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Optimizing Heat Treatment Conditions for *Cinnamomum cassia* Wood Modified with Natural Oleoresin and Waste Cooking Oil

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Abstract: This study examined how heat-treatment conditions influence the equilibrium moisture content, water-repellent efficiency, anti-swelling efficiency, Brinell hardness, modulus of rupture, and modulus of elasticity of *Cinnamomum cassia* wood treated in a mixed oil medium composed of natural oleoresin and waste cooking oil. The oleoresin, a non-timber forest product obtained from Dipterocarp species, was combined with recycled cooking oil collected from an oil recovery facility. Heat treatment was conducted using an oleoresin–waste cooking oil mixture at a mass ratio of 20:80, with treatment temperatures between 130 and 170 °C and durations ranging from 90 to 180 min. Response surface methodology was applied to model the relationships between process variables and wood properties, resulting in four linear and two quadratic models with high adjusted coefficients of determination, indicating good model reliability. The findings revealed marked enhancements in the dimensional stability of *Cinnamomum cassia* wood, while treatment parameters significantly affected its mechanical performance, allowing optimal heat-treatment conditions using the oleoresin–waste cooking oil system to be determined.

Keywords: *Cinnamomum cassia* wood, Heat treatment, Oleoresin, Response surface methodology, Waste cooking oil

I. Introduction

Cinnamomum cassia Blume wood is widely planted in central and north-central Vietnam, primarily for the production of cinnamon bark and cinnamon essential oil. Despite its abundance, the utilization of cinnamon wood as a structural or value-added material remains limited. Similar to many fast-growing or underutilized wood species, *C. cassia* wood is expected to exhibit certain inherent drawbacks, including dimensional instability, moderate mechanical performance, and sensitivity to moisture variations, which restrict its application in demanding service environments [1].

Thermal modification has been widely recognized as an effective and environmentally friendly wood modification technique, as it alters the chemical structure of wood components to reduce hygroscopicity, enhance dimensional stability, improve thermal performance, and increase resistance to biological degradation, thereby extending wood service life without the use of toxic chemical preservatives [2].

Recently, oil-based heat-transfer media have been increasingly adopted in thermal modification due to their ability to enhance heat uniformity, improve wood properties, and reduce environmental impacts compared to conventional chemical treatments. Haseli et al. reported that oil heat treatment of poplar wood at 180–200 °C enhanced dimensional stability and weathering resistance after accelerated exposure, accompanied by increased surface wettability and marked color changes, although reductions in water absorption were not statistically significant and lignin degradation was not effectively prevented [3]. Kapçak et al. showed that waste olive oil heat treatment of oriental beech at 200–230 °C increased oven-dry density and reduced water absorption, while compression strength parallel to the grain initially increased and then declined with increasing temperature and treatment duration [4]. Altaner et al. found that oil heat-treated Eucalyptus nitens exhibited high resistance to brown- and white-rot fungi and darker coloration, despite reductions in stiffness and strength, while still retaining structural-grade performance [5]. Tang and Nguyen demonstrated that heat treatment of rubberwood using blends of natural oleoresin and waste cooking oil at 130–180 °C significantly improved dimensional stability, with treatment temperature, duration, and oleoresin ratio exerting notable effects on moisture-related and strength properties [6].

Natural oleoresins derived from Dipterocarpus species in Southeast Asia, including Vietnam, have been traditionally used in coatings, varnishes, and protective materials due to their hydrophobic characteristics, and have recently attracted attention as eco-friendly agents for wood and lignocellulosic material modification aimed at improving physical performance and durability [7]. In this study, heat treatment using a mixture of natural oleoresin and reused cooking oil was applied to *C. cassia* wood to improve its physical and mechanical properties. The treatment parameters were optimized with respect to equilibrium moisture content (EMC), water-repellent efficiency (WRE), anti-swelling efficiency (ASE), Brinell hardness (BH), modulus of rupture (MOR), and modulus of elasticity (MOE) using response surface methodology (RSM), aiming to enhance the dimensional stability and mechanical performance of cinnamon wood for value-added applications.

II. Materials and methods

2.1 *Cinnamomum cassia* wood samples

C. cassia wood was obtained from trees harvested in Lao Cai Province, Vietnam. The logs were sawn into samples with nominal dimensions of 25 mm (thickness) × 65 mm (width) × 500 mm (length). All samples were carefully labeled with identification codes corresponding to their respective experimental batches. Prior to treatment, the specimens were oven-dried at 65°C for 10 days to achieve a target moisture content in the range of 10–12%. After drying, the samples were divided into eleven treatment groups and one untreated control group, with five replicates per group, for subsequent thermal modification experiments.

2.2 Oleoresin and used cooking oil

The oil mixture used in the heat treatment process consisted of natural oleoresin and recycled vegetable oil, blended at a mass ratio of 20:80. The natural oleoresin, with a viscosity of 190 cP, was extracted from *Dipterocarpus alatus* Roxb. and sourced from a natural oleoresin harvesting facility in Quang Nam Province, Vietnam. The recycled vegetable oil, derived from soybean oil, was supplied by an oil recycling company in Ho Chi Minh City, Vietnam, and exhibited a viscosity of approximately 30 cP at room temperature.

2.3 Response surface methodology and central composite design

In this study, response surface methodology (RSM) combined with a central composite design (CCD) was employed to evaluate the effects of treatment temperature (°C) and treatment duration (min) on the physical and mechanical properties of *C. cassia* wood samples. The response variables analyzed included EMC, WRE, ASE, BH, MOR, and MOE.

The CCD consisted of an 11-run experimental design, including factorial and center points, and was generated using Minitab software (version 21.2). The investigated ranges of the independent variables were 130–170°C for treatment temperature and 90–180 min for treatment duration. Each factor was coded at multiple levels to establish predictive models describing the relationships between treatment conditions and the resulting wood properties. The experimental design matrix and factor levels are presented in Table 1.

Table 1: Tabulation of the coded and actual values for three independent variables

Variable	Coded and actual values				
	–α	–1	0	1	α
Temperature (°C)	122	130	150	170	178
Duration (min)	71	90	135	180	199

2.4 Evaluation of physical and mechanical properties

To evaluate EMC, WRE, and ASE, test specimens were prepared from both treated and untreated *C. cassia* wood samples with dimensions of 20 × 20 × 23 mm in the radial, tangential, and longitudinal directions, respectively. The determination of WRE and ASE was conducted in accordance with the Vietnamese National Standard TCVN 13352:2021 [8].

For EMC determination, the specimens were conditioned in a Memmert HPP260eco climatic chamber at 20°C and 65% relative humidity until constant mass was achieved, after which the mass at equilibrium moisture content was recorded. The specimens were subsequently oven-dried in a Memmert UN260 drying oven at 103 ± 2°C until reaching oven-dry condition, and the corresponding dry mass was measured.

The BH was determined according to the EN 1534:2020 standard, using specimens with dimensions of 20 × 50 × 50 mm [9].

The MOR and MOE were determined in accordance with ASTM D143-23 using specimens with dimensions of 20 × 20 × 330 mm [10].

For each property, including EMC, WRE, ASE, BH, MOR, and MOE, five replicate specimens were tested for each treatment condition. The mean values and standard deviations were calculated to characterize the physical and mechanical properties of the wood.

III. Results and discussion

The physical and mechanical properties, including EMC, WRE, ASE, BH, MOR, and MOE, of treated and untreated *C. cassia* wood samples are presented in Table 2.

Table 2: EMC, WRE, ASE, BH, MOR, and MOE of the treated and untreated *C. cassia* wood samples

Run	Temperature (°C)	Duration (min)	EMC (%)	WRE (%)	ASE (%)	BH (N/mm^2)	MOR (MPa)	MOE (GPa)
1	130	90	9.24 (0.13)	28.6 (2.28)	9.58 (1.24)	14 (1.3)	103.75 (4.97)	9.75 (0.22)
2	170	90	8.53 (0.15)	33.21 (4.67)	13.4 (1.06)	14.18 (1.31)	81.37 (0.49)	7.82 (0.7)
3	130	180	8.73 (0.05)	38.7 (1.84)	16.76 (1.28)	14.97 (1.35)	94.04 (0.92)	9.19 (0.54)
4	170	180	8.48 (0.07)	48.66 (1.41)	26.9 (0.99)	18.32 (2.31)	80.64 (2.87)	7.74 (0.39)
5	122	135	9.13 (0.04)	36.29 (0.65)	16.32 (0.59)	14.3 (1.81)	104.53 (1.56)	9.77 (0.22)
6	178	135	8.11 (0.19)	46.72 (0.26)	24.12 (1.04)	17.1 (1.28)	78.09 (2.19)	7.56 (0.56)
7	150	71	8.83 (0.16)	22.49 (0.24)	8.83 (0.21)	13.89 (0.91)	102.26 (0.76)	9.59 (0.49)
8	150	199	8.51 (0.27)	47.31 (3.64)	26.18 (0.71)	17.57 (1)	83.44 (2.18)	8.21 (0.28)
9	150	135	7.78 (0.27)	45.5 (1.86)	20.91 (0.57)	16.25 (1.79)	90.19 (4.49)	9.02 (0.74)
10	150	135	7.81 (0.25)	46.03 (2.15)	20.06 (0.68)	15.86 (1.12)	88.46 (2.35)	8.68 (0.65)
11	150	135	7.76 (0.28)	43.21 (1.35)	19.86 (0.48)	15.24 (0.98)	89.58 (3.59)	8.82 (0.35)
Control	-	-	12.05 (0.11)	-	-	13.33 (0.98)	104.57 (2.51)	9.78 (0.48)

Values in parentheses represent the standard deviations based on five replicates.

3.1 Effect of treatment parameters on EMC, WRE, and ASE

The relative contributions of the main variables and their interactions to equilibrium moisture content (EMC) were evaluated using a Pareto chart of standardized effects (Figure 1). In this chart, the vertical reference line denotes the statistical significance limit corresponding to a 95% confidence level. Among the investigated parameters, treatment temperature and duration were found to be the dominant factors affecting EMC. Increasing both temperature and treatment time generally resulted in a reduction in the EMC of *C. cassia* wood. The minimum EMC value of 7.76% was observed at a treatment condition of 150 °C for 135 min (Table 2), after which a slight increase in EMC occurred (Figure 2). Overall, this condition achieved a 35.6% decrease in EMC relative to the untreated control.

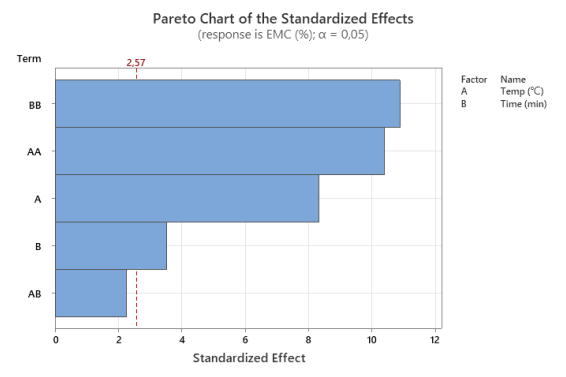

Figure 1: Pareto chart illustrating the relative influence of each treatment parameter on EMC

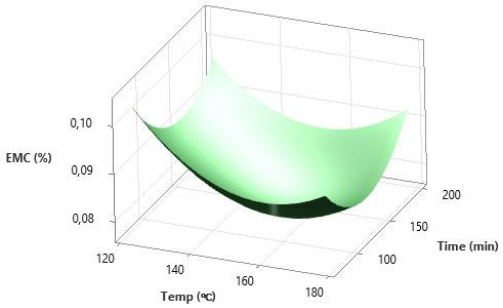

Figure 2: Three-dimensional plot depicting the relationship between EMC and the treatment parameters

The observed decrease in EMC can be explained by a series of structural changes induced by heat treatment in the wood matrix. These changes involve the breakdown of moisture-sensitive hydroxyl groups, a reduction in the ability of residual hydroxyl sites to bind water due to increased cellulose crystallinity, and the development of cross-linked networks resulting from condensation reactions in the lignin component [11–14].

In a similar manner, the Pareto chart analysis (Figure 3) indicated that both treatment temperature and duration had statistically significant effects on water-repellent efficiency (WRE) and anti-swelling efficiency (ASE), with treatment duration exerting the strongest influence. Increasing levels of these parameters led to higher WRE and ASE values, as illustrated in Figure 4. The maximum performance was achieved at a treatment condition of 170 °C for 180 min (Table 2). These enhancements are mainly associated with the decreased hygroscopic nature of the wood and the effective penetration of oleoresin into internal wood voids during heat treatment, which together limited water uptake and reduced thickness swelling [15,16].

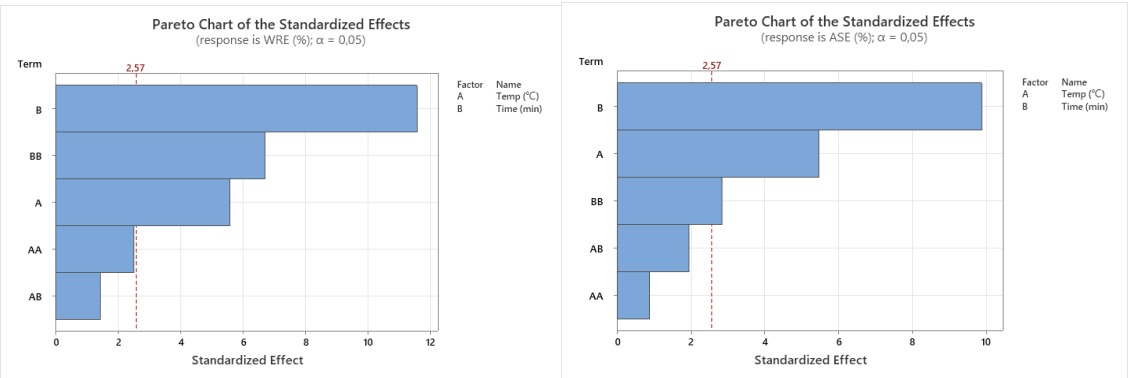

Figure 3: Pareto chart illustrating the relative influence of each treatment parameter on WRE and ASE

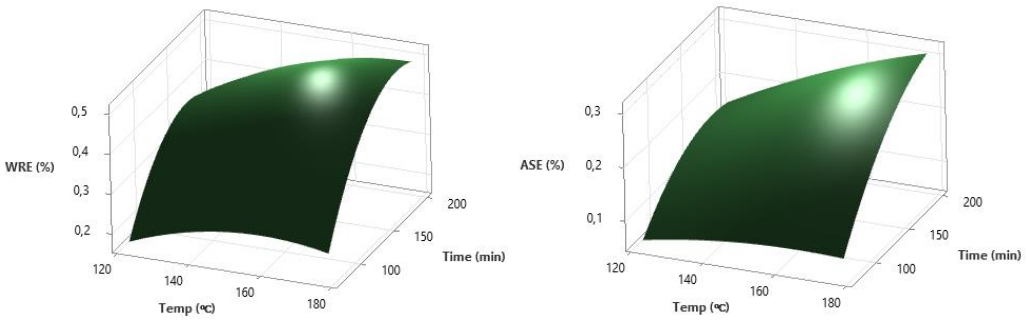

Figure 4: Three-dimensional plot depicting the relationship between WRE, ASE and the treatment parameters

Across all the treatment conditions investigated, notable improvements were observed in the physical performance of *C. cassia* wood samples, with dimensional stability showing the most pronounced enhancement. These outcomes are consistent with earlier research by Lee et al. and Mandraveli et al., who demonstrated that heat treatment using vegetable oils leads to significant gains in wood dimensional stability [15,16]. Comparable improvements were also reported by Çiftçi and Altay for oriental beech wood subjected to oil-based heat treatment [17]. In addition, the present results agree with the findings of Tang and Nguyen, who documented similar improvements in bamboo treated with oleoresin under elevated temperatures [18].

3.2 Effect of natural oleoresin heat treatment on BH

The Pareto chart of standardized effects (Figure 5) showed that both the linear terms and the interaction between treatment time and temperature had statistically significant effects on BH. Among the examined parameters, treatment duration exerted the strongest influence, whereas treatment temperature contributed to a lesser but still positive extent. In general, longer treatment times and higher temperatures resulted in increased BH values, as illustrated in Figure 6.

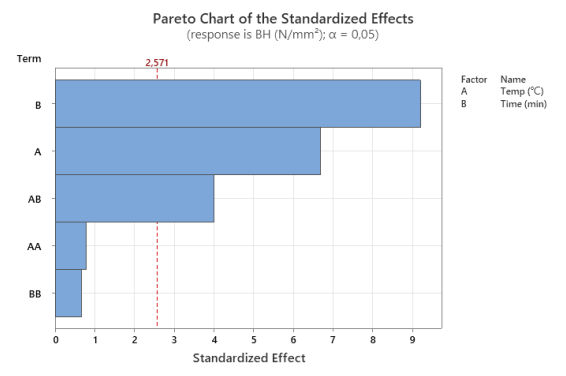

Figure 5: Pareto chart illustrating the relative influence of each treatment parameter on BH

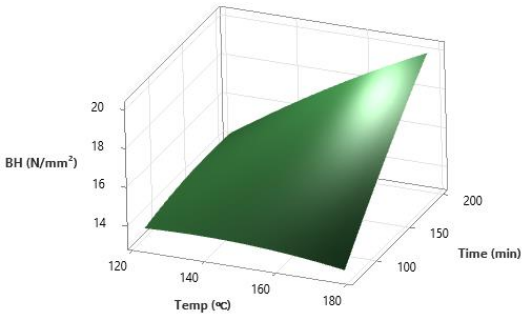

Figure 6: Three-dimensional plot depicting the relationship between BH and the treatment parameters

The maximum BH was obtained at a treatment condition of 170 °C for 180 min, corresponding to a 37.43% improvement relative to the untreated control (Table 2). These findings are in agreement with those of Mandraveli et al., who reported enhanced hardness in wood subjected to vegetable oil-based thermal treatments [16]. The observed increase in hardness may be associated with a rise in wood density, potentially caused by enhanced compaction or a reduction in internal porosity following oleoresin-assisted heat treatment [19].

3.3 Effect of natural oleoresin heat treatment on MOR and MOE

Analysis of the Pareto chart of standardized effects (Figure 7) showed that both treatment temperature and duration, as well as their interaction, had statistically significant influences on the modulus of rupture (MOR) and modulus of elasticity (MOE) of heat-treated *C. cassia* wood. In general, increases in temperature and treatment time led to reductions in both MOR and MOE, with temperature identified as the dominant factor affecting these mechanical properties (Figures 7 and 8).

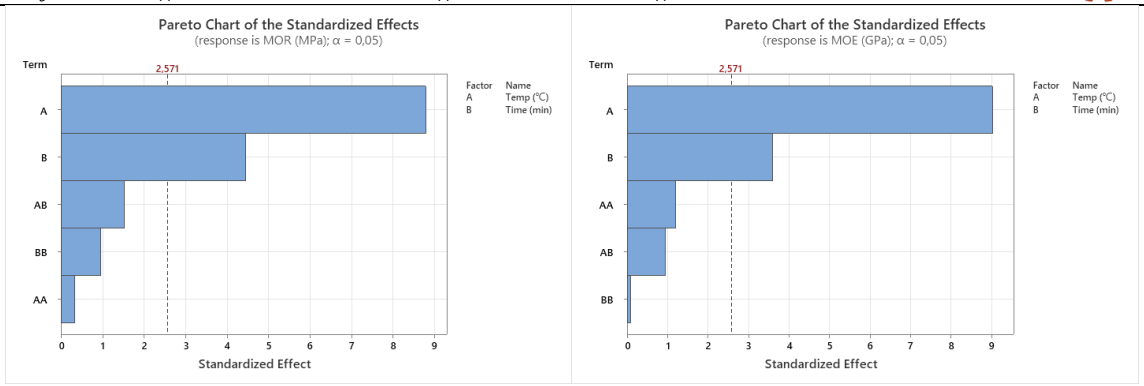

Figure 7: Pareto chart illustrating the relative influence of each treatment parameter on MOR and MOE

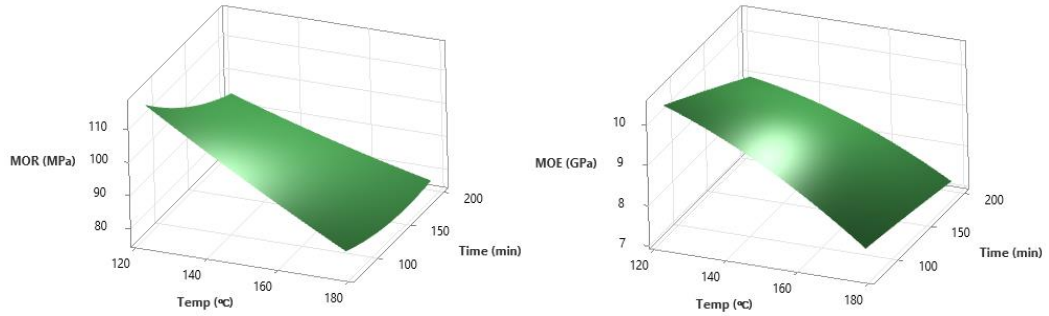

Figure 8: Three-dimensional plot depicting the relationship between MOR, MOE and the treatment parameters

As summarized in Table 2, most treatment conditions resulted in decreased MOR and MOE values compared with the untreated control, and the extent of reduction became more evident at higher temperatures and longer exposure times. These observations are consistent with earlier reports by Lee et al. and Mandraveli et al., who documented declines in bending strength and elastic modulus in wood subjected to oil-based thermal treatments [15,16]. Comparable behavior was also reported by Tang and Nguyen for bamboo treated with oleoresin at elevated temperatures [18].

Previous studies have attributed the reduction in MOR and MOE primarily to the thermal degradation of hemicellulose during extended heat exposure, which weakens the bonding framework within the wood cell wall [13]. Lee et al. further demonstrated that oil heat treatment induces chemical alterations in all major wood polymers, including hemicellulose, cellulose, and lignin [15]. These constituents contribute differently to mechanical performance: hemicellulose acts as a bonding matrix, cellulose is responsible for tensile strength, and lignin supports compressive resistance. The deterioration of hemicellulose combined with disruptions in cellulose structure ultimately compromises the integrity of the wood matrix, leading to a measurable decline in bending strength and modulus of elasticity.

3.4 Regression analysis and model adequacy

Model performance was assessed using the coefficient of determination (R^2), which reflects the proportion of experimental variance accounted for by the fitted models. High R^2 values were obtained for all response variables, reaching 98.13% for EMC, 97.70% for WRE, 96.53% for ASE, 96.69% for BH, 95.25% for MOR, and 95.08% for MOE, demonstrating excellent agreement between predicted and measured data. These results indicate that more than 95% of the total variability was captured by the models, with less than 5% attributed to unexplained error.

The adequacy of the models was further verified through adjusted R^2 values, which account for the number of predictors included in the regression. The adjusted coefficients were 96.25% for EMC, 95.39% for WRE, 93.05% for ASE, 93.37% for BH, 90.50% for MOR, and 90.16% for MOE. The close correspondence between R^2 and adjusted R^2 values confirms the stability of the models and supports their applicability under practical processing conditions.

After model development, the assumptions required for analysis of variance (ANOVA) were examined. Residual normality was evaluated using the Ryan–Joiner test, which is well suited for datasets with fewer than 50 observations. In this test, p-values greater than 0.05 indicate no significant departure from normality. In the present study, the Ryan–Joiner test produced non-significant results ($p > 0.1$), and the residuals were closely

aligned along a straight line in the normal probability plot, confirming that the residuals followed a normal distribution and that the model predictions were statistically reliable (Figure 9).

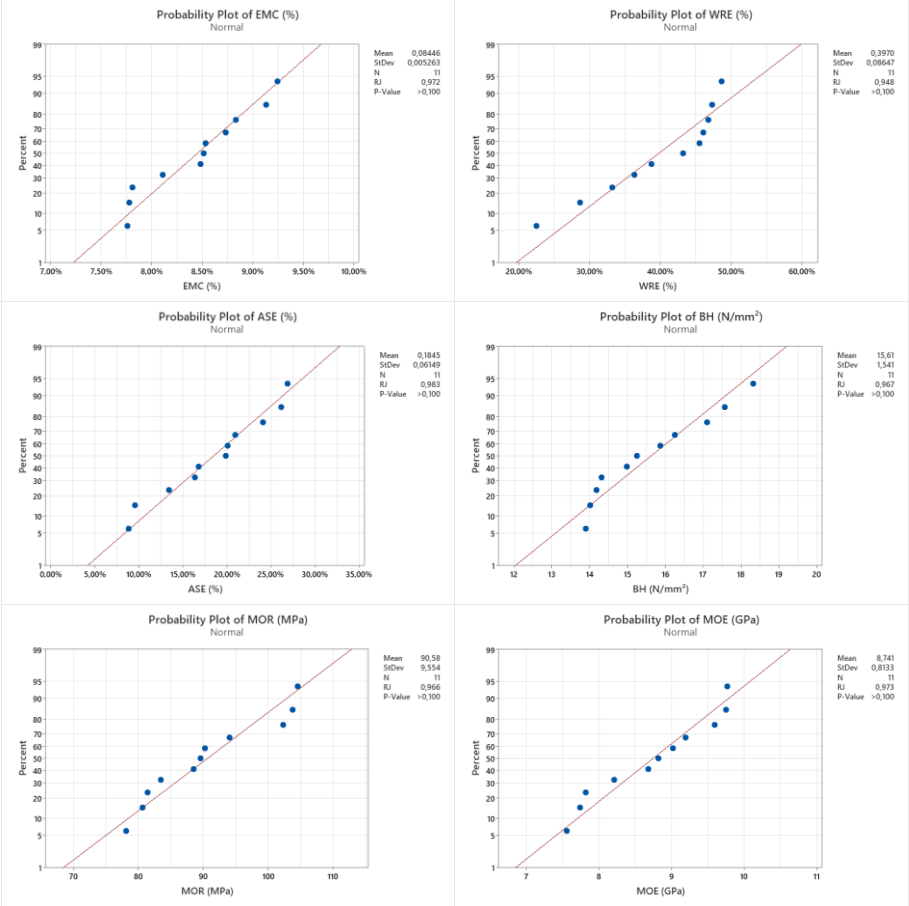

Figure 9: Ryan-Joiner normality test results for EMC, WRE, ASE, BH, MOR, and MOE

The final predictive equations describing the responses of heat-treated *C. cassia* wood in the oleoresin–waste cooking oil system, including only statistically significant terms, are provided in Equation (1)–(6).

EMC (%) =0,4001–0,003541 Temp–0,000644 Time + 0,000011 Temp² + 0,000002 Time² (1)

WRE (%) = –0,488 + 0,001842 Temp + 0,00783 Time – 0,000023 Time² (2)

ASE (%) = –0,2203 + 0,001571 Temp + 0,001253 Time (3)

BH (N/mm²) = 22,53 – 0,0718 Temp – 0,1035 Time + 0,000881 Temp×Time (4)

MOR (MPa) = 173,39 – 0,4596 Temp – 0,1028 Time (5)

MOE (GPa) = 15,842 – 0,04087 Temp – 0,00719 Time (6)

3.5 Optimal treatment conditions

The optimal processing conditions were determined based on a composite desirability value of 0.6441. The identified optimal parameters consisted of a treatment temperature of 147 °C and a treatment duration of 156 min. Under these conditions, the model predicted an equilibrium moisture content of 7.87%, a water-repellent efficiency of 46.75%, an anti-swelling efficiency of 22.02%, a Brinell hardness of 16.2 N/mm², a modulus of rupture of 88.53 MPa, and a modulus of elasticity of 8.78 GPa.

IV. Conclusion

This study demonstrates that natural oleoresin combined with waste cooking oil can serve as an effective heat-treatment medium to enhance the physical and mechanical properties of *C. cassia* wood. Using response surface methodology, the optimal conditions were identified as a treatment temperature of 147 °C and a duration of 156 min. Under these conditions, the predicted values were 7.87% for equilibrium moisture content, 46.75% for water-repellent efficiency, 22.02% for anti-swelling efficiency, 16.2 N/mm² for Brinell hardness, 88.53 MPa for modulus of rupture, and 8.78 GPa for modulus of elasticity. These improvements suggest that the treated

wood is suitable for value-added applications such as flooring, exterior cladding, and outdoor furniture, where moisture resistance and dimensional stability are essential. Future work should focus on long-term weathering performance and the scalability and economic feasibility of this treatment for industrial applications.

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