**Improvement in the Decay Resistance of *Melia Dubia* Wood against White Rot Fungi and Changes in Properties due to Thermo-Hydro-Mechanical Modification**

## **ABSTRACT**

Despite extensive studies on thermal modification, limited research has focused on fast-growing, short-rotation species like *Melia dubia*. While *Melia dubia* holds significant industrial importance due to its rapid growth and high demand in the pulpwood, plywood, and timber sectors, the juvenile wood produced in short-rotation plantations is often less durable. Thermo hydro mechanical (THM) modification combines thermal and mechanical treatment under controlled conditions, offers a sustainable, eco-friendly alternative to chemical preservative treatments. In the current study, specimens from *Melia dubia* wood were used to obtain wood material with improved decay resistance by using THM treatment, performed at four temperatures: 160°C, 170°C, 180°C, and 190°C. Fungal resistance was tested under laboratory conditions through a soil block bioassay against white rot fungi *Trametes versicolor*, which indicated that decay resistance increased with increasing temperature. The highest weight loss was recorded in the untreated control samples, whereas the samples treated at 190°C showed the lowest weight loss percentage, indicating enhanced decay resistance. At the same time, noticeable changes in color, weight loss, and thickness were observed post-treatment. Correlation analysis derived from a scatterplot matrix revealed a positive correlation between temperature and density (r = 0.51), a significant negative correlation between temperature and weight (r = -0.45), and a weak, non-significant negative trend between weight and density (r = -0.14). These findings highlight that higher temperatures increase density while reducing weight and thickness, improving wood durability.

***Keywords:***Thermo-hydro-mechanical modification, density, color, *Melia dubia*, *Trametes versicolor*, Soil block Bioassay.

## **INTRODUCTION**

Wood has been used as a construction material for thousands of years worldwide to meet anthropogenic needs. With the increasing population and its wide range of applications, the demand for wood has also risen (Ramage *et al.*, 2017). However, the gradual decline in the availability of high-quality raw materials necessitates the more efficient use of existing resources (Domaracka *et al.,* 2022). *Melia dubia*, recognized as one of the fastest-growing trees globally, is particularly valuable as a short-rotation species due to its high demand in the pulpwood, plywood, and timber industries in India (Goswami *et al.,* 2020). Although *Melia dubia* can be harvested industrially after just 3-4 years, these short-rotation plantations often produce juvenile wood, which can have inferior properties (Prakash *et al.,* 2018). Therefore, implementing thermo-hydro-mechanical (THM) modification presents a promising alternative to enhance the properties of *Melia dubia* wood. THM treatment is an innovative and eco-friendly approach that improves the intrinsic properties of wood, resulting in a modified material that meets functional requirements without compromising the environmental benefits associated with wood (Navi and Sandberg, 2012). The densification of wood is an important factor in the THM treatment. The wood density is one of the most influential factors controlling the strength and several other physical properties. Most of the mechanical properties are correlated with density (Saranpää, 2003). High-density wood is required for structural purposes and thus many attempts have been made to develop a suitable process for the densification of wood (Kutnar and Šernek, 2007). Densification makes it possible for low-density wood to substitute the harder species so that low-density species can be modified into effective and high-value material (Kumar *et al.,* 2021). Thermal modification under saturated steam can be performed at lower temperatures with shorter duration to obtain similar or better mechanical properties compared to modification under superheated steam (Skyba *et al*., 2008). The decay resistance of Thermo Hydro (TH) and THM densified spruce (*Picea abies* L. Karst) and pine sapwood (*Pinus sylvestris* L.) in comparison with Thermo Mechanical (TM) and THM with additional steam post-treatment and untreated wood was studied, where less mass losses were found for both TM and THM modification by *Coniphora puteana* when steam treatment was applied after densification (Welzbacher*et al.,* 2004). The color characteristics in Pinewood due to thermal modification at a temperature of 120℃ to 150℃ and hot pressing at a press pressure of 5 to 7 MPa for 60 minutes caused color changes in the wood, with increasing pressure at high temperatures (Atik *et al.,* 2013). Densification of wood under saturated steam at 140°C improves the mechanical properties and also reduces the hygroscopicity of wood (Heger *et. al.,*2004). The combination treatment of hygrothermal treatment and densification of poplar wood improved dimensional stability, mechanical properties, and water-repellency (Hajihassani *et. al*., 2018). The density of the Norway spruce *(Picea abies)* and Beech wood*(Fagus sylvatica)* specimens increased after THM and densification also removed the compression set recovery (Skyba *et al*., 2008). Despite the advances in wood modification, there is limited research specifically focused on improving the properties of fast-growing, short-rotation species like *Melia dubia* through eco-friendly processes such as THM treatment. Most studies on wood modification have targeted slower-growing hardwoods, such as spruce, pine, and beech, with little application to tropical species or fast-growing trees.

## **MATERIALS AND METHODS**

### ***Procurement of material***

*Melia dubia* wood logs were collected from the Silviculture and Forest Management Division, Forest Research Institute, Dehradun (30°19ˈN, 78°04ˈE).

The culture of white rot fungi (*Trametes versicolor)* was obtained from Pathology Discipline, Forest Protection Division, Forest Research Institute, Dehradun.

### ***Preparation of samples***

Wood logs procured were cut into samples of dimensions 14.6cm x 9.8cm x 3.7cm. The samples were planed and sanded. The initial dimensions and weight of the samples were taken using a vernier caliper and weighing balance.

### ***Treatment of wood***

Several successive steps were taken during the wood sample treatment process to guarantee uniformity in the outcome. In order to minimize the risk of cracking or warping during the steaming phase, the wooden samples were first completely saturated with water for two to three days. This ensured that the wood absorbed enough moisture to allow for subsequent steam penetration and prevent uneven modification during the thermal treatment. This made the wood's cellular structure fully hydrated and receptive to the steam treatment. The wood samples were taken for steaming once they were fully wet in an autoclave for 45 minutes at various temperatures (160, 170, 180, and 190 °C). The steam pressure inside the autoclave was then gradually decreased to avoid thermal shock, which could otherwise result in the wood warping or splitting from abrupt temperature fluctuations. In order to prevent exposure to the air, the wood samples were then carefully taken out of the autoclave and promptly packed in plastic bags.

This wrapping technique helps the samples keep moisture and avoid drying out too quickly, which could cause shrinkage or uneven cooling. The samples were then wrapped and cold pressed for eighteen hours at a regulated pressure between 0.5 and 2 MPa. The wood was further compressed by the cold pressing process, which lowers its moisture content and improves its structural stability. To improve the density of the wood without generating undue distortion, a pressure range of 0.5 to 2 MPa was used.

The wood samples were left to stable for a day at room temperature following the cold pressing procedure. Before additional drying, this time allows the wood to achieve equilibrium moisture content and guarantees that any remaining tensions or moisture imbalances from the pressing operation are eliminated. After that, the wood samples were dried in an oven set at 45°C. To determine the oven-dry weight of the wood, the samples must be completely dry, which is made possible by the oven-drying procedure.

The samples were oven-dried and then spent 14 days in a solar kiln. The wood was able to dry slowly and carefully since the solar kiln kept the temperature at 45°C and the relative humidity at 72% RH throughout this time.Since a solar kiln uses solar energy for drying instead of traditional energy sources, it is very beneficial for environmentally friendly wood processing. To ensure full drying the wood samples were kept in the kiln for 14 days to adequately dry to their equilibrium moisture content during for further examination and analysis.

### ***Color Variation***

Changes in the color were made according to visual observation by directly inspecting the wood samples to assess any noticeable differences in color before and after treatment. Color changes were categorized as follows:

**Table 1:** Categorization according to changes in color

|  |  |  |
| --- | --- | --- |
| S.No | Change Pattern | Characteristics |
| 1 | No Change | If there was no perceptible difference in the color before and after treatment. |
| 2 | Slight Change | A minor shift in color, such as lightening or darkening that was noticeable but not extreme. |
| 3 | Moderate Change | A more significant change in color, where the treated wood visibly differed from the untreated samples. |
| 4 | Severe Change | A dramatic color shift, from the typical color before treatment |

### ***Density of Thermo-Hygro-Mechanical Modified Wood Samples***

Density is a fundamental property of wood that significantly influences its performance in various applications, such as construction and furniture manufacturing. It is defined as the mass per unit volume of the material, measured at a consistent moisture content. In this study, the density of the wood samples was determined following the Thermo-Hygro-Mechanical (THM) modification process.

The density (ρ) of each sample was calculated using the formula:

Density =

where Wo​ represents the oven-dry weight of the sample, and Vg​ is the volume of the sample after THM modification. This method ensures consistency in measurements and enables comparison of the density changes induced by the THM process.

### ***Decay test of Thermo-Hygro-Mechanically treated wood***

The decay resistance of wood is an important factor for determining its suitability in various outdoor and industrial applications, where exposure to fungal attack is common. The decay test evaluates the effectiveness of the treatment in enhancing the wood's natural durability.

The THM-treated wood samples were cut into small blocks with dimensions (1.9 × 1.9 × 1.9 cm)³.These samples were small enough to expose all surfaces to fungal attack while also being large enough to represent the characteristics of the material.

The decay test was conducted using the Soil Block Bioassay method, which is a standard procedure for assessing wood durability (as per IS 4873:2008).Samples were exposed to fungi by placing them in test bottles in which there are actively growing mycelia of *T. versicolor* on feeder strips.These feeder strips provide the necessary nutrients for the fungal growth, which then spreads onto the wood samples.Then, the test bottles were placed in Biological Oxygen Demand(BOD) incubator at 25 ºC ± 2 ºC and 75 % ± 5 % RH for growth of fungi on samples.The wood blocks were weighed before (W1) and after 4 weeks of exposure of fungi (W2) in test bottles. The efficacy of treatment was categorized on the basis of weight loss percentage.This weight loss is indicative of the extent to which the wood has been decayed by the fungus. Weight loss was calculated as follows.

Where, W1 is the weight of wood blocks before exposure to fungi (gm) and W2 is the weight of wood blocks after 4 weeks exposure of fungi (gm).

### ***Statistical Analysis***

ONE WAY ANOVA and Post-hoc test (Tukey's HSD) was done with the help of R studio to find the compare mean weight loss across the different temperature groups.Where the Hypothesis was: The means of the groups i.e., weight loss at different temperatures were unequal. The probability that the observed data would occur if the null hypothesis (no effect of temperature) were true. A p-value less than 0.05 indicate statistical significance. For the Post hoc tests: Tukey’s test was used to determine which groups differ from each other. In order to visualize the relationships between the experimental variables, a scatterplot matrix was constructed to explore the pairwise correlations among Temperature, Thickness, Weight, and Density. This matrix allowed us to observe the linear relationships and potential patterns between each pair of variables, providing an intuitive way to assess how these factors interact with each other in the context of the thermo-hygro-mechanical (THM) treatment on *Melia dubia* wood.

## **RESULTS AND DISCUSSION**

### ***Color variation after Thermo-Hygro-Mechanical modification***

Color changes in wood samples subjected to thermo-hydro-mechanical (THM) treatment were pronounced, with treated samples exhibiting a darker hue than control, which intensified with increasing temperatures **(Fig 1, Table 2).**

**Table 2:** Color variations among the wooden blocks

|  |  |  |  |
| --- | --- | --- | --- |
| **S,No** | **Temperature (°C)** | **Category** | **Observation for Blocks** |
| 1. | Control | No Change | All blocks show natural wood color, with no visible darkening or change; uniform in appearance. |
| 2. | 160 | Slight Change | Some blocks show minor darkening, while others appear closer to the control; slight unevenness in effect. |
| 3. | 170 | Moderate Change | Darkening is more pronounced across most blocks, but a few exhibit lighter tones, indicating minor variation. |
| 4. | 180 | Severe Change | Most blocks are significantly darker, but a few exhibit slightly lighter hues, showing variation in treatment intensity. |
| 5. | 190 | Severe Change | Nearly all blocks are uniformly dark, with a few showing extreme blackening, suggesting slight over-treatment or higher intensity in spots. |

This darkening is attributed to chemical transformations within the wood matrix under thermal processing conditions. Sundqvist and Moren (2002) found that extractives, along with hemicelluloses and lignin, are integral to color formation during hydrothermal treatment.

Similarly, Wiberg (1996) demonstrated in studies on Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*) that extractives migrate towards the wood surface during drying, imparting a reddish tone to the outer layers while yellow-colored compounds remain within. These observations indicate that the redistribution and transformation of extractives and other wood constituents under heat contribute significantly to the darker appearance observed in THM-treated wood.

      **Control 160 0C 1700C 180 0C 1900C**

**Fig 1:** Change in color of the test blocks after treatment

### ***Density***

There is an increase in the average wood density of the wooden samples from 0.542 g/cm³ at 160°C to 0.591 g/cm³ at 190°C that can be attributed to a series of complex physicochemical transformations induced by higher thermo-hydro-mechanical (THM) treatment temperatures. Elevated temperatures initiate molecular rearrangements within the wood matrix, primarily affecting hemicelluloses and partially lignin, which are more susceptible to thermal degradation. This molecular reconfiguration enhances the wood's rigidity, as heat and pressure facilitate the breakdown of hemicelluloses, releasing bound moisture and volatile organic compounds (Hill *et al.,* 2021). The moisture reduction leads to the collapse of cell lumens, thereby compressing the wood structure and decreasing porosity (Thybring and Fredriksson, 2021). Furthermore, the mechanical pressure applied during THM treatment plays a significant role in compacting the wood’s internal structure by realigning of cellulose microfibrils followed by densification of cell walls. *Pinus pinaster* also showed similar results to the present study where the increase in density of the samples was due to the reduced void volume of lumens due to the treatment (Esteves *et. al*., 2017). Similarly, on spruce species, the samples were densified and achieved an increment in density (Welzbacher *et al.,* 2004).

**Fig 2:** Average Density after THM treatment

### ***Decay test***

The durability of *Melia dubia* wood treated at different temperatures was tested against the decay fungus *Trametes versicolor* by measuring the mass loss percentage after a soil block bioassay. Results showed that as the treatment temperature increased, the wood’s resistance to decay improved: samples treated at 160°C, 170°C, 180°C, and 190°C had average weight losses of 1.26%, 1.25%, 0.79%, and 0.49%, respectively. In comparison, control samples showed a higher weight loss of 1.33%. Based on 4 weeks of observation maximum weight loss was observed in control samples and minimum in samples treated at 190°C. This suggests that wood treated at this temperature had the highest resistance to fungal decay. This improvement is likely due to changes in the wood structure at higher temperatures, which reduce the wood’s moisture absorption and make it less prone to the fungus to break down the wood.

**Fig 3:** Weight loss percentage of the THM-treated samples

The heat treatment improves the resistance of wood to biological decay and has been reported in studies. The densification and heat treatment carried out in *Pinus pinaster* increased durability against *Trametes versicolor* (Esteves *et. al*., 2017). In an experimental study combined hydro-thermo-mechanically modified poplar wood was tested for bio resistance. The treatment was carried out at 120°C, 150°C, and 180°C then was exposed against brown rot and soft rot. The wood possessed an increase in fungal resistance post-treatment (Bami and Mohebby, 2011). Biological resistance of mechanically densified pine sapwood after exposure against *T. versicolor* and *Coniophora puteana* for 12 weeks was found that the highest mass loss occurred in control samples compared to treated samples, highest decay resistance was obtained in samples treated at 212°C (Pelit and Yalem, 2017). Decay resistance against brown rot (*Gleophyllum trabeum*) and white rot (*Trametes versicolor*) study in hybrid poplar (*Populus deltoids* × *Populus trichocarpa*) and Douglas fir (*Pseudotsuga menziesii*) treated by THM showed that resistance of densified hybrid poplar wood was less than Douglas fir heartwood (Lesar *et. al.,* 2013).

### ***Statistical Analysis***

### ***One Way Anova:***

Table 3 indicates a statistically significant effect of treatment temperature on the weight loss of wood due to fungal decay. The overall F-value of 5.044 (p = 0.0174) reveales that temperature significantly influences the decay resistance of the wood, as reflected by the weight loss percentages. This means that the variation in weight loss between the temperature groups is not due to random chance but rather an effect of the temperature treatment.

**Table 3:** Results for the one- way Anova

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Source of Variation** | **Degrees of Freedom (Df)** | **Sum of Squares (Sum Sq)** | **Mean Square (Mean Sq)** | **F-Value** | **p-value (Pr(>F))** |
| *Temperature* | *4* | *1.6302* | *0.4076* | *5.044* | *0.0174 \** |
| |  | | --- | | *Residuals* |  |  | | --- | |  | | *10* | *0.8081* | *0.0808* |  |  |

### ***Post-hoc analysis(Tukey's HSD test)***

Table 4 presents the results of the Tukey’s Honest Significant Difference (HSD) post-hoc test for pairwise comparisons of weight loss percentages across different THM treatment temperatures. The table summarizes the differences in weight loss between each pair of treatment groups, including the adjusted p-values (p adj) and the corresponding confidence intervals for each comparison. The p-values are adjusted for multiple comparisons to control for Type I error.

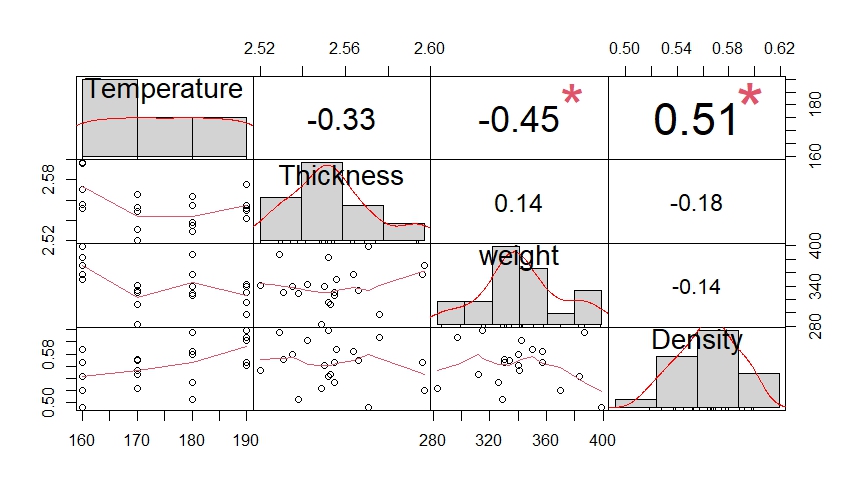
Significant differences are indicated by the adjusted p-values less than 0.05, with 190°C showing a significant improvement in durability compared to both 170°C (p = 0.0480) and the Control group (p = 0.0300), as highlighted in the table. These results suggest that higher temperature treatments, particularly at 190°C, significantly reduce weight loss and improve the decay resistance of *Melia dubia* wood. Comparisons between other temperatures, such as 160°C, 170°C, and 180°C, did not yield significant differences in durability, indicating that the temperature effect on decay resistance becomes pronounced only at higher treatment temperatures.

**Table 4:** Results of Turkey’s test

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Comparison** | **Difference (diff)** | **Lower Bound (lwr)** | **Upper Bound (upr)** | **Adjusted p-value (p adj)** | **Significance** |
| 170°C - 160°C | 0.0067 | -0.7572 | 0.7705 | 0.9999 | Not significant |
| 180°C - 160°C | -0.4667 | -1.2305 | 0.2972 | 0.3271 | Not significant |
| 190°C - 160°C | -0.7633 | -1.5272 | 0.0005 | 0.0502 | Marginally significant |
| Control - 160°C | 0.0767 | -0.6872 | 0.8405 | 0.9970 | Not significant |
| 180°C - 170°C | -0.4733 | -1.2372 | 0.2905 | 0.3152 | Not significant |
| 190°C - 170°C | -0.7700 | -1.5339 | -0.0061 | 0.0480 | Significant |
| Control- 170°C | 0.0700 | -0.6939 | 0.8339 | 0.9979 | Not significant |
| 190°C - 180°C | -0.2967 | -1.0605 | 0.4672 | 0.7094 | Not significant |
| Control- 180°C | 0.5433 | -0.2205 | 1.3072 | 0.2092 | Not significant |
| Control- 190°C | 0.8400 | 0.0761 | 1.6039 | 0.0300 | Significant |

### ***Correlation Analysis***

The correlation between temperature, thickness, weight, and density shows how the variables interact with each other. Temperature shows a relatively uniform distribution, while thickness shows a concentrated distribution with a slide skew to the right. The density curb indicates that most values are around the central range and have fewer observations at the extremes. For weight, the distribution appears relatively symmetrical with some variations. The moderate correlation between temperature and density could imply that temperature changes impact density, possibly due to expansion or contraction effects.



**Fig 4:** Scatterplot matrix of the temperature (oC), thickness (cm), weight (gm), and density (gm/cm3) after THM.

The inverse correlation between temperature and weight indicates that as temperature increases, weight tends to reduce due to factors like loss of mass or changes in measurement and different temperatures. The weight and thickness loss of the wood after heat treatment depends on wood species, heating medium, temperature, and treatment medium (Esteves *et al*., 2008).

## **CONCLUSION**

Through this study, it can be concluded that the durability as well as properties of THM modified wood were increased as compared to control samples. The highest decay resistance and improved density were observed in samples treated at 190°C. It was also observed that density of the wood increased and mass loss % reduced with an increase in temperature. The color parameters also showed a pronounced effect in the THM treatment. The darkening of wood kept on increasing with an increase in temperature due to condensation of lignin and pyrolysis of major chemical constituents of wood (Cellulose, Hemicellulose, and Lignin). The research experiment suggests that the THM treatment in wood has the potential to improve the properties viz. color, density and durability. Since the THM process is an eco-friendly approach and can improve the natural decay resistance, more studies can be conducted to further explore and improve the properties of wood. THM treatment in *Melia dubia* wood is an approach which are intended to be used in various applications, its durability is of great importance. Such THM-modified wood can become a suitable substitute that can maximize wood potential. Further, there is more scope for studies that should focus on treatments that could enhance the mechanical and other useful propertieson a pilot basis in-ground application.

### ***Acknowledgment***

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No specific permits were required for the described field studies because no human or animal subjects

were involved in this research.

### ***Originality and plagiarism***

This is original research work and any work and/or words of others, has been appropriately cited.

### ***Consent for publication***

All the authors agreed to publish the content.

### ***Competing interests***

There were no conflict of interest in the publication of this content

### ***Data availability***

All the data of this manuscript are included in the MS. No separate external data source is required.

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