sites in random-effect parameters were supported by the statistical results of the Tukey–Kramer test (Fig. 2). Based on the results, it is considered that selecting mother trees at the site level can be effective in improving wood properties and decay resistance in the future tree breeding program of this species in Mongolia.

Based on the loading values in the principal component analysis (Table S1), each quadrant in Fig. 3 was characterized as follows: the first quadrant=higher mechanical properties and lower decay resistance, the second quadrant=higher Young's modulus but lower decay

resistance, the third quadrant=higher decay resistance with lower mechanical properties, and the fourth quadrant=higher mechanical properties (except Young's modulus) and decay resistance. Thus, if the trees in the fourth quadrant were selected as mother trees in tree breeding programs, offspring with superior wood quality and natural decay resistance might be obtained. According to the principal components analysis biplot (Fig. 3), the data was separated by quadrant at the site level: trees in Sites 1 and 5 existed in the first and second quadrants, while trees in Site 3 were found in the third quadrant. Trees in Site 2 existed around the origin. Trees of Site 4 were mainly found in the fourth quadrant. Thus, trees with higher wood strength properties with lower decay resistance might be obtained in Site 1. In addition, trees in Site 4 might have higher mechanical properties (except Young's modulus) and decay resistance. So, if the tree breeding programs of *P. sylvestris* in Mongolia aim to produce high-strength property lumber with higher natural durability against fungus, mother trees should be selected, considering the among-site variations in these properties.

Conclusion

In the present study, the growth characteristics, stress-wave velocity of stems, wood properties, chemical components, and decay resistance of the heartwood of *P. sylvestris* naturally growing in Mongolia were investigated. Among-site differences in these properties were also evaluated using an intercept-only linear mixed-effects model. Characterization of wood properties in each site was conducted using principal component analysis. The results showed that lignin content significantly negatively correlated with mass loss caused by *T. versicolor* but not with *F. palustris*. In contrast, monosaccharide content exhibited a significant negative correlation with mass loss by *F. palustris* but not with *T. versicolor*. Although polyphenol content did not significantly correlate with decay resistance, it was negatively correlated with monosaccharide content. Furthermore, among-site variations were observed in polyphenol content, and physical and mechanical properties. From the results of principal components analysis, trees from Site 4 showed higher mechanical properties (except Young's modulus) and more excellent decay resistance compared to other Sites. Based on the results, it was concluded that (1) when we use the *P. sylvestris* wood naturally growing in Mongolia, site selection should be conducted concerning the quality of final products, and (2) when we produce the plantation of this species, wood quality including natural durability against fungus can be enhanced by selecting the mother trees in the appropriate tree breeding program. Although the total polyphenol content was

determined in this study, the extractive compounds were not identified. Further research is needed to identify and quantify these specific extractives for understanding their role in decay resistance and supporting the improvement of genetic selection strategies for durable, high-quality wood.

Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s10086-025-02240-x>.

Additional file 1

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Author contributions

TG and FI designed the research layout. TG, HA, KM, TE, BT, GC, and FI conducted field sampling. TG, IN, M, JO, SY, and FI conducted laboratory experiments. TG, IN, and FI conducted statistical analysis. All authors have read and agreed to the published version of the manuscript.

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Availability of data and materials

The datasets in the present study are available for the corresponding author upon reasonable request.

Declarations

Competing interests

The authors declare that they have no competing interests.

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