Mechanical and Physicochemical Characterization of Wood Materials Produced from *Larix decidua* and *Pinus sylvestris* L. Tree Species

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This study focused on mechanical and physicochemical characterization of wood materials produced from *Larix decidua* and *P. sylvestris* L. species. Fourier transform infrared spectroscopy with attenuated total reflectance (FTIR-ATR) and scanning electron microscopy (SEM) analyses were employed to examine the structure, chemical bonding, and surface morphology. Mechanical properties, such as tensile strength and elasticity, were evaluated to assess durability and potential applications. The results revealed considerable differences in the chemical composition and mechanical properties of the two species, underscoring their distinct suitability for specific industrial applications. *L. decidua* exhibited superior mechanical performance compared to *P. sylvestris* L., with higher bending strength (90.5 N/mm²), compressive strength parallel to the grain (42.1 N/mm²), and density (0.62 g/cm³). Moreover, *L. decidua* showed greater resistance to decay under outdoor weather conditions compared to *P. sylvestris* L. These findings provide valuable insights into the potential uses of these wood species in construction, furniture production, and other industries requiring durable and versatile natural materials.

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INTRODUCTION

Wood is one of the most diverse and widely used natural building materials across various industries, including construction, furniture, and marine applications, and it has been utilized since ancient times (Fridley 2002). *Larix decidua* and *Pinus sylvestris* L. are widely used due to their distinct mechanical properties and resistance to environmental factors. Both species belong to the Pinaceae family; however, because of their differing characteristics, they are suitable for different applications (Moris *et al*. 2017; Tomczak *et al*. 2020). *Larix decidua* is particularly known for its high density, strength, and good resistance to harsh environmental conditions. Its dense structure and low knot frequency make it a favorable choice for outdoor applications such as cladding, decking, and shipbuilding. *L. decidua* is ideal for external structures due to its resistance to moisture, fungal decay, and water. Although *P. sylvestris* L. is also widely used, it has a softer and lighter structure (Şendağ and As 2024). Because of this feature, it is easier to process (Yaman 2007). However, it is more prone to deformation and damage when exposed to moisture and other environmental stress factors. Its primary applications include interior decoration, furniture, and lightweight structural elements (Šprdlík *et al.* 2017; Brichta *et* *al.* 2023). Wood is a heterogeneous and anisotropic material. Even the mechanical properties of wood from the same species can differ depending on environmental conditions. These properties may also vary with the fiber orientation, the cutting direction, and the chemical composition of the wood (Fridley 2002). Due to the growing demand for durable and sustainable building materials, understanding the physicochemical properties of woods is essential for species discrimination (Perçin 2022).

The aim of this study was to comparatively investigate the mechanical and physicochemical properties of Scots pine (*P. sylvestris* L.) and larch (*L. decidua*) wood. For this purpose, the following properties were determined for both species: bending strength (N/mm^2), compressive strength parallel to the fibers (N/mm^2), water absorption rate (%), density (g/cm^3), modulus of elasticity (N/mm^2), shock resistance (J/cm^2), and Brinell hardness (N/mm^2). In addition, structural characterization was performed using Fourier transform infrared spectroscopy with attenuated total reflectance (FTIR-ATR), while morphological features were examined by scanning electron microscopy (SEM). The results were compared to identify the similarities and differences between the two species.

EXPERIMENTAL

In this study, wood materials obtained from *L. decidua* and *P. sylvestris* L. trees imported into Turkey from Russia's Krasnoyarsk region were used. For technical evaluation, samples were randomly selected from products whose species were determined to differ based on macroscopic examination. Mechanical, physical, and ATR-FTIR analyses were performed in the laboratories of the Department of Forestry and Forest Products, Çaycuma Vocational School, Zonguldak Bülent Ecevit University.

Fig. 1. *L. decidua* and *P. sylvestris* specimens are seen mixed in the piles

For the compression strength parallel to the fibers, test specimens prepared in 20 × 20 × 30 mm^3 dimensions according to TS ISO 13061-5 (2021) were used. The cross-sectional dimensions and fiber lengths of the samples at approximately 12% moisture content were measured with a precision of ± 0.01 mm and weights were measured with a precision of ± 0.001 g. A total of 50 samples were prepared. The experiment was conducted with a universal testing machine. The test speed was set so that the samples were broken in 1.5 to 2 min in the machine and the force at the moment of breakage (F_{max}) was measured. Compression strength parallel to the fibers was calculated by Eq. 1. In the equation, F_{max} is the force at break (Newton), whereas *a* and *b* are the sample cross-sectional dimensions (mm):

$$B = \frac{Fmax}{a\ x\ b}\ (\text{N/mm}^2) \tag{1}$$

P. sylvestris and *L. decidua* L. wood samples were prepared in 20 × 20 × 300 mm^3 dimensions in 20 ± 2 ºC temperature and 65 ± 5% relative humidity in an air conditioning cabinet in accordance with TS ISO 13061-3 (2021) standard. The specimens were broken with a universal testing machine, and the maximum force was determined. Bending resistance was calculated using Eq. 2. In the equation, P_{max} is the force at break (N), *Ls* is the distance between the fulcrum points (mm), *b* is the sample width (mm), *h* is the sample thickness (mm):

$$Bending\ resistance = \frac{3Pmax\ x\ Ls}{2\ x\ b\ x\ h^2} \tag{2}$$

Brinell Hardness values test specimens were prepared in 50 × 50 × 50 mm^3 dimensions with a total of 30 specimens according to TS 2479 (1976) and acclimatized. A pressure of 1000 Newton was applied to the samples with the test device and the radius of the sphere formed was measured. Brinell hardness value was calculated with Eq. 3. The BHN is the Brinell hardness value, *F* is the applied force (N), *D* is the Brinell sphere diameter (mm), and *d* is the pit diameter (mm) on the sample surface:

$$BHN = \frac{2P}{\pi D(D - \sqrt{D^2 - d^2}} \tag{3}$$

The samples were prepared from 1-m trunk sections taken from 2 to 4 m parts of the trees, with a total of 113 pieces measuring 20 × 20 × 300 mm^3 in size. The prepared samples were monitored in an acclimatization room at 20 ± 2 °C and 65 + 5% relative humidity until they reached equilibrium moisture content. The width and thickness of the specimens, acclimatized to approximately 12% moisture content, were measured at the midpoints with a precision of ± 0.01 mm. The test speed was adjusted so that the specimens fractured within 1.5 ± 2 min after loading. The maximum force (F_{max}) at the moment of fracture was measured with a precision of ± 1 kp, and the bending resistance was calculated using the following equation. Bending resistance test specimens were also used to determine the modulus of elasticity in bending and the tests were carried out in accordance with TS 2478 (1976).

$$E = \frac{\Delta F\ x\ L^3}{4\ x\ b\ x\ h^3\ x\ \Delta f} \tag{4}$$

Additional timber samples were prepared with dimensions of 20 × 20 × 30 mm^3, and their weights were measured in the wet condition. They were then dried in a forced-air oven at 103 ± 2 ºC until they reached constant weight. The full dry weight was recorded after cooling in a desiccator, and the moisture content was determined as a percentage. The moisture content was found to be 13% for European hybrid and 14% for *P. sylvestris*. The results of these measurements were consistent with those obtained from on-site inspection devices. The 20 × 20 × 30 mm^3 samples were subsequently re-dried in a drying oven at a constant temperature of 103 ± 2 °C until completely dry. These samples were then cooled in a desiccator and measured to a precision of ± 0.001 g, and dimensions to ± 0.01 mm. Their densities were calculated by finding their weights at fully dry moisture content (0%).

The FTIR-ATR and SEM analyses of the samples were performed in the laboratories of Zonguldak Bülent Ecevit University. A PerkinElmer Frontier Fourier-transform infrared spectrometer with an attenuated total reflectance (FTIR-ATR) accessory was used. Spectra were collected in the mid-IR region from 500 to 4000 cm^{-1} at a scan resolution of 4 cm^{-1}. Each sample was analyzed in triplicate, and results are expressed as percent transmittance (%T). Measurements were performed at room temperature to minimize noise. After each run, the ATR crystal was cleaned with ethyl alcohol and distilled water. For SEM analysis, powdered samples were mounted on carbon adhesive tape and sputter-coated with 12.5 to 15 nm gold. Images were acquired between 10 and 15 kV using a QUANTA 450 Field Emission Gun (FEG) Scanning Electron Microscope (FEI Company, USA) at Zonguldak Bülent Ecevit University.

RESULTS AND DISCUSSION

The mechanical and physical test results of the products as a result of the analyses are given in Table 1.

Table 1. Mechanical and Physical Analysis Results of the Samples

Tree Species	Modulus of Rupture (N/mm^2)	Compression Strength Parallel to Grain (N/mm^2)	Water Absorption Rate (%)	Density g/cm^3 (Air-Dry)	Modulus of Elasticity (N/mm^2)	Impact Bending (J/cm^2)	Primary Hardness (N/mm^2)
L. decidua	90.46 (6.11)*	42.10 (3.74)	0.43 (0.2)	0.62 (0.2)	11 900 (1500)	6.0 (1.1)	20.54 (2.1)
P. sylvestris	78.28 (7.25)	38.4 (4.32)	0.68 (0.4)	0.49 (0.3)	11 000 (1200)	5.8 (0.5)	17.96 (0.8)

*The numbers in the parentheses represent standard deviations.

The mechanical and physical test results were statistically evaluated using a paired t-test with 95% confidence interval. The differences in compression strength, modulus of elasticity, and impact bending were not statistically significant, while the remaining results showed statistically significant differences.

Some trees genetically develop a highly branched and consequently gnarled trunk form. In general, the proportion of knots decreased in trees with a small crown structure, whereas it increases in trees with larger crowns. Species with high density are preferred for applications where high resistance is required, such as load-bearing elements in buildings, bridges, scaffolding, and foundation poles. Conversely, species with relatively lower density are preferred in some areas (*e.g.*, light carpentry works, furniture parts) where qualities, such as softness, ease of processing ability, and reduced labor requirements, are prioritized over high resistance.

The FTIR spectra of *P. sylvestris* L. and *L. decidua* samples, along with their second derivatives, are presented in Figs. 2 and 3, respectively. A comparison of the raw FTIR spectra is also provided in Fig. 4. In the FTIR spectra of both *P. sylvestris* L. and *L. decidua*, a broad absorption band was observed in the range of 3000 to 3500 cm^{-1}, corresponding to overlapping –OH stretching vibrations and –NH symmetric stretching (Yong *et al*. 2019). Notably, the absorption intensity of this band was higher in *P. sylvestris* compared to *L. decidua*, indicating a greater concentration of O–H or N–H functional groups in *P. sylvestris*. Characteristic bands at 2925 cm^{-1} and 2877 cm^{-1}, typically associated with C–H stretching vibrations (Poletto *et al.* 2014), were observed in this study near 2750 cm^{-1}.
Two prominent bands were identified at 1403 cm^{-1} and 1153/1063 cm^{-1}. The former corresponds to $–CH_2$ bending and $–C–CH_3$ deformation modes, while the latter are attributed to asymmetric –O–C stretching and C–O stretching vibrations, respectively (Poletto *et al*. 2014; Halász and Csóka 2018). These peak positions align with previous studies; however, the intensity values for *P. sylvestris* were considerably higher than those reported for analogous lignocellulosic materials in the literature. The absorbance peak at 1022 cm^{-1} primarily arises from C–O stretching vibrations found in functional groups such as alcohols, ethers, carboxylic acids, and esters. This band also signifies the C–O–C stretching characteristic of polysaccharides, especially cellulose and hemicellulose. Additionally, it reflects the anhydroglucosidic C–O–C vibrational modes associated with the β-1,4-glycosidic bonds that form the core structure of cellulose. In Fig. 3, the peak in the spectrum of *L. decidua* 1022 cm^{-1} shifted to 1026 cm^{-1} in Fig. 2 for *P. sylvestris* L. and its intensity increased.

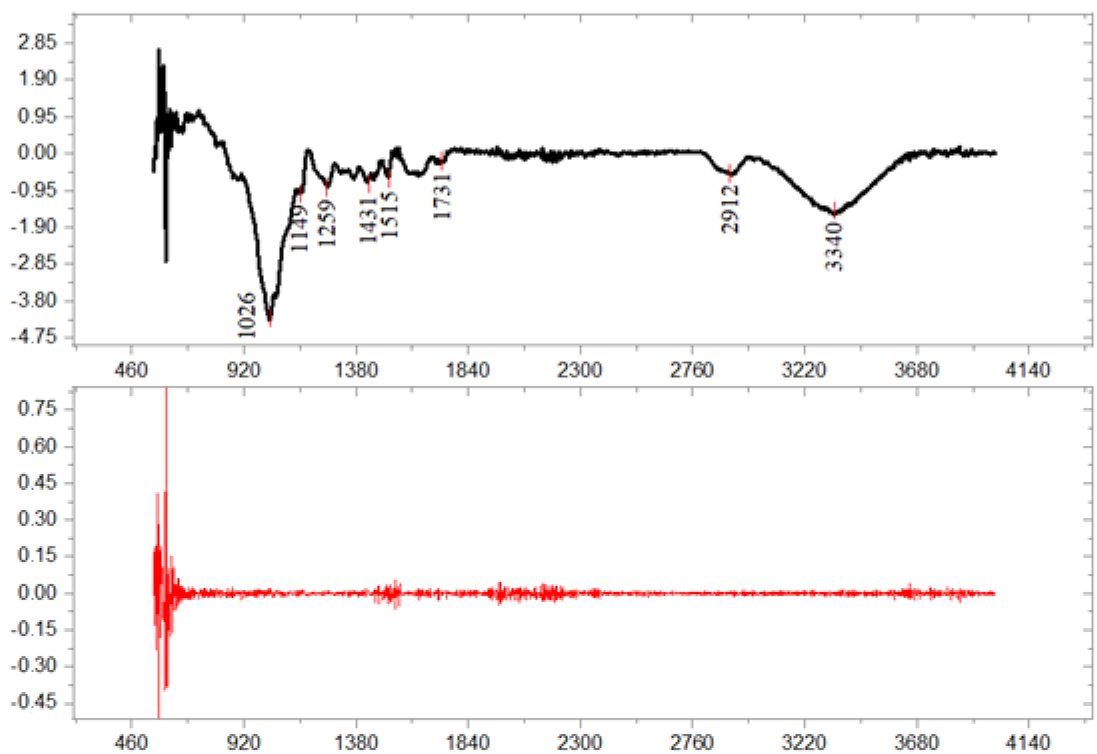

Fig. 2. FTIR spectrum of *P. sylvestris* L. sample (with 2nd derivative)

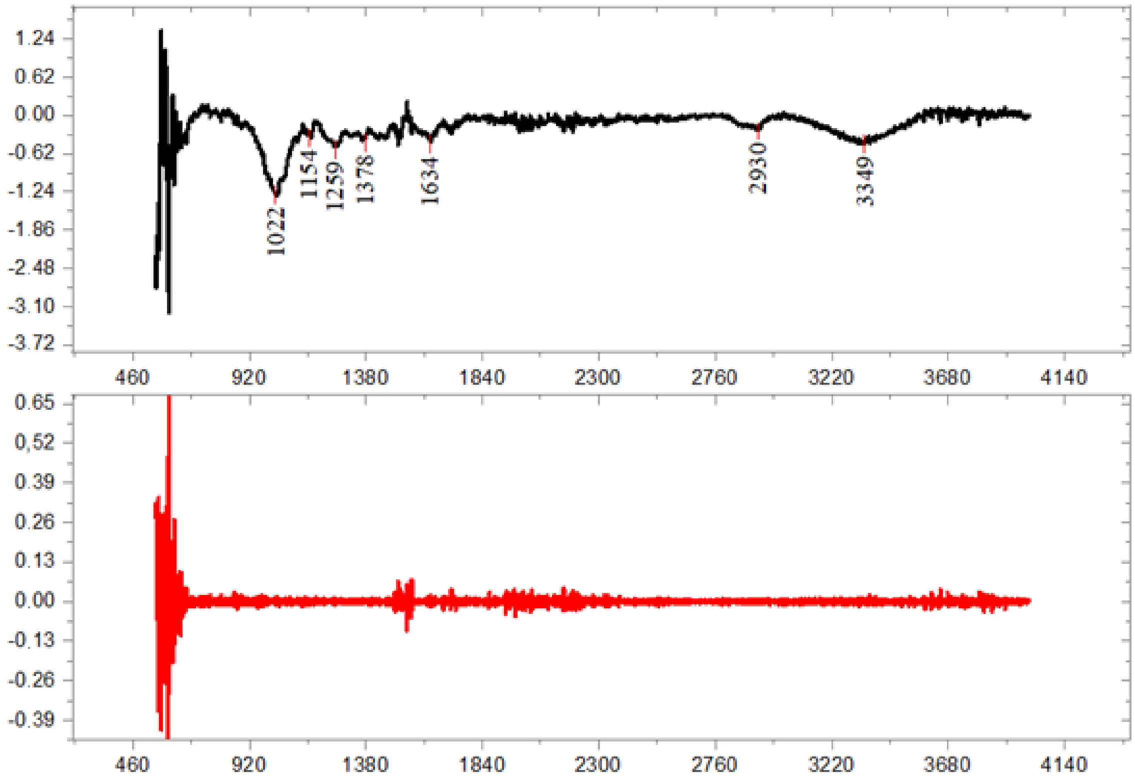

Fig. 3. FTIR spectrum of *L. decidua* (with 2nd derivative)

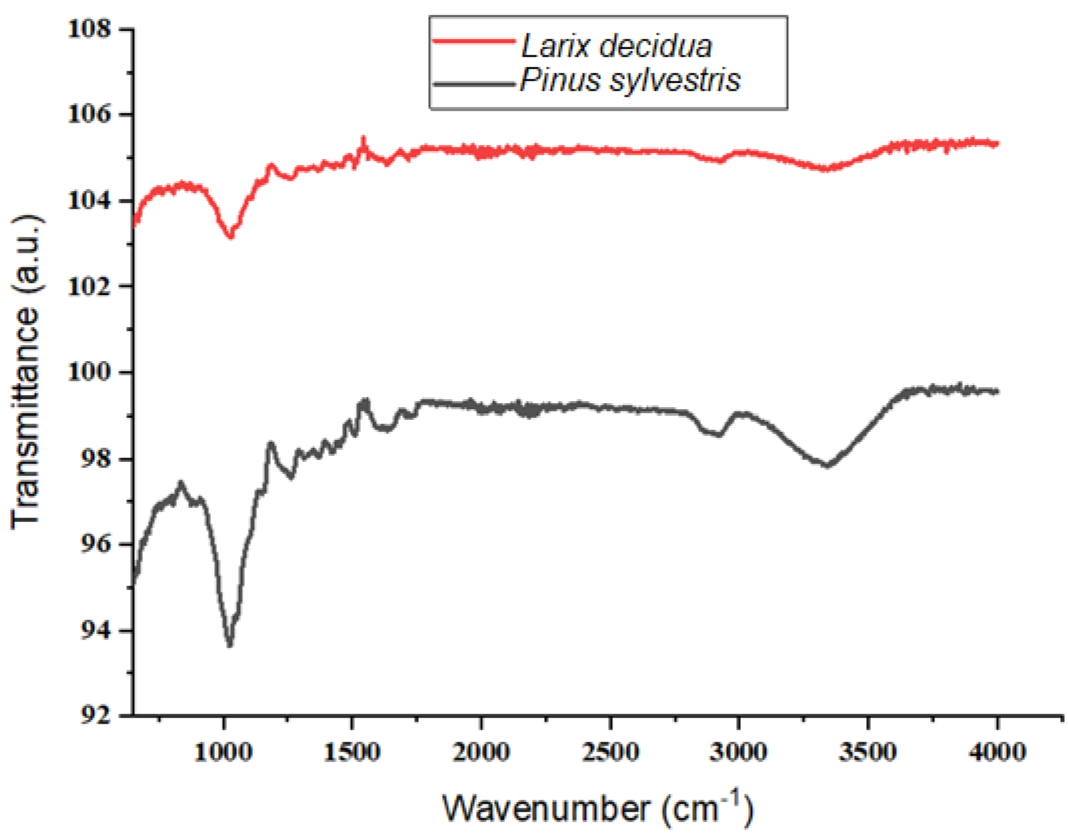

Fig. 4. Comparison of the raw spectra of *L. decidua* and *P. sylvestris* L.

The provided scanning electron microscopy (SEM) images of *L. decidua* (European larch) and *P. sylvestris* (Scots pine) were obtained under standardized analytical conditions as detailed below.

Table 2. Technical Parameters for SEM Imaging of *L. decidua* and *P. sylvestris*

Parameter	Value
Magnification (mag)	50×
Detector (det)	Backscattered Electron Detector (BSED)
Mode	Z-Contrast (Z Cont)
Vacuum Mode	High vacuum
Working Distance (WD)	12.2 mm
Accelerating Voltage (HV)	20.00 kV
Microscope Model	JSM-7001F

Larix decidua

In the SEM images, anatomical structures typical of softwood were distinctly observed. Elongated and uniform tracheids with bordered pits on their cell walls were visible, which facilitate water transport and mechanical stability. Resin canals are generally absent under standard conditions; however, traumatic resin canals are rarely observed in cross-sections under stress. The uniseriate ray parenchyma is arranged as thin horizontal lines between tracheids. Cell walls, rich in lignin, are highlighted as high-contrast regions in BSED mode due to their atomic composition(Fig. 5). The cell wall thickness of dry wood was measured as 4.61 µm± 0.6 and found in accordance with Farsi and Kiaei (2014).

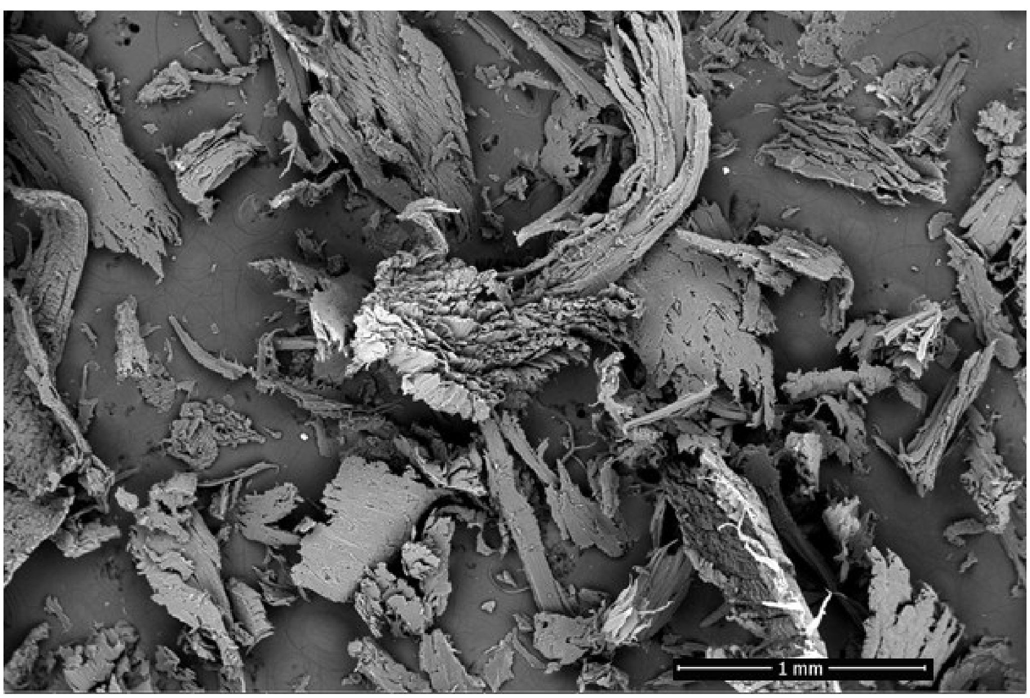

Fig. 5. SEM Image of *L. decidua*

Pinus sylvestris

The SEM images reveal thick-walled tracheids with pronounced lignification and distinct annual growth rings. Earlywood regions exhibited thin-walled cells with wide lumina, whereas latewood regions displayed densely lignified cells with narrow lumina. Axial and radial resin canals, surrounded by epithelial cells, were clearly identifiable. Heterocellular rays, composed of both parenchyma and tracheid cells, demonstrated a complex tissue organization. Z-contrast imaging accentuates density variations in cell wall lamination, emphasizing differences between lignin-rich and cellulose-rich regions (Fig. 6). The average cell wall thickness of dry wood was measured as 6.54 µm± 0.38. It was in accordance with the study of Jelonek *et al.* (2019).

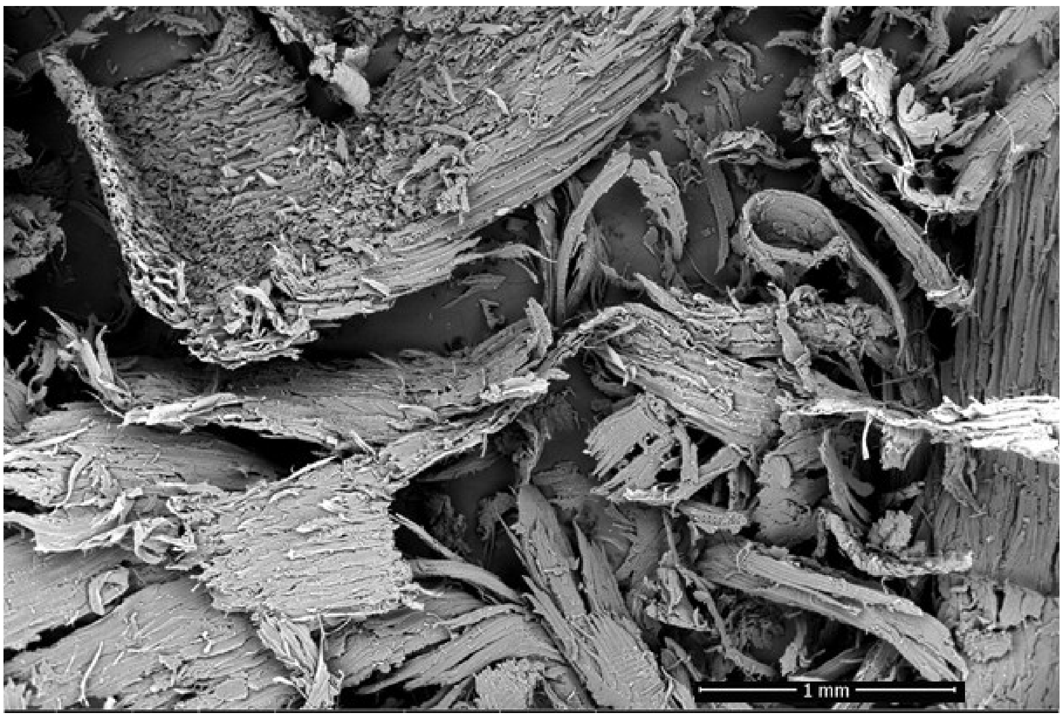

Fig. 6. SEM Image of *Pinus sylvestris*

Larix decidua and *P. sylvestris* L. wood species are notable for their distinct properties and areas of use. *L. decidua* is characterized by its resistance to water, outdoor weather conditions, and hardness, while *P. sylvestris* is softer and preferred for its easier workability. Both species are valued in the decoration and construction sectors for their natural and organic structures. *L. decidua* typically grows as a tall tree with a straight, columnar trunk, which is only rarely forked.

Larix decidua, when properly dried under suitable conditions, is much more resistant to humidity, UV rays, and various external influences than *P. sylvestris*. Due to its high density and hardness, *L. decidua* is particularly used as a load-bearing element and beam material in construction, demonstrating long-lasting durability and strong resistance to fungi and insects outdoors. *P. sylvestris*, in contrast, is softer and less resistant to moisture, so it is generally shorter-lived in outdoor environments. *L. decidua*, mechanically, has a flatter and smoother structure during processing. It has better surface quality for painting and polishing. *P. sylvestris* is a lighter and softer wood than *L. decidua*, so during cutting and processing, it produces a rougher surface. This is disadvantageous in terms of finishing quality. The hardness and density of *L. decidua* makes it particularly suitable for demanding construction and high-quality furniture applications.

CONCLUSIONS

1. Clear differences were observed between *L. decidua* and *P. sylvestris* in their mechanical, physicochemical, and structural characteristics.
2. *L. decidua* exhibited higher bending strength (90.5 N/mm^2), compressive strength (42.1 N/mm^2), and density (0.62 g/cm^3) compared to *P. sylvestris* (0.49 g/cm^3).
3. The SEM observations revealed dense, lignin-rich cell walls in *L. decidua*, contributing to its greater durability and moisture resistance.
4. *P. sylvestris*, with its lower density, showed easier processability, making it suitable for lightweight furniture and indoor decorative applications.
5. The FTIR-ATR analysis confirmed distinct structural and chemical differences between the two species, explaining their variation in mechanical and environmental performance.
6. Overall, *L. decidua* is more suitable for uses requiring high mechanical strength and weather resistance, whereas *P. sylvestris* is better suited for lightweight indoor applications.

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