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Enhanced strength and chemical stability of *Salix tetrasperma* wood through thermal modification

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Thermal modification of *Salix tetrasperma* wood was conducted at temperatures ranging from 60 to 200 °C for durations of 2, 4, and 6 h to evaluate changes in its chemical and mechanical properties. The treatment induced notable alterations in extractives and structural components. Peak values for cold-water (7.44%) and hot-water (11.56%) soluble extractives were recorded at 140 °C and 120 °C, respectively, while the lowest values (5.17% and 8.76%) occurred at 200 °C. Alcohol-benzene extractives and lignin content increased with temperature, reaching maxima of 13.61% and 24.77% at 200 °C, compared to 9.03% and 16.49% in the untreated control. Conversely, holocellulose content showed a declining trend with heat, dropping from 79.18% in the control to 70.89% at 200 °C. Mechanically, tensile strength peaked at 0.059 kN/mm^2 at 140 °C and declined to 0.040 kN/mm^2 at 200 °C. Bending strength was highest in the control (0.010 kN/mm^2) and lowest (0.007 kN/mm^2) at 180 °C and 200 °C. Compression strength parallel to grain reached its maximum at 160 °C (0.037 kN/mm^2), whereas perpendicular compression was highest in the control (0.031 kN/mm^2). Minimum compression values were noted at 200 °C. These results underscore the potential of thermal modification to strategically tailor the physico-chemical properties of *Salix tetrasperma* wood, improving its dimensional stability, durability, and overall performance for industrial and structural applications.

Keywords Thermal treatment, *Salix tetrasperma*, Hemicellulose, Tensile strength, Lignin, Compression strength

Wood is a naturally engineered, sustainable biomaterial composed of diverse cell types that collectively fulfill vital physiological functions in living plants. Its intricate porous architecture formed by biopolymers such as cellulose, hemicellulose, and lignin confers an exceptional strength-to-weight ratio along with distinctive properties like grain texture, coloration, density, and visual appeal[1]. These inherent traits have enabled wood's enduring use across millennia in structural engineering, fine craftsmanship, musical acoustics, and various utilitarian applications[2]. As a renewable, energy-efficient, and widely available resource, wood continues to rank among the most preferred materials for sustainable construction[3].Wood is anatomically classified as secondary xylem but consists of chemical components like cellulose, hemicelluloses, lignin, and extractives such as resins, lipids, waxes, terpenes, and more. These chemical constituents collectively determine wood's properties, which play a crucial role in its strength attributes. Both the physical and chemical attributes of wood influence its suitability and ability to withstand various forces like tension, compression, bending, shear, and cleavage[4]. Despite its versatile properties, wood does have limitations, including sensitivity to moisture, dimensional instability, limited durability, and vulnerability to insect and fungal attacks. To address these limitations and expand its applications, wood modification methods are employed. Wood modification can be categorized as either active (altering wood's chemical nature) or passive (making changes without affecting chemical parameters). Chemical treatments are environmentally hazardous and costly, making thermal modification a more attractive option. Thermal wood modification is a process involving the treatment of wood at high temperatures in an oxygen-free environment. This process alters wood properties by modifying its constituents and changing the chemical composition of wood cells. Primarily, it decomposes cell wall constituents like hemicellulose, cellulose, and extractives. The result is improved quality, increased durability, enhanced dimensional stability, reduced hygroscopicity, and lower equilibrium moisture content of wood[5–8]. Proper heat treatment increases hydrophobic properties, reduces mass, and modifies other physical characteristics of wood, such as color, specific

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gravity, density, swelling, shrinkage, and weathering resistance[9,10]. These changes are particularly noticeable in wood's elasticity and dimensional stability, making it more suitable for construction purposes[11]. While thermal modification has been extensively studied for several temperate and softwood species, limited literature exists on its effects in *Salix tetrasperma* Roxb., a fast-growing willow species abundant in riparian and agroforestry systems of South Asia. *Salix tetrasperma* comes under the class of perishable durability. This species is traditionally used for low-value applications such as match splints, baskets, and fuelwood, primarily due to its moderate strength, high hygroscopicity, and susceptibility to biodegradation[12]. This study is the first systematic investigation of thermal treatment effects on *Salix tetrasperma* integrating mechanical, and chemical characterization, thus filling a significant gap in wood science literature for tropical and subtropical willow species. Thermal wood treatment is regarded as highly effective in producing sustainable building materials with low toxicity since all improvements in wood properties are achieved solely through heat treatment, without the need for chemical additives. Consequently, thermally modified wood has emerged as an environmentally friendly alternative to treated wood[13].

Experimental details

For the present studies, wood from 30 year old tree of *Salix tetrasperma* Roxb. was procured from the Botanical Garden of Dr. Y S Parmar University of Horticulture and Forestry Nauni, Solan (HP). Destructive method was followed to prepare wood samples for chemical and mechanical analysis[14]. Tree was felled on 22th of November, 2021 and was converted into 9 logs of 1 m length for the investigations and were brought to saw mill for sawing purpose (Plank formation). Planks were converted to the required dimensions in the Wood Workshop of the Department of Forest Products. The samples were prepared of the following dimensions as per the specifications[15].

i. Central cross-section 7 × 7 mm (for tensile strength parallel to the grain)
ii. 5 × 5 cm × 100 cm (for static bending)
iii. 5 × 5 cm × 15 cm (for compression perpendicular to the grain)
iv. 5 × 5 cm cross-section (for compression parallel to the grain)

Treatment of wood samples in heat stabilized oven

Table 1 represents the different temperature gradients and duration period treatments for thermal modification of wood. The wood samples were initially conditioned at 20 ± 2 °C and 65 ± 5% relative humidity (RH) until constant weight was achieved, and the initial moisture content was determined using the oven-dry method for representative specimens. Thermal modification was carried out in a PID-controlled, forced-air heat-stabilized oven equipped with a steam injection and exhaust system for RH regulation, thermocouple ports, and vacuum/pressure connections. Prior to heating, the chamber was evacuated using a vacuum pump to − 0.8 to − 0.95 bar for 15–30 min to facilitate the removal of entrapped air and reduce the boiling point of bound water. The oven temperature was increased gradually at a rate of 1–5 °C min^{-1} to the target levels (60–200 °C). Samples were held at the target temperature for 2, 4 and 6 h under continuous monitoring of oven air temperature. In selected treatments, vacuum pressure cycles were applied during the holding phase to improve heat uniformity and relieve internal stresses. After the thermal exposure period, the oven was cooled gradually while maintaining low

Sr. no	Temperature (°C)	Durations (h)
1	Control	
2	60	2 h 4 h 6 h
3	80	2 h 4 h 6 h
4	100	2 h 4 h 6 h
5	120	2 h 4 h 6 h
6	140	2 h 4 h 6 h
7	160	2 h 4 h 6 h
8	180	2 h 4 h 6 h
9	200	2 h 4 h 6 h

Table 1. Different temperature gradients and duration period treatments for thermal modification of wood.

RH, with an optional brief vacuum applied during cooling to prevent condensation within the wood structure. The treated samples were then reconditioned at 20 ± 2 °C and 65 ± 5% RH to equilibrium before subsequent testing. For determination of each observation 75 samples, were used (9 treatments including control, with 3 replications in each, having three samples in each replication, 72 + 3 = 75).

Determination of chemical characteristics of wood

The proximate chemical analysis was carried out by employing TAPPI (Technical Association of Pulp and Paper Industry, 1959) standard methods.

Preparation of samples

The thermally treated wood samples were finely powdered with the help of Wood Chipper cum Grinder and further dried in the oven for 24 h at 150 ± 1 °C. The experiment was laid out CRD factorial. In total, 3 replicates for given species were taken and 3 samples were used in each replication.

Determination of water soluble extractives

Cold water solubility[16]

Two g of oven dried coarsely ground wood was weighed and transferred into a conical flask containing 300 ml of distilled water. The mixture was digested at room temperature with frequent stirring for 48 h. The material was then filtered through IG-1 crucible and washed thoroughly with cold distilled water and dried to a constant weight in an oven at 105 ± 2 °C. The cold water solubility was determined by calculating the loss in weight of sample taken and was expressed as percentage on the basis of oven dry weight of wood.

Hot water solubility[16]

Two g of oven dried coarsely ground wood was taken in a flask having 100 ml of double distilled water fitted with reflux condenser. It was digested on boiling water bath for 3 h. The contents were then filtered through IG-1 crucible and residue was dried in an oven at 105 ± 2 °C till constant weight. The solubility was determined by calculating the loss in weight of the sample taken and expressed as percentage.

Alcohol-benzene extractives[17]

Ten g of oven dried coarsely ground wood was placed in a porous thimble (oven dried and weighed). The thimble was placed in a soxhlet apparatus and extracted with 200 ml of alcohol-benzene (1:2 v/v) for six hours. The porous thimble was then taken out and allowed to dry in open air and finally in an oven at 105 ± 2 °C till constant weight. The alcohol-benzene solubility was determined by calculating the loss in weight of the sample taken and expressed in percentage.

Klason-lignin content[18]

Two g of oven dried samples pre-extracted with alcohol-benzene (1:2 v/v) was treated with 15 ml of 72 per cent sulphuric acid for 2 h at 18–20 °C with constant stirring. The material was brought down to 3 per cent by adding 545 ml of double distilled water. The solution was refluxed for 4 h and then allowed to settle. The contents were filtered and washed with hot distilled water. The material was then dried in an oven at 105 ± 2 °C till constant weight and expressed in percentage.

Holocellulose[19]

Five g of oven dried sample pre-extracted with alcohol-benzene (1:2 v/v) was taken in a conical flask and 160 ml of distilled water was added to it. The contents were treated with 1.5 g of sodium chlorite and 10 drops of acetic acid at 70–80 °C on a water bath for one hour. The process was repeated four times till the meal became white. The contents were then filtered through IG-2 crucible, washed with water and finally with acetone. The sample was dried in an oven at 105 ± 2 °C to a constant weight. The extracted holocellulose content was calculated on the basis of the oven dry weight.

Determination of mechanical strength properties

The mechanical properties of wood were determined as per the procedure followed for testing in Universal Testing Machine (Model:UTN-10) in the Wood Workshop of the Department of Forest Products, Dr YS Parmar University of Horticulture and Forestry, Nauni-Solan (HP). The mechanical tests of wood samples were determined by the procedure prescribed by Indian Standard IS:1708[15]. All the tests were conducted on the standard sized wood samples at 8–12 per cent moisture content. The experiment was laid out in CRD factorial. In total, three replicates for each treatment were taken.

Tensile strength parallel to the grain (kN/mm^2)

The standard size of the wood specimens taken for conducting this test was central cross-Section 7 × 7 mm. The computer-generated data and graphs were drawn by using Universal Testing Machine (Model:UTN-10), so as to derive the values of maximum load, maximum displacement and breaking pattern for all the samples. Proper care was taken, so that each specimen faced similar type of test measures[15]

Static bending strength (kN/mm^2)

The standard size of the specimens taken was 5 × 5 cm × 100 cm tested for bending strength on Universal Testing Machine (UTN-10). Proper care was taken so that each specimen faced similar type of test measures. The data generated were used for further analysis and comparison[15]

Compression strength

Compression strength parallel to the grain (kN/mm^2)

This test was done in the direction along the grain and the data were generated in the Universal Testing Machine (Model: UTN-10). The standard size of specimens for this compression test was 5 × 5 cm cross-section[15].

Compression strength perpendicular to the grain (kN/mm^2)

The specimen size of 5 × 5 cm × 15 cm was taken across the direction of grain for carrying out this test. The data recorded were used for further analysis and interpretation of results[15].

Results and discussions

Chemical properties of wood

Cold water soluble extractives (%)

Among temperatures, In Cold water-soluble extractives of thermally modified wood of *Salix tetrasperma* (Table 2) the maximum value (7.44%) was observed at 120 °C and the minimum (5.14%) was observed in control. The interactions between temperature and duration also showed significant results. The highest value (7.88%) was found at 120 °C (2 h) and the lowest value (4.99%) was found at 200 °C (6 h).

Tannins, gums, sugars, and inorganic salts constitute the primary cold water-soluble extractives in wood. Upon thermal exposure, the extractive content generally decreases, likely due to the volatilization or degradation of specific compounds during heating. Higher extractive levels are often associated with enhanced wood durability and dimensional stability. However, extractive concentrations can vary significantly across species, between individuals of the same species, and even within different portions of a single tree[20]. Esteves et al.[5], in their study on *Eucalyptus globulus*, observed an initial increase in extractives followed by a reduction at 190 °C and 200 °C across treatment durations of 2, 4, and 6 h. Similarly, Silva et al.[21]reported a decline in extractive content in *Corymbia citriodora* wood treated at 160–200 °C, with values dropping from 17.80 to 9.60%. This reduction is attributed to the thermal removal or transformation of water-soluble compounds during prolonged exposure.

Hot water soluble extractives (%)

Interpretation of the data for hot water soluble extractives of thermally modified wood of *Salix tetrasperma* (Table 3), showed significant variation at different temperatures. The maximum value (11.56%) was recorded at 120 °C and minimum (8.76%) was noticed at 200 °C. Among time durations, the value of hot water extractives varied from 9.92 to 9.91 per cent and was found to be statistically non significant. The interactions between temperatures and durations were also found statistically significant and the maximum value (11.75%) was noticed at 120 °C (6 h) and the minimum (8.52%) was found at 200 °C (6 h).

Wood contains various organic extractives such as lipids, waxes, alkaloids, and phenolic compounds, which exhibit higher solubility in hot water than in cold water. This enhanced solubility is primarily due to hydrolytic reactions that occur during boiling. Typically, thermal treatment initially causes a slight increase in hot water-soluble extractives; however, with rising temperatures and prolonged exposure, the extractive content eventually declines. Yalcin and Sahin[22], observed this pattern in thermally modified narrow-leaved ash wood. Similarly, Yildiz[23], reported a decrease in hot water-soluble extractives in beech wood when subjected to temperatures ranging from 180 to 200 °C. Sikora et al.[24]found that in pine wood, the extractive content initially increased between 100 and 160 °C due to the migration of fats and waxes to the surface. However, decomposition processes commenced at 180 °C, and above 200 °C, the breakdown of resin acids contributed to a marked reduction in extractives.

Duration(h) **Temperature (°C)**	**2 h**	**4 h**	**6 h**	**Mean**	**SD**	**CV**
60 °C	5.17	5.25	5.35	5.26	0.09	1.72
80 °C	5.93	6.07	6.25	6.08	0.16	2.64
100 °C	6.34	6.45	6.66	6.48	0.16	2.51
120 °C	7.88	7.28	7.15	7.44	0.39	5.24
140 °C	6.93	6.98	6.84	6.92	0.07	1.03
160 °C	6.75	6.43	6.15	6.44	0.30	4.66
180 °C	6.25	6.13	6.04	6.14	0.11	1.72
200 °C	5.46	5.06	4.99	5.17	0.25	4.90
Control	5.14	5.14	5.14	5.14		
Mean	6.21	6.09	6.06			

$CD_{0.05}$	
Temperature (T)	0.32
Duration (D)	NS
Temperature × Duration (T × D)	0.56

Table 2. Cold water-soluble extractives of thermally modified wood of *Salix tetrasperma* (%).

Duration(h) Temperature (°C)	2 h	4 h	6 h	Mean	SD	CV
60 °C	9.83	9.96	10.06	9.95	0.12	1.16
80 °C	10.15	10.25	10.36	10.26	0.11	1.02
100 °C	10.55	10.63	10.96	10.71	0.22	2.03
120 °C	11.37	11.56	11.75	11.56	0.19	1.64
140 °C	10.25	10.03	9.92	10.07	0.17	1.67
160 °C	9.76	9.59	9.32	9.56	0.22	2.32
180 °C	9.16	9.08	9.03	9.09	0.07	0.72
200 °C	8.93	8.83	8.52	8.76	0.21	2.44
Control	9.30	9.30	9.30	9.30		
Mean	9.92	9.92	9.91			

$CD_{0.05}$	
Temperature (T)	0.05
Duration (D)	NS
Temperature × Duration (T × D)	0.09

Table 3. Hot water soluble extractives of thermally modified wood of *Salix tetrasperma* (%).

Duration(h) Temperature (°C)	2 h	4 h	6 h	Mean	SD	CV
60 °C	9.27	9.49	9.95	9.57	0.35	3.63
80 °C	10.17	10.31	10.43	10.30	0.13	1.26
100 °C	10.58	10.74	10.95	10.76	0.19	1.73
120 °C	11.09	11.25	11.36	11.23	0.14	1.21
140 °C	11.62	11.79	11.93	11.78	0.16	1.32
160 °C	12.13	12.34	12.56	12.34	0.22	1.74
180 °C	12.76	12.96	13.11	12.94	0.18	1.36
200 °C	13.36	13.60	13.86	13.61	0.25	1.84
Control	9.03	9.03	9.03	9.03		
Mean	11.11	11.28	11.47			

$CD_{0.05}$	
Temperature (T)	0.06
Duration (D)	0.03
Temperature × Duration (T × D)	0.10

Table 4. Alcohol benzene soluble extractives of thermally modified wood of *Salix tetrasperma* (%).

Alcohol benzene extractives (%)

The values obtained for alcohol benzene soluble extractives in thermally modified wood of *Salix tetrasperma* (Table 4), revealed significant difference at different temperatures, durations and their interactions at 5 per cent level of significance. For different temperatures, the maximum value (13.61%) was recorded at 200 °C and the minimum (9.03%) was noticed in control. Among different duration the highest value (11.47%) was observed at 6 h and the lowest (11.11%) was noticed at 2 h. For interactions between temperature and duration, maximum value (13.86%) was noticed at 200 °C (6 h) and the minimum (9.27%) was observed at 60 °C (2 h).

Extractives that can be dissolved in alcohol and benzene, primarily derived from substances like oleoresins, fats, waxes, and oils, play various roles in tree functions. These roles encompass aspects such as tree metabolism, energy storage, defense mechanisms against microbial attacks, and influencing the quality of wood for pulping. Yalcin and Sahin[22], discovered that in thermally modified *Fraxinus angustifolia* wood, alcohol-benzene soluble extractives are initially lower in the untreated wood but increase with higher temperatures and longer treatment times. Similarly, Wang et al.[25] observed comparable outcomes in thermally modified *Eucalypt pellita* wood treated within the temperature range of 80–280 °C, with alcohol-benzene extractive content rising from 1.59 to 2.18%. Gupta[26] and Thakur[27] also found similar trends in heat-treated wood of *Pinus roxburghii* and *Acrocarpus fraxinifolius*, respectively, with the highest levels of alcohol-benzene soluble extractives occurring at 200 °C (6 h), and the lowest levels in untreated wood. Sikora et al.[24] reported analogous results in thermally modified Spruce and Oak wood, with the highest levels (2.68 ± 0.21 and 9.87 ± 0.16) observed at 210 °C, and the lowest levels (0.96 ± 0.08 and 4.31 ± 0.06) in untreated wood.

Klason-lignin Content (%)

The data revealed statistically significant variation for Klason lignin content among different temperatures, durations and their combinations at 5 per cent level of significance (Table 5). For different temperatures, the highest lignin content (24.77%) was recorded at 200 °C and lowest lignin content (16.49%) was found in control. Among the durations, the maximum value (20.50%) was observed at 6 h and the minimum value (20.04%) was noticed at 2 h. For combinations of temperatures and durations the highest value (25.23%) was found at 200 °C (6 h) and the lowest value (16.49%) was found in control.

Lignin, a complex phenolic polymer predominantly located in the middle lamella and distributed throughout the secondary cell wall, is composed of hydroxyl- and methoxy-substituted phenylpropane units. It plays a vital role in imparting mechanical strength and rigidity to wood, promoting cell wall adhesion, and maintaining tissue cohesion[28]. Lignin is particularly significant for the mechanical performance of wood[29]and exhibits a high resistance to thermal degradation[30]. Thermal treatment has been shown to increase lignin content in various wood species. Akyildiz et al.[31]reported a rise in lignin content in Anatolian black pine when treated between 130 and 230 °C for durations of 2 to 8 h. Similarly, Silva et al.[32]observed the highest lignin content (44%) in *Corymbia citriodora* at 200 °C. Repellin and Guyonnet[33] further noted that Klason lignin content increases with temperature, with significant changes occurring only after exposure to 200 °C for at least two hours. This increment is often attributed to enhanced cross-linking and condensation reactions within the lignin structure. Moreover, the relative increase in lignin content is commonly associated with the thermal degradation of polysaccharides, particularly hemicelluloses and cellulose[5,34].

Holocellulose content (%)

The data recorded on holocellulose content reflected significant differences in thermally modified wood of *Salix tetrasperma* (Table 6), at different temperatures, durations and their combinations at 5 per cent level of significance. Among different temperatures, the maximum value (79.18%) was found in control and the minimum value (70.89%) was noticed at 200 °C. Amongst durations, the highest value (75.71%) was noticed at 2 h and the lowest value (75.17%) was found at 6 h. The maximum value (79.18%) for interactions between temperatures and durations was found in control and the minimum value (70.46%) was found at 200 °C (6 h).

The holocellulose, comprising approximately 40–45% cellulose and 15–25% hemicelluloses, constitutes the carbohydrate portion of wood, accounting for about 65–70% of the wood's dry weight[3]. The reduction in holocellulose content observed in thermally modified wood is likely attributed to the depolymerization of hemicelluloses during hydrothermolysis and some breakdown of cellulose during curing[35] Similarly, Sikora et al.[24] have noted that hemicelluloses are the least stable wood component during thermal treatment, with their quantity decreasing in treated wood, while cellulose and lignin, which are thermally stable and decompose at higher temperatures. Khalid et al.[36] found similar outcomes in Acacia hybrid wood, suggesting that changes in wood composition are primarily due to the loss of polysaccharide content. In the case of thermally treated *Bombax ceiba* and *Acrocarpus fraxinifolius* wood by Pingale[37] and Thakur[38], respectively, the highest holocellulose content was observed in the untreated samples and decreased with increasing temperature, with the most significant decrease occurring at 200 °C for 6 h. An earlier study by Bhoru[39] also noted that at 200 °C, the holocellulose content decreased as temperature and duration increased, reaching 67%, which is approximately 5% lower than the control samples of *Pinus radiata*. Comparable results were found by Mburu et al.[40] in heat-treated *Grevillea robusta* wood, where lignin increased, and hemicelluloses decreased.

Mechanical properties of wood

Tensile strength of wood (kN/mm^2)

The statistical analysis of the data on tensile strength (Table 7), reflected significant differences at different temperatures, durations and their combinations at 5 per cent level of significance. The tensile strength (0.059 kN/

Duration(h) Temperature (°C)	2 h	4 h	6 h	Mean	SD	CV
60 °C	17.74	17.65	18.15	17.85	0.27	1.49
80 °C	18.44	18.57	18.66	18.56	0.11	0.60
100 °C	18.74	18.84	19.15	18.91	0.21	1.13
120 °C	19.27	19.47	19.68	19.47	0.21	1.05
140 °C	20.14	20.55	20.66	20.45	0.27	1.34
160 °C	21.54	22.14	22.35	22.01	0.42	1.91
180 °C	23.54	23.66	24.16	23.79	0.33	1.38
200 °C	24.46	24.63	25.23	24.77	0.40	1.63
Control	16.49	16.49	16.49	16.49		
Mean	20.04	20.22	20.50			

$CD_{0.05}$	
Temperature (T)	0.068
Duration (D)	0.039
Temperature × Duration (T × D)	0.117

Table 5. Klason-lignin content of thermally modified wood of *Salix tetrasperma* (%).

Duration(h) Temperature (°C)	2 h	4 h	6 h	Mean	SD	CV
60 °C	78.24	78.43	77.46	78.04	0.51	0.66
80 °C	77.23	77.19	77.03	77.15	0.11	0.14
100 °C	76.96	76.85	76.41	76.74	0.29	0.38
120 °C	76.43	76.11	76.05	76.20	0.20	0.27
140 °C	75.54	75.24	75.14	75.31	0.21	0.28
160 °C	74.23	73.59	73.36	73.73	0.45	0.61
180 °C	72.39	71.71	71.47	71.86	0.48	0.66
200 °C	71.17	71.05	70.46	70.89	0.38	0.54
Control	79.18	79.18	79.18	79.18		
Mean	75.71	75.48	75.17			

CD$_{0.05}$	
Temperature (T)	0.10
Duration (D)	0.06
Temperature × Duration (T × D)	0.16

Table 6. Holocellulose content of thermally modified wood of *Salix tetrasperma* (%).

Duration(h) Temperature (°C)	2 h	4 h	6 h	Mean	SD	CV
60 °C	0.049	0.049	0.047	0.049	0.0012	2.3890
80 °C	0.048	0.056	0.047	0.050	0.0049	9.8004
100 °C	0.053	0.055	0.054	0.054	0.0010	1.8519
120 °C	0.070	0.059	0.047	0.059	0.0115	19.6084
140 °C	0.048	0.049	0.047	0.048	0.0010	2.0833
160 °C	0.048	0.045	0.040	0.044	0.0040	9.1161
180 °C	0.046	0.042	0.044	0.044	0.0020	4.5455
200 °C	0.041	0.042	0.038	0.040	0.0021	5.1612
Control	0.049	0.049	0.049	0.049		
Mean	0.050	0.049	0.046			

CD$_{0.05}$	
Temperature (T)	0.003
Duration (D)	0.002
Temperature × Duration (T × D)	0.006

Table 7. Tensile strength parallel to the grain of thermally modified wood of *Salix tetrasperma* (kN/mm^2).

mm^2) was recorded to be maximum at 120 °C and the minimum (0.040 kN/mm^2) was noticed at 200 °C. Among the durations, the highest value (0.050 kN/mm^2) was noticed at 2 h and the lowest value (0.046 kN/mm^2) was found at 6 h. Among interactions of temperature and duration, the highest value (0.070 kN/mm^2) was observed at 120 °C (2 h) and the lowest value (0.038 kN/mm^2) was noticed at 200 °C (6 h).

Tensile stresses occur when external forces pull on a piece of lumber away from its end. The resistance of the wood to these stretching forces, where the fibers or tracheids are pulled apart, is what we refer to as its tensile strength. Wood has been a construction material for centuries due to its unique properties, and it undergoes various stresses during its use. In the case of *Corymbia citriodora*, Silva et al.[41] noted a significant 55% decrease in tensile strength parallel to the grain as the temperature increased. Boonstra et al.[11] found that thermally modified softwood species also experienced a decline in tensile strength parallel to the grain compared to untreated wood. This change in mechanical properties due to heat treatment can be attributed to alterations in wood's primary components. Tensile strength decreases as the content of extractives, hemicelluloses, and the amorphous region of cellulose decreases. Cellulose is the primary contributor to wood's tensile strength, as indicated by Kollman[42] and Stamm[43]. The degradation of amorphous cellulose polymers is significant following heat treatment, as noted by Boonstra and Tjeerdsma[44]. The observed reduction in tensile strength can likely be attributed to this phenomenon.

Bending strength of wood (kN/mm^2)

The data pertaining to bending strength of thermally modified wood of *Salix tetrasperma* (Table 8), showed significant variation among different temperatures at 5 per cent level of significance. The maximum bending strength (0.012 kN/mm^2) was recorded in control and minimum (0.007 kN/mm^2) at 160, and 180 °C. Among

Duration(h) Temperature (°C)	2 h	4 h	6 h	Mean	SD	CV
60 °C	0.011	0.01	0.011	0.011	0.0006	5.4127
80 °C	0.010	0.011	0.009	0.010	0.0010	10.0000
100 °C	0.010	0.009	0.008	0.009	0.0010	11.1111
120 °C	0.010	0.009	0.009	0.009	0.0006	6.1859
140 °C	0.008	0.008	0.007	0.008	0.0006	7.5307
160 °C	0.007	0.008	0.007	0.007	0.0006	7.8730
180 °C	0.007	0.007	0.008	0.007	0.0006	7.8730
200 °C	0.007	0.006	0.006	0.006	0.0006	9.1161
Control	0.012	0.012	0.012	0.012		
Mean	0.009	0.009	0.009			

$CD_{0.05}$	
Temperature (T)	0.001
Duration (D)	NS
Temperature × Duration (T × D)	NS

Table 8. Static Bending strength of thermally modified wood of *Salix tetrasperma* (kN/mm^2).

Duration(h) Temperature (°C)	2 h	4 h	6 h	Mean	SD	CV
60 °C	0.033	0.030	0.030	0.031	0.002	5.587
80 °C	0.030	0.034	0.031	0.032	0.002	6.574
100 °C	0.032	0.037	0.034	0.034	0.003	7.330
120 °C	0.042	0.035	0.041	0.039	0.004	9.625
140 °C	0.033	0.034	0.032	0.033	0.001	3.030
160 °C	0.032	0.036	0.031	0.033	0.003	8.017
180 °C	0.031	0.030	0.029	0.030	0.001	3.333
200 °C	0.028	0.029	0.029	0.029	0.001	2.014
Control	0.031	0.031	0.031	0.031		
Mean	0.032	0.033	0.031			

$CD_{0.05}$	
Temperature (T)	0.004
Duration (D)	0.002
Temperature × Duration (T × D)	0.006

Table 9. Compression parallel to the grain of thermally modified wood of *Salix tetrasperma* (kN/mm^2).

the durations, non significant results were found and was recorded as 0.009 kN/mm^2. The combinations of temperatures and durations were also found to be non significant and ranged between 0.006 and 0.012 kN/mm^2.

Bending strength refers to a material's capacity to withstand forces that induce bending, making it suitable for use in construction where its ability to resist failure is crucial. To assess bending properties, test specimens are subjected to applied forces for a specified duration until they fail. In the case of *Radiata pine*, Boonstra et al.[11] observed a notable reduction in bending strength following heat treatment. This decrease can be attributed to the presence of a substantial amount of juvenile wood in pine. Juvenile wood has a distinct chemical composition compared to mature wood, with higher levels of hemicelluloses and lignin. Romagnoli et al.[45] reported a slight decline in bending strength with increasing temperature for Douglas fir (*Pseudotsuga menziesii*) and Corsican pine (*Pinus nigra*), while the duration of heat treatment had a relatively minor impact. Similar decreases in bending strength were also documented for thermally treated wood of *Pinus roxburghii* and *Toona ciliata* by Gupta[46] and Sharma[47], respectively. In our current study, we observed a reduction in bending strength for *Salix tetrasperma*, which can be attributed to the degradation of hemicelluloses, resulting in decreased mechanical performance.

Compression parallel to grain (kN/mm^2)

The data regarding Compression parallel to the grain of thermally modified wood of *Salix tetrasperma* presented in (Table 9), depicted the significant variation among different temperatures, durations and their combinations for compression parallel to grain at 5 per cent level of significance. For different temperatures, the maximum compression parallel to grain was recorded to be 0.039 kN/mm^2 at 120 °C and the minimum (0.029 kN/mm^2) for compression parallel to grain was found at 200 °C. Among the time durations, the highest value (0.033 kN/mm^2) was observed at 4 h and the lowest value (0.031 kN/mm^2) was noticed at 6 h. The maximum value (0.042 kN/

Duration(h) Temperature (°C)	2 h	4 h	6 h	Mean	SD	CV
60 °C	0.028	0.029	0.029	0.029	0.001	2.014
80 °C	0.029	0.028	0.028	0.028	0.001	2.038
100 °C	0.027	0.026	0.028	0.027	0.001	3.704
120 °C	0.026	0.025	0.026	0.026	0.001	2.249
140 °C	0.025	0.024	0.025	0.025	0.001	2.341
160 °C	0.024	0.022	0.024	0.023	0.001	4.949
180 °C	0.023	0.022	0.021	0.022	0.001	4.545
200 °C	0.022	0.021	0.021	0.021	0.001	2.706
Control	0.030	0.030	0.030	0.030		
Mean	0.026	0.029	0.026			

$CD_{0.05}$	
Temperature (T)	0.003
Duration (D)	0.001
Temperature × Duration (T × D)	0.0041

Table 10. Compression perpendicular to the grain of thermally modified wood of *Salix tetrasperma* (kN/mm^2).

mm^2) for interactions between temperatures and durations were found at 120 °C (6 h). The minimum value (0.028 kN/mm^2) was found at 200 °C (2 h).

Compressive strength refers to wood's capacity to withstand forces that attempt to bring its opposite ends closer together. Variations in compression strength parallel to the grain in different wood species are influenced by factors such as wood porosity and cellular composition. Additionally, the presence of extractives and lignin depositions affects wood's compressive strength. Generally, wood is strongest in the direction parallel to the grain due to the alignment of cells and their strong interconnections. Aydin et al.[48] conducted experiments on thermally treated Oriental beech wood using hot air at temperatures of 125 °C, 155 °C, and 185 °C for durations of 2, 6, and 10 h. They found a reduction in compression strength parallel to the grain following most of the heat treatments, except for the cases of 2 and 6 h of heating at 125 °C. Boonstra et al.[11] obtained similar results at temperatures of 165 °C and 185 °C for durations of 30, 45, 60, and 90 min. They concluded that higher levels of bound water are required to influence compression strength parallel to the grain, but during thermal treatment, the amount of bound water in wood decreases. Consequently, this reduction in bound water content leads to a 28% increase in compressive strength parallel to the grain. Similarly, Yildiz et al.[49] observed a slight increase in compression strength parallel to the grain in thermally modified beech wood when subjected to temperatures of 130 °C, 150 °C, 180 °C, and 220 °C for durations of 2 and 6 h.

Compression perpendicular to grain (kN/mm^2)

The data pertaining to compression perpendicular to grain is presented in (Table 10), which showed significant variation among different temperatures and their combinations at 5 per cent level of significance. The maximum compression perpendicular to grain (0.033 kN/mm^2) was recorded at 120 °C whereas, the minimum (0.021 kN/mm^2) was recorded at 200 °C. Among durations, the highest value (0.028 kN/mm^2) was found at 2 h and the lowest value (0.027 kN/mm^2) was noticed at 4 h and 6 h. The maximum value (0.035 kN/mm^2) for combinations of temperatures and durations were observed at 120 °C (2 h). The minimum value 0.021 kN/mm^2 was observed at 180 °C (6 h) and 200 °C (4 h and 6 h).

Compressive strength and hardness across the grain (perpendicular to the grain) are notably lower compared to those along the grain (parallel to the grain). This disparity arises from the presence of various types of bonds in wood, such as strong and rigid bonds running parallel to the grain, contrasted with weaker and softer secondary bonds in the transverse direction of the grain. Additionally, the orientation of polymer molecules in wood, including factors like the microfibril angle of crystalline cellulose and the angular structure of the lignin polymer network, contributes to this difference[50]. In a previous study, Boonstra et al.[11] discovered that compression perpendicular to the grain significantly decreased at 165 °C and 185 °C compared to the control and was lower than the compression strength parallel to the grain. In the case of *Picea sitchensis*, Kubojima et al.[51] observed an initial increase in compression perpendicular to the grain during the first 2 h of treatment at 120 °C and 160 °C, followed by a stabilization. However, at 200 °C, the compressive strength initially increased but then decreased. This behavior can be attributed to the rise in cellulose crystallinity and the reduction in wood moisture. Crystallinity's impact is more pronounced at the beginning of the treatment, but as the temperature increases, heat-induced degradation becomes more significant, leading to a decrease in wood's compressive strength. Additionally, the decline in compressive strength across the grain is influenced by the anisotropy in crystalline cellulose[5,50]. In the current study, we observed a decrease in compressive strength perpendicular to the grain as the temperature increased, with the highest value (0.031 kN/mm^2) recorded in the control samples. These results align with the previously mentioned findings.

Conclusion

The present study demonstrates that thermal modification of *Salix tetrasperma* wood significantly influences its chemical composition and mechanical behavior, with the extent of change being dependent on both treatment temperature and duration. Moderate heat treatments (120–160 °C) enhanced certain functional attributes such as increased extractives and lignin content while retaining satisfactory mechanical performance. The observed rise in alcohol-benzene extractives and lignin, particularly at higher temperatures, indicates improved hydrophobicity and potential biological resistance, though accompanied by a reduction in holocellulose content and tensile/bending strengths at extreme thermal levels (≥ 180 °C). Optimal tensile strength was recorded at 140 °C, and maximum parallel-to-grain compression strength at 160 °C, suggesting these conditions strike a balance between structural integrity and chemical stability. In contrast, severe treatments at 200 °C, though maximizing extractives, caused pronounced degradation of cellulose and reduced mechanical capacity. These findings suggest that thermal modification at controlled mid-range temperatures can be strategically employed to tailor *Salix tetrasperma* for applications requiring improved durability, dimensional stability, and resistance to biodegradation, without severely compromising load-bearing performance.

Data availability

The raw data will be provided on reasonable request, if required. The corresponding author (Sufiya Shabir-sufu1914@gmail.com) will provide data on reasonable request. The procurement of wood samples of Salix tetrasperma and its research were conducted by followed all relevant institutional, national and international guidelines and legislation.

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Author contributions

Sufiya Shabir, Main author of the research who has conducted research and prepared the paper for publication. Dr. Bhupender Dutt, Major advisor of the research, who helped in formulating the hypothesis and procedure of the research. Dr. Rajneesh Kumar, Co-advisor of research., who helped in data analysis. Dr. Dinesh Sharma, advisory committee member, who helped in procurement of wood samples. Irtizah Mushtaq, helped and guided how to formulate a research paper.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

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