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ARTICLE

Enhancing the Performance and Durability of Oil Palm Trunk Particleboards through Chemical Pre-Treatment and Bio-Based Antifungal Modification

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ABSTRACT: This study examined the impact of various pre-treatment techniques on the physical and mechanical characteristics of particleboards derived from oil palm trunks (OPT). Thermal and chemical pre-treatments of the fibers, including hot water, sodium hydroxide (NaOH), and acetic acid, were applied prior to board production. In addition, antifungal agents were incorporated as supplementary additives during the manufacturing process at varying percentages to evaluate their effect on panel performance. Morphology of the treated OPT fibers was examined, and panel properties such as thermal behavior, bending strength, bonding strength, and dimensional stability were evaluated. Statistically significant improvements ($p < 0.05$) were observed across key performance indicators. The highest modulus of elasticity (MOE), 3247.2 N/mm^2, was recorded in boards pre-treated with 1.5% NaOH and wood vinegar (WV), while the highest modulus of rupture (MOR), 29.9 N/mm^2, was observed in hot water pre-treated boards with 1.0% WV. Internal bonding (IB) was significantly affected by treatment type ($p < 0.001$), with hot water pre-treatment and 1.5% WV yielding the highest IB value of 2.9 N/mm^2. Statistical analysis was significantly influenced by the pre-treatment and antifungal concentration. Tukey's Honestly Significant Difference (HSD) test revealed that hot water and acetic acid pre-treatments, particularly at moderate WV concentrations, consistently outperformed other treatments in mechanical strength and dimensional stability. Findings affirm that optimizing pre-treatment methods, especially using eco-friendly agents like WV, can significantly enhance the performance of OPT-based particleboards, supporting their application as sustainable, high-performance alternatives to conventional wood composites.

KEYWORDS: Oil palm trunk; particleboard; pre-treatment; antifungal agents; mechanical properties

1 Introduction

Particleboards are composite materials manufactured from wood particles bonded with synthetic adhesives and hot-compressed into panels. They are widely used in furniture and construction industries due to their cost-effectiveness and versatility compared to solid wood or plywood [1,2]. Enhancing the properties of particleboards is crucial in broadening their applicability and ensuring long-term performance. Improving mechanical attributes such as strength and bonding enhances the boards' ability to withstand higher loads and mechanical stress, thereby increasing their durability and reliability across various applications [3]. In addition, improving the dimensional stability of particleboards, particularly under humid conditions, is essential for preserving the structural integrity of furniture and construction components over time [4].

There has been increasing interest in the utilization of agricultural by-products, such as oil palm biomass, to produce particleboard. This approach not only offers a sustainable alternative to conventional wood-based materials but also contributes to improved biomass waste management. The incorporation of agricultural residues and other lignocellulosic materials particularly oil palm trunks (OPT), into particleboard manufacturing enhances resource efficiency and promotes environmental sustainability [5]. This strategy reduces dependency on traditional timber sources, mitigates waste generation, and facilitates the valorization of agricultural by-products. Furthermore, the development of high-performance particleboards with enhanced properties could potentially compete with other engineered wood products, including plywood and medium-density fiberboard (MDF), thereby opening new market opportunities and applications [6].

Numerous pre-treatment methods were studied to enhance the physical and mechanical properties of particleboards made from lignocellulosic materials, which inherently possess disadvantages such as high hydrophilicity, poor dimensional stability, and limited durability under humid conditions. These pre-treatments include thermal, chemical, and hybrid techniques, each aiming to improve attributes such as strength, dimensional stability, and moisture resistance [7,8]. Hot water soaking, for instance, effectively removed extractives and reduced hemicellulose content, leading to improved bonding quality and enhancements in modulus of rupture (MOR) and modulus of elasticity (MOE). Steam exposure prior to pressing further improved internal bonding (IB) and reduced thickness swelling, contributing to greater dimensional stability [9]. Chemical pre-treatments, particularly alkaline treatments using sodium hydroxide, improved particle surface roughness, thereby enhancing resin adhesion and mechanical performance through partial degradation of lignin and hemicellulose [10]. Acidic treatments, such as acetic acid, modified the particle surface chemistry to improve adhesion and mechanical properties. However, overly high concentrations can compromise cellulose integrity.

Synergistic effects have been reported when combining thermal and chemical treatments. For example, sequential hot water and alkaline treatments can significantly enhance both mechanical strength and dimensional stability [9,11]. Moreover, pre-treatment techniques frequently enhance mechanical qualities, including MOR, MOE, and IB strength. Furthermore, heat and chemical treatments improved the dimensional stability of particleboards by diminishing thickness swelling (TS) and water absorption (WA) properties [12,13]. Biological treatment methods using anti-fungal agents during panel production to inhibit microbial degradation, enhance durability of the particleboards, and extend their service life under humid or biologically active environments have been explored [14]. These anti-fungal treatments were particularly beneficial when using high-sugar or high-starch lignocellulosic materials, such as OPT, which are more susceptible to fungal attack. Incorporating anti-fungal agents can also contribute to maintaining the structural integrity and mechanical performance of particleboards during long-term exposure to biological stressors.

Furthermore, recent studies have highlighted the potential of bio-based and natural additives, such as tannins, starches, and organic acids, to improve bonding performance, reduce formaldehyde emissions, and enhance the eco-friendly profile of wood composites. For instance, Oktay et al. [15] successfully developed a cornstarch Mimosa tannin sugar adhesive system that demonstrated strong bonding efficiency and durability comparable to conventional urea–formaldehyde resins [15]. More recently, Oktay et al. [16] reported on tannin-based wood panel adhesives, emphasizing the ability of natural polyphenols to form strong covalent and hydrogen-bonded networks with lignocellulosic substrates, thereby improving bonding performance and sustainability Oktay et al. [17]. In addition, Madsen et al. [18] introduced novel urea glyoxal and urea melamine glyoxal adhesive systems hardened with acid ionic liquids, offering an environmentally friendly alternative to formaldehyde-based resins for particleboard production [18]. Similarly, Oktay et al. [16,17] demonstrated that chemical modification of starch can yield efficient bio-based wood adhesives with improved cross-linking and adhesion properties. These findings collectively support the feasibility of employing bio-derived compounds, such as wood vinegar (WV), as functional additives capable of modifying resin–fiber interactions, enhancing adhesion, and improving the physical and mechanical performance of OPT particleboards.

While prior research has largely focused on individual thermal or chemical treatments, limited attention has been given to their combined effects, especially when applied to OPT particles. Given its abundant availability in Malaysia, OPT presents an untapped and sustainable resource for particleboard production. Thus, this study aimed to evaluate the synergistic effects of combining pre-treatment methods and antifungal agents on the thermal, physical, and mechanical properties of particleboards manufactured from OPT, based on the observed gaps. Additionally, viability of OPT as sustainable raw material was assessed and development of standardized pre-treatment protocols to ensure consistent and comparable research outcomes was made.

2 Methodology

2.1 Material Collection and Preparation

OPT was obtained from Stesen Penyelidikan Malaysian Palm Oil Board (MPOB) Hulu Paka, Malaysia and was prepared following the study by Ibrahim et al. [19]. The palms used in this study were 25–27 years old at the time of felling. A total of three (n = 3) trunks were collected and measured prior to processing, with trunk heights ranging from 8 to 10 m. The OPT samples were derived from replanting operations and were not rejuvenated, as the material was processed within 48 h after felling to minimize biological degradation. Although the trunk diameter was not measured, all samples were selected from trees of similar age and size class to ensure uniformity of raw material characteristics. The outer bark was retained, and each trunk was divided into three equal sections (bottom, middle, and upper) to obtain representative sampling across the trunk height.

The biomass was processed into chips (Fig. 1) using a laboratory-scale Maier chipper, and the resulting chips were oven-dried at 100°C until the moisture content reached approximately 10% (dry basis). The dried chips were then hammer-milled using a laboratory hammer mill operating at 3600 rpm, followed by vibratory screening to segregate particle size fractions. Particles passing through a 6.0 mm sieve were collected and used for subsequent experimental analyses. The outer bark was manually removed before processing to eliminate surface contaminants and fibrous impurities. Each trunk was sectioned into three equal parts, namely bottom (0–1 m), middle (1–2 m), and upper (>2 m) to ensure representative sampling across the trunk height. The entire cross-sectional area of each section (including both outer and inner regions) was used for subsequent chipping.

Figure 1: OPT log processed into chip

2.2 Pre-Treatment

The particles were separately soaked in hot water, 0.4% sodium hydroxide (NaOH), and 0.4% acetic acid (CH_3COOH) solutions at room temperature for 24 h. After the soaking process, the particles were filtered and subsequently washed three times with hot distilled water to ensure thorough removal of residual chemicals and soluble impurities. Each washing step involved immersing the particles in an excess of distilled water, gently stirring for approximately 10 min, and decanting the supernatant before repeating the process. The washed particles were then oven-dried at 100°C until they reached a moisture content of 4%–5% (dry basis) prior to further processing. The moisture content (MC) was determined using a portable moisture content meter (Sartorius AG Gottingen MA45-000230V1) which provides a rapid and accurate reading. Notably, visible color variations among the pre-treated OPT particles brown (hot water), light brown (acetic acid), and blackish-brown (NaOH) correspond to the extent of chemical modification, primarily due to partial removal or condensation of lignin and extractives during the treatments as shown in Fig. 2.

Figure 2: OPT particles of different pre-treatments (**a**) hot water, (**b**) acetic acid and (**c**) NaOH

2.3 Particleboard Production

Particleboards were fabricated from OPT particles following the methodology outlined by Ibrahim et al. [20]. The prepared particles, as described in Section 2.1, were blended with commercial urea-formaldehyde (UF) resin containing 65% solid, at 10% resin loading based on oven-dry particle weight. The resin was uniformly applied using a rotating drum blender to ensure even distribution, resulting in the formation of mats composed of resinated particles. This approach allowed homogeneous coating of the particles and consistent distribution of resin throughout the furnish. During the blending process, two types of antifungal agents, namely commercial antifungal and WV, were incorporated as supplementary additives at 1.0%, 1.3%, and 1.5% (based on the oven-dry weight of particles). Both antifungal additives were premixed with the UF resin before blending to ensure uniform dispersion, and the resin–additive mixture was then sprayed onto the OPT particles in a rotating drum blender. The commercial antifungal was supplied by a local wood-based panel manufacturer; that are commonly used in industrial panel production. While, the WV was produced as a by-product during the pyrolysis of palm kernel shell and purified through natural settling and filtration prior to use. These mats were initially subjected to cold pressing at 50 kg/cm^2 for 3 min, followed by hot pressing at 160 kg/cm^2 and 175°C for 5 min. The targeted board density was 700 kg/m^3, with dimensions of 300 mm × 300 mm × 12 mm. After pressing, the boards were conditioned in a controlled environment at 20°C ± 2°C and 65% relative humidity until equilibrium moisture content (EMC) was achieved.

2.4 Particleboard Properties Evaluation

The mechanical, physical, and thermal properties of the particleboards were evaluated, in accordance with JIS A 5908:2003 and ANSI A208.1:1999 standards which include thickness swelling (TS), water absorption (WA), IB, MOR and MOE, following the procedures described by Fiorelli et al. [21]. Each test was conducted on three replicates (n = 3), and the mean values with standard deviations were reported. Samples for TS, WA, and IB tests were prepared in dimensions of 5 mm × 5 mm, while specimens for

MOR and MOE testing measured 300 mm × 5 mm. TS and WA were assessed using 24-h water immersion method, and mechanical properties were measured using a Zwick Universal Testing Machine (UTM) with a 10,000 N load cell. The results of these analyses provided comprehensive insights into the effects of the different pre-treatment and antifungal modifications on the structural integrity and performance of the OPT particleboards.

2.5 Characterization

The prepared OPT particles and fabricated particleboards were characterized using several analytical and testing methods to evaluate their structural, thermal, and mechanical performance. Stability and degradation behaviour of untreated and chemically pre-treated OPT fibers were analyzed using a thermogravimetric analysis (TGA) using a PerkinElmer Pyris 1 analyzer at 0 to 900°C with 20°C/min heating rate to evaluate the thermal stability and decomposition characteristics of the pretreated particleboards. The surface morphology of the untreated and pre-treated OPT fibers was examined using a Scanning Electron Microscope (SEM) (Hitachi S-3400N) to observe structural changes induced by different pre-treatment methods. These observations provide information on the effectiveness of each treatment in enhancing fiber roughness, porosity, and potential for improved resin adhesion.

2.6 Statistical Analysis

The data analysis was performed for the physical and mechanical properties of the oil palm particleboards. It was conducted using single-factor analysis of variance (ANOVA) to assess the effects of pre-treatment and WV concentration on MOE, MOR, IB, TS and WA. Subsequently, a comparison between the averages was performed using the Tukey's honestly significant difference (HSD), adopting a significance level of 5%.

3 Results and Discussion

3.1 Microscopic Characterization of OPT Particles

SEM analysis of OPT fibers before and after various pre-treatment methods revealed distinct structural modifications that influence their suitability for particleboard production (Fig. 3a–d). The untreated OPT fiber (Fig. 3a) had a smooth, compact surface with prominent vascular bundles, indicative of natural extractives, lignin, and silica bodies that can hinder resin penetration and adhesion [22]. Following hot water treatment (Fig. 3b), the fiber surface showed increased roughness, mild fibrillation, and formation of small pores. These changes suggested partial removal of extractives, although the overall fiber structure remained largely intact [23]. The moderate enhancement in surface roughness may facilitate improved mechanical interlocking, contributing to enhanced MOR values in mechanical performance tests.

Acetic acid pre-treatment (Fig. 3c) further increased surface roughness and porosity through partial delignification, exposing cellulose microfibrils while preserving the overall structural integrity of the fibers. This indicated selective removal of hemicellulose and amorphous lignin, thereby improving resin adhesion [24]. However, the presence of intact fiber bundles suggested that delignification was not as extensive as in alkaline-treated fibers. The most pronounced morphological changes were observed in NaOH-treated fibers (Fig. 3d), which showed deep etching, extensive fibrillation, and a highly porous structure. The alkaline treatment effectively removed significant amount of lignin and hemicellulose, resulting in a cellulose-rich surface with enhanced surface area for resin bonding [25]. However, excessive alkali exposure may compromise fiber integrity, highlighting the need for optimized treatment conditions.

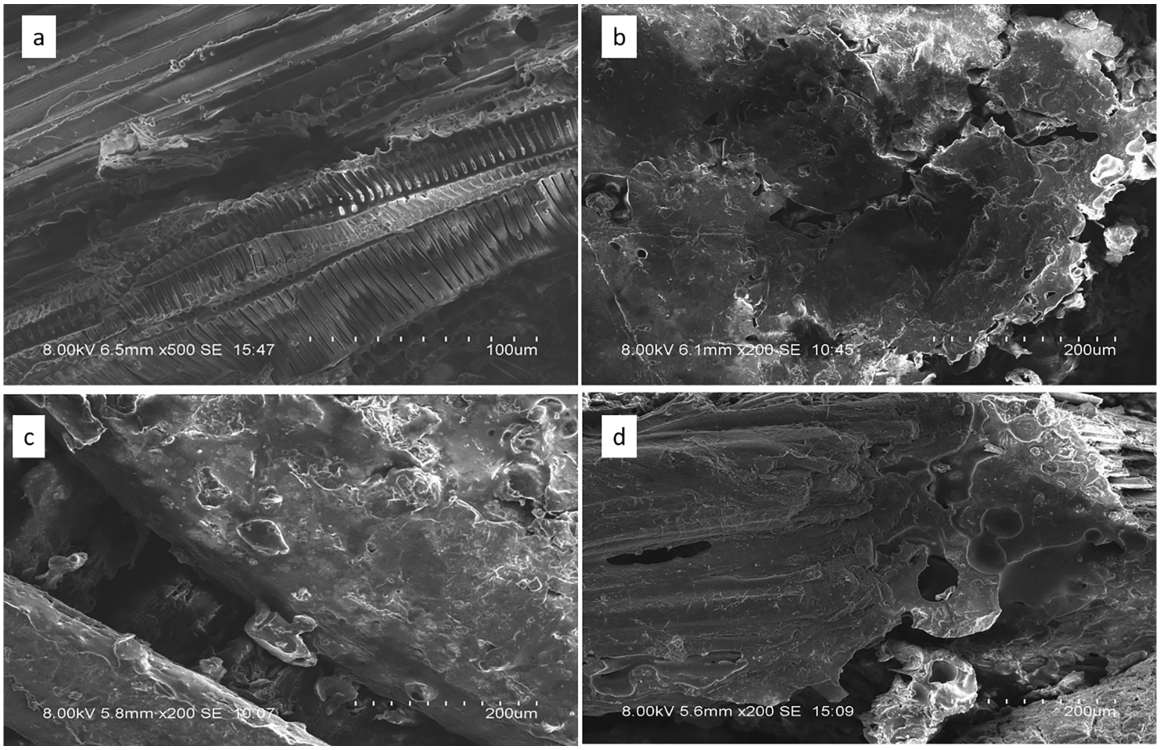

Figure 3: Surface morphology of (**a**) untreated OPT particles, (**b**) hot water pre-treatment, (**c**) acetic acid pre-treatment and (**d**) NaOH pre-treatment

In summary, NaOH treatment yielded the most substantial improvement in fiber morphology for interfacial bonding and mechanical performance, while acetic acid treatment provided moderate enhancement through controlled delignification. Hot water treatment had a limited effect but still contributed to improved fiber-resin interaction. These findings emphasize the critical role of chemical pre-treatments in tailoring fiber characteristics for high-performance particleboard applications.

3.2 Physical Properties

Dimensional Stability

Both WA and represent key indicators of dimensional stability and long-term durability in fiber-reinforced composites. WA refers to the amount of water the board takes up after immersion, reflecting its hydrophilicity and resistance to moisture penetration, while TS indicates the degree of dimensional expansion caused by water uptake and fiber relaxation. These properties are critical in evaluating the performance of particleboards under humid or water-exposed conditions [26]. Different fiber pre-treatment methods significantly influenced water resistance properties (Fig. 4). The untreated fibers had the highest WA and TS values, reflecting their inherently hydrophilic nature due to the abundant hydroxyl groups in cellulose, hemicellulose, and lignin. The absence of any chemical modification permitted extensive water uptake, leading to excessive swelling, loss of mechanical integrity, and potential degradation over time [27]. This observation was supported by SEM analysis (Fig. 3), where untreated fibers had waxy surfaces with minimal surface roughness and poor interfacial adhesion with the matrix that facilitates capillary action and water access.

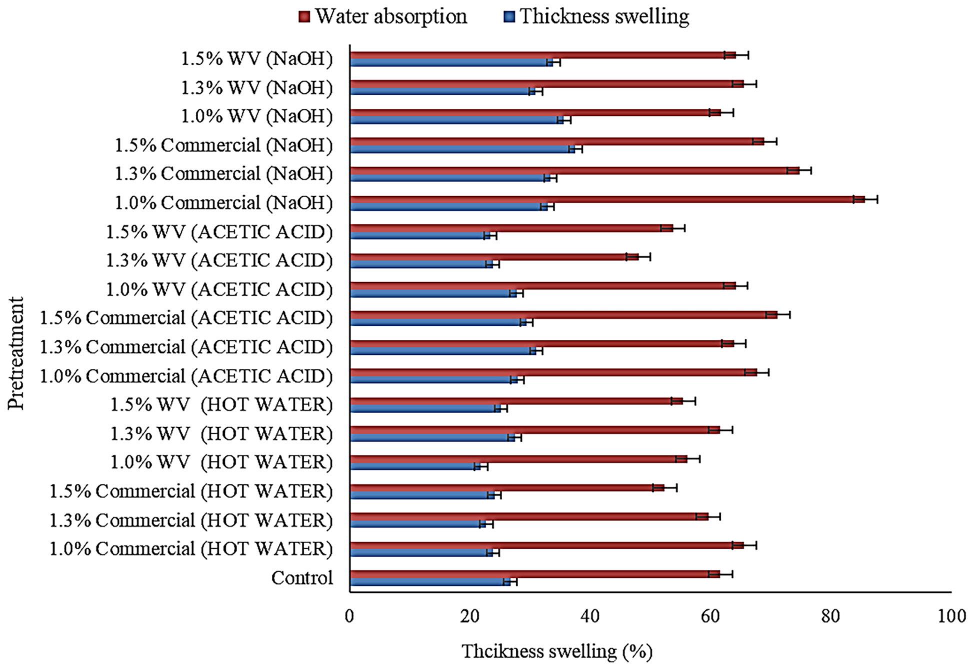

Figure 4: Effect of various pre-treatments and antifungal agents concentrations on dimensional stability of OPT particleboards

3.3 Mechanical Properties

3.3.1 Bending Strength

Fig. 5 presents the MOE of OPT particleboards subjected to various pre-treatment methods in combination with antifungal agents. The MOE of the untreated control sample was 1792.5 N/mm^2, serving as a baseline for comparison. The highest MOE (2990.9 N/mm^2) was observed in boards pre-treated with NaOH and supplemented with 1.5% WV, indicating significant enhancement in stiffness and elastic behavior. This improvement was attributed to the synergistic effects of the alkaline treatment, which enhanced fiber-resin interfacial bonding by removing hemicellulose and surface impurities, and the bioactive components in WV that may have contributed to additional cross-linking or surface modification [28]. NaOH pre-treated samples, with 1.3% and 1.0% WV also showed elevated MOE values, though slightly lower than 1.5% WV variant, suggesting a concentration-dependent enhancement. Acetic acid pre-treatment combined with 1.3% WV led to the second-highest MOE value (2945.4 N/mm^2), indicating that partial delignification and increased porosity can also facilitate improved mechanical interlocking and stress transfer within the composite matrix. Bioactive components in WV, such as acetic acid, phenolic compounds, and ketones, can interact with hydroxyl groups on lignocellulosic fibers, promoting partial esterification or hydrogen bonding that enhances fiber–matrix bonding adhesion [29]. These interactions may lead to improved surface energy and compatibility with resin systems, effectively contributing to additional cross-linking and better interfacial bonding in composite materials.

In contrast, hot water pre-treatment showed modest improvements in MOE across all WV concentrations but consistently lower values than both NaOH- and acetic acid-treated samples. The results suggested that while hot water removed some extractives, it did not significantly alter the fiber structure to enhance elasticity to the same extent as chemical treatments. It was observed that NaOH pre-treatment combined with 1.5% WV was the most effective combination for improving MOE, followed closely by acetic acid with 1.3% WV. These findings highlighted the importance of optimizing the types of pre-treatments and antifungal agent concentration to achieve desired mechanical properties. The notably lower MOE values in untreated and chemically unmodified samples highlight the critical role of chemical and bio-based treatments in enhancing the elastic performance of lignocellulosic composites [30].

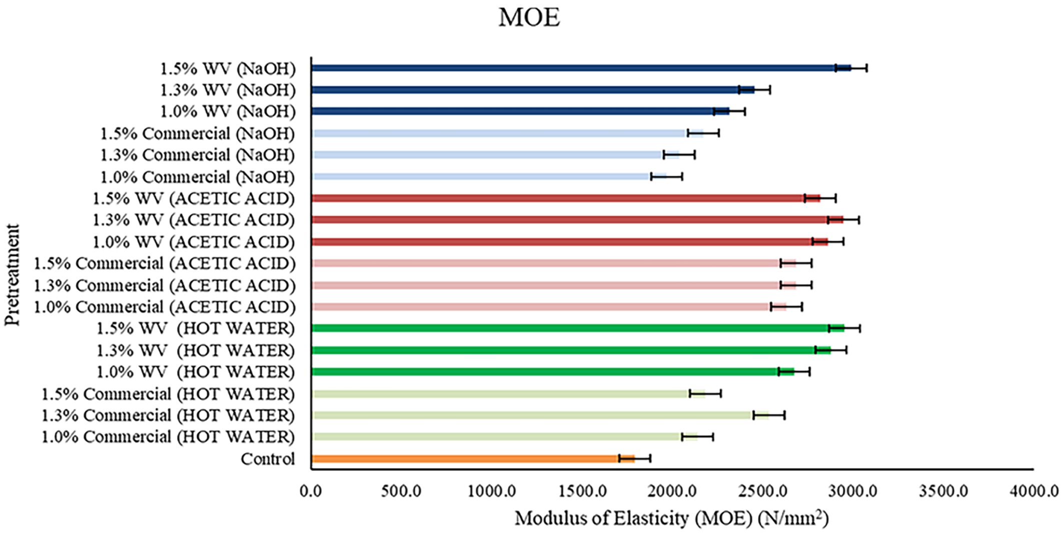

Figure 5: Effect of various pre-treatments and antifungal agents concentrations on MOE of OPT particleboards

Fig. 6 shows the MOR values for OPT particleboards subjected to the same pre-treatment and antifungal agent conditions. The control sample recorded a baseline MOR of 16.1 N/mm^2. The highest MOR (29.1 N/mm^2) was achieved in particleboards treated with acetic acid and 1.3% WV, indicating a substantial increase in flexural strength. The partial delignification and improved fiber surface morphology from acetic acid treatment likely enhanced mechanical interlocking and bonding efficiency, leading to greater resistance against applied stress [31].

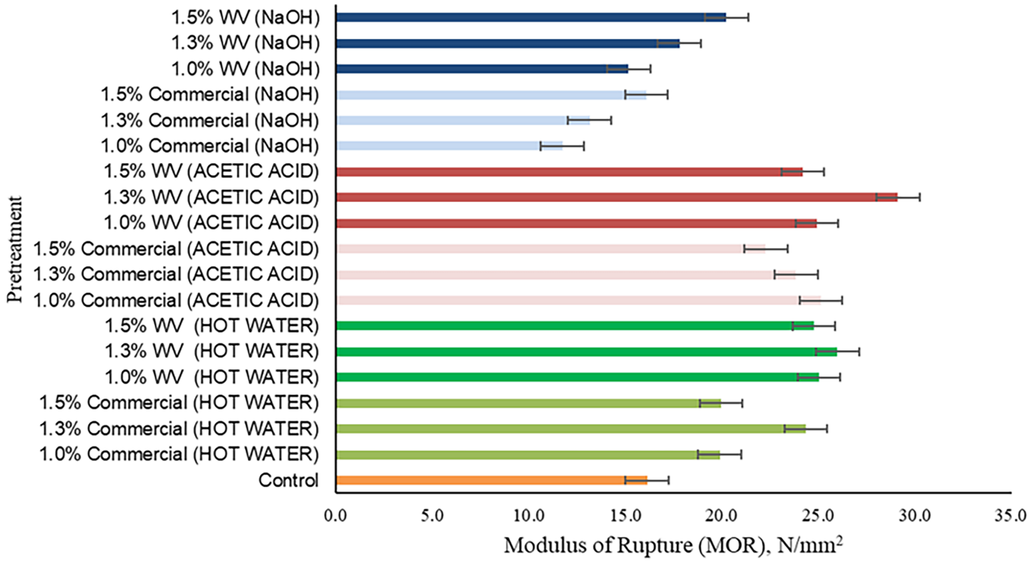

Figure 6: Effect of various pre-treatments and antifungal agents concentrations on MOR of OPT particleboards

A consistent trend across treatments showed that increasing the concentrations of antifungal agents generally correlated with improved MOR values. NaOH pre-treated samples showed a progressive increase in MOR with higher WV concentrations. However, the peak values remained slightly lower than acetic acid-treated samples. For instance, MOR of samples treated with 1.3% WV and hot water was 26.0 N/mm^2, while MOR of samples with 1.0% commercial antifungal and acetic acid pre-treatment was 25.1 N/mm^2. Hot water pre-treatment, although less effective than chemical methods, still contributed to improved MOR values when combined with higher concentrations of WV, suggesting a mild synergistic effect.

The findings confirmed that acetic acid pre-treatment, particularly when paired with 1.3% WV, offered the most effective enhancement of MOR. This implied that delignification to an optimal degree improved stress distribution and load-bearing capacity. The use of antifungal agents not only enhanced biological durability but also played a significant role in mechanical performance, likely due to chemical interactions with the resin matrix or fiber surface modification. The low MOR values in control samples emphasized the necessity of incorporating suitable treatments to meet structural performance requirements [32]. The improved mechanical performance can be attributed to the chemical interactions between the bioactive compounds in WV and the lignocellulosic fibers as well as the resin matrix. Components such as acetic acid, phenolic compounds, and carbonyl compounds in WV can react with fiber hydroxyl groups through partial esterification and hydrogen bonding, thereby strengthening fiber–matrix adhesion. The reaction between acetic acid and cellulose hydroxyl groups can be represented as:

$$-OH + CH_3COOH \rightarrow -OCOCH_3 + H_2O,$$

where –OH denotes hydroxyl groups on cellulose or hemicellulose. Phenolic and carbonyl compounds may also form hydrogen bonds with UF resin functional groups, enhancing interfacial adhesion. These reactions and secondary interactions contribute to stronger interfacial bonding, improved stress transfer, and greater bending strength in WV-treated particleboards.

3.3.2 Bonding Properties

Fig. 7 shows the significant influence of various pre-treatment methods and antifungal additives on the IB of OPT particleboard composites. The untreated control samples had the lowest IB strength, barely exceeding 1.0 N/mm^2. This poor bonding performance was attributed to the presence of surface impurities, waxes, and naturally lignin, which inhibited effective adhesion between the fibers and the resin matrix. These results highlighted the essential role of pre-treatment strategies in improving fiber–matrix interactions and enhancing composite performance [33].

Chemical and thermal pre-treatments resulted in notable variations in IB strength. The highest IB value, 3.0 N/mm^2, was recorded in particleboards pre-treated with acetic acid and treated with 1.0% commercial antifungal agent. In contrast, the lowest IB values of 0.9 N/mm^2 were observed in samples treated with 1.5% commercial acetic acid and 1.3% WV following NaOH pre-treatment. These findings suggested that the type and concentration of pre-treatment agents critically affected the adhesion and structural performance of particleboards altering the fiber surface chemistry, removing amorphous and non-cellulosic components, such as hemicellulose and lignin, and modifying the availability of functional groups that facilitate adhesive bonding [11]. However, excessive concentrations may lead to over-degradation of fiber structures, resulting in reduced mechanical interlocking and fewer reactive sites for resin interaction, ultimately weakening internal bonding.

Hot water pre-treatment led to moderate improvements in IB strength. IB strength of the sample treated with 1.0% commercial antifungal (hot water) was 2.6 N/mm^2, the highest among hot water-treated groups, while IB strength of the sample treated with 1.3% WV (hot water) was 2.5 N/mm^2. However, further increased in concentrations (1.5% WV and 1.5% commercial) led to reduced IB values (2.0 and 2.1 N/mm^2, respectively), likely due to excessive leaching of hemicellulose and lignin, both important for maintaining fiber integrity and bonding sites [34]. Acetic acid pre-treatment emerged as the most effective chemical strategy. At low concentration (1.0% commercial), sample treated with acetic acid had the highest IB strength (3.0 N/mm^2), likely due to enhanced fiber surface activation, extractives removal, and improved resin penetration [35]. However, increasing the concentrations to 1.3% and 1.5% resulted in a steep decline in IB (1.9 and 0.9 N/mm^2, respectively), possibly due to fiber degradation, loss of cohesive strength, and diminished interfacial bonding. WV-based acetic acid treatments followed a similar declining trend. The IB strength decreased from 1.7 N/mm^2 at 1.0% WV to 1.3 and 1.6 N/mm^2 at 1.3% and 1.5% WV, respectively. These results showed that excessive acetic acid concentrations, regardless of antifungal source, can compromise fiber structure and diminish bonding performance.

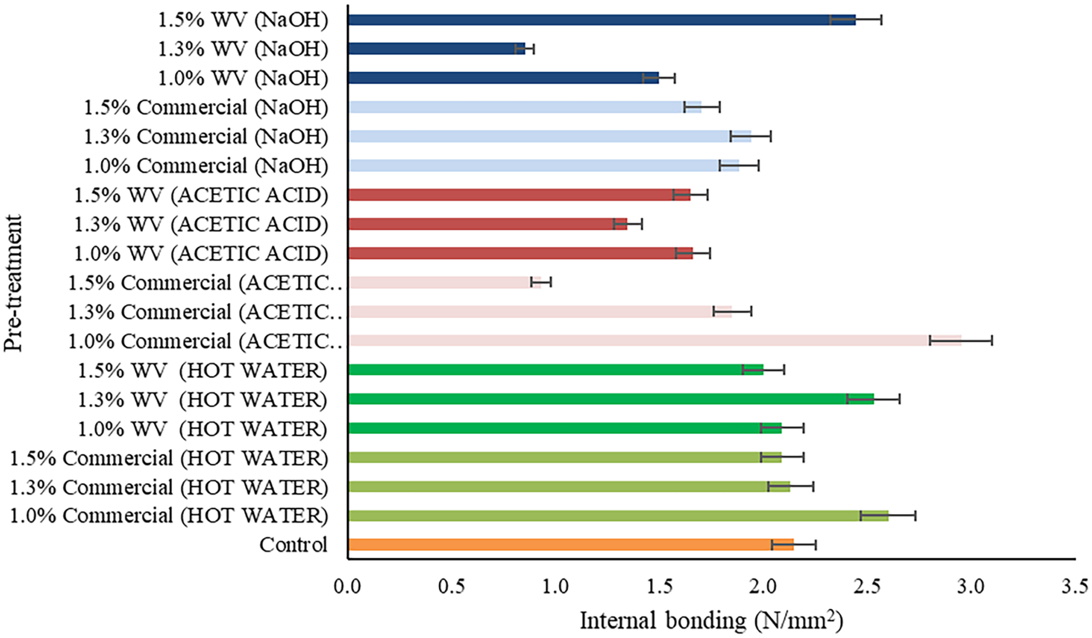

Figure 7: Effect of various pre-treatments and antifungal agents concentrations on IB of OPT particleboards

NaOH pre-treatment led to variable outcomes depending on the concentration of the antifungal. Sample treated with 1.5% WV (NaOH) had the highest IB among alkaline-treated boards (2.4 N/mm^2), reflecting effective lignin and hemicellulose removal and increased surface roughness for adhesive anchoring [36]. However, samples treated with lower concentrations (1.0% and 1.3% WV NaOH) showed significantly reduced bonding strengths (1.5 and 0.9 N/mm^2), indicating insufficient chemical modification. Commercial NaOH-treated samples performed slightly better, with IB values ranging from 1.7 to 1.9 N/mm^2, likely due to more consistent fiber modification than WV-derived treatments [37].

From the results, NaOH pre-treatment, particularly with optimized antifungal concentration (1.5% WV), provided the best enhancement in IB, attributed to its superior delignification and surface activation capacity. Acetic acid treatments offered moderate improvement at lower concentrations but negatively impacted performance when overapplied. Hot water treatment showed limited benefits, emphasizing the need for effective chemical treatments in achieving durable fiber–matrix interfaces. These findings demonstrated the pivotal role of pre-treatment strategy and antifungal dosage in optimizing the IB strength of bio-composite materials for structural applications [38].

The results of ANOVA on the mechanical properties MOE and MOR of the treated samples, summarized in Table 1, indicate that the mechanical parameters were significantly influenced by the applied treatments. For MOE, the ANOVA revealed a statistically significant effect (F = 2.4, $p = 0.04$), indicating that variations in pre-treatment and WV concentration moderately, yet significantly, impact material stiffness at the 5% significance level. This indicates that treatment-induced modifications, maybe in cell wall rigidity or fiber bonding, may affect the elastic response of the wood matrix [39].

Table 1: ANOVA table: effect of pre-treatment and WV concentration on MOE and MOR

Source	**Degree of freedom (DF)**		**F-Value**		***p*-Value**	
	MOE	**MOR**	**MOE**	**MOR**	**MOE**	**MOR**
Between groups	8	8	2.4	7.4	0.04	0.00003
Within groups	27	27	–	–	–	–

In contrast, the effect on MOR was more pronounced, with a highly significant F-value of 7.4 ($p = 0.00003$). The findings highlight the susceptibility of bending strength to treatment conditions, indicating that the relationship between pre-treatment and WV concentration significantly modifies the material's load-bearing capacity. Such modifications may result from optimised lignin structure, reduced micro-cracking, or increased interfacial bonding [40]. The results together indicate that both MOE and MOR are considerably influenced by the treatment variables; however, MOR exhibits a more pronounced response, highlighting its effectiveness as a performance metric in structural applications. Thus, the optimisation of treatment settings is essential for enhancing mechanical reliability.

3.3.3 Statistical Analysis of Mechanical Properties

Table 1 shows the effect of pre-treatment and WV concentration on MOE and MOR. Despite observable patterns in mechanical performance among groups, Tukey's post hoc test was unable to demonstrate statistically significant differences between individual treatment pairs at $\alpha = 0.05$. This indicates that although the overall treatment effects are significant, additional refining of treatment settings may be required to attain clear and statistically identifiable enhancements in performance.

Following the significant ANOVA results for MOE ($p = 0.0427$) and MOR ($p = 0.000033$), group-wise comparisons were conducted to identify which treatment combinations contributed most to the observed effects. Tukey's HSD post hoc test was used to evaluate pairwise differences among the pre-treatment and antifungal agent concentration groups.

For MOE, all pre-treatment methods led to statistically significant increases in stiffness compared to the untreated control (mean MOE = 1792.5 N/mm^2). The most pronounced improvement was observed in the NaOH (1.5%) group, with a mean MOE of 3247.2 N/mm^2, followed by hot water (1.0%) at 3154.3 N/mm^2 and Acetic Acid (1.3%) at 3059.6 N/mm^2 (Table 2). These findings indicate improved inter-fiber adhesion and microstructural stability resulting from chemical or hydrothermal treatment. Notably, Acetic Acid (1.3%) treatment also exhibited low variability (Std. Dev. (SD) = 208.2), indicating consistent mechanical performance. In contrast, the NaOH (1.5%) group, while achieving the highest MOE, showed high variability (SD = 801.7), possibly due to uneven chemical penetration or partial fiber degradation.

Table 2: Mean and standard deviation of modulus of elasticity (MOE) and modulus of rupture (MOR) for OPT-based particleboards affected by different pre-treatment and antifungal agent concentrations

Pre-treatment	Mean MOE (N/mm^2)	Std. Dev. (SD)	Mean MOR (N/mm^2)	Std. Dev. (SD)
Control	1792.5	145.2	19.2	3.9
Hot water (1.0%)	3154.3	404.5	29.9	3.6
Hot water (1.3%)	2391.5	355.4	20.9	3.5
Hot water (1.5%)	2979.9	457.7	24.9	3.4
Acetic acid (1.0%)	2934.8	251.5	24.4	1.7
Acetic acid (1.3%)	3059.6	208.2	28.7	1.1
Acetic acid (1.5%)	2837.7	96.0	24.7	1.4
NaOH (1.0%)	2423.9	317.1	15.6	3.2
NaOH (1.3%)	2581.1	332.4	18.0	2.3
NaOH (1.5%)	3247.2	801.7	22.1	6.8

The MOR results revealed even clearer differentiation among treatments. Hot water (1.0%) yielded the highest MOR (29.9 N/mm^2), significantly outperforming both the control (19.2 N/mm^2) and all NaOH-treated groups. Acetic Acid (1.3%) and Acetic Acid (1.0%) also produced substantial gains in bending strength (28.7 and 24.4 N/mm^2, respectively). In contrast, NaOH treatments were less effective in improving MOR. The lowest values were recorded for NaOH (1.0%) at 15.6 N/mm^2 and NaOH (1.3%) at 18.0 N/mm^2, while NaOH (1.5%) showed a moderate MOR (22.1 N/mm^2) but with high variability (SD = 6.8). These findings suggest that while alkaline treatments may enhance stiffness, they can simultaneously compromise bending strength likely due to over-degradation of hemicelluloses and weakening of the fiber–matrix interface [41].

The divergent trends observed between MOE and MOR emphasize the need to tailor pre-treatment strategies depending on the targeted mechanical property. Treatments such as hot water (1.0%) and acetic acid (1.3%) emerged as optimal, offering significant improvements in both stiffness and strength with relatively low variability, making them promising candidates for structural applications. On the other hand, high-concentration NaOH treatments, despite boosting MOE, showed inconsistent and sometimes detrimental effects on MOR, raising concerns about their mechanical reliability.

These outcomes suggest that hot water and acetic acid treatments enhance mechanical integrity by partially removing amorphous components and stabilizing lignin–carbohydrate complexes, leading to improved fiber bonding. In contrast, the performance decline observed in NaOH-treated samples may stem from excessive degradation of key matrix components.

In summary, the combined ANOVA and post hoc analyses confirm that both pre-treatment type and antifungal agent concentration significantly influence the mechanical behaviour of OPT-based particleboards. Hot water (1.0%) and acetic acid (1.3%) treatments, in particular, demonstrated superior and consistent performance, highlighting their suitability for industrial-scale production of mechanically robust bio-composites.

ANOVA was also performed to evaluate the effect of different pre-treatment strategies and WV concentrations on the IB strength of OPT-based particleboards. The results showed a statistically significant treatment effect on IB strength (F (9, N) = 11.5, p = 0.0018), indicating that at least one treatment group significantly differed from the others (Table 3). This confirms that both the type and concentration of pre-treatment play a critical role in influencing the bonding performance of the particleboards.

Table 3: One-way ANOVA summary table for comparison of internal bonding (IB) strength among treatment groups

Source	DF	Sum of squares (SS)	Mean square (MS)	F-Value	*p*-Value
Between groups	9	9.4	1.0	11.5	<0.0001
Within groups	31	2.8	0.1	–	–
Total	40	12.2	–	–	–

The between-group sum of squares (SS = 9.4) was markedly higher than the within-group variability (SS = 2.8), suggesting that most of the variation in IB strength was attributable to the treatment effects rather than random experimental error (Table 3). These findings support the hypothesis that chemical and thermal modifications have a significant and measurable impact on the internal cohesion of OPT-based composites, reinforcing their potential for performance enhancement through optimized pre-treatment strategies.

Table 4 shows the IB strength of OPT-based particleboards subjected to various pretreatments. IB values ranged from 1.2 N/mm^2 (1.3% WV + NaOH) to 2.9 N/mm^2 (1.5% WV + hot water), while the control group had a moderate value of 2.2 N/mm^2.

Table 4: Internal bonding (IB) values for OPT particleboards

Pretreatment group	Mean IB (N/mm^2)	SD
Control	2.2	0.2
1.0% WV (Hot Water)	2.7	0.2
1.3% WV (Hot Water)	2.2	0.1
1.5% WV (Hot Water)	2.9	0.5
1.0% WV (Acetic Acid)	1.5	0.1
1.3% WV (Acetic Acid)	2.2	0.4
1.5% WV (Acetic Acid)	1.9	0.2
1.0% WV (NaOH)	1.7	0.3
1.3% WV (NaOH)	1.2	0.4
1.5% WV (NaOH)	2.0	0.4

Hot water treatments gave the best overall performance. All concentrations tested resulted in higher IB values than the control, with 1.5% WV (hot water) showing the highest strength. This suggests that hydrothermal treatment improves adhesive bonding, likely by softening cell wall components and enhancing resin penetration [42]. Acetic acid treatments showed mixed results. The 1.3% concentration performed similarly to the control, but the 1.0% and 1.5% groups had lower IB values. Acid hydrolysis or surface changes may have interfered with proper adhesion [25]. NaOH treatments resulted in the lowest IB strengths, especially at 1.3% WV, likely due to fiber degradation or excessive removal of lignin. Although the 1.5% NaOH treatment showed some improvement, the high variability suggests inconsistent bonding quality. In summary, hot water at 1.5% WV was the most effective pretreatment for improving internal bond strength in OPT particleboards, offering better bonding performance than chemical treatments.

Table 5 presents the results of Tukey's HSD post hoc test, identifying significant pairwise differences in internal bond (IB) strength among the various pretreatment groups. The 1.3% WV + NaOH treatment consistently recorded significantly lower IB strength compared to other groups. Specifically, it differed significantly from the control (Δ = 1.0 N/mm^2, p = 0.001), 1.0%

WV + hot water (Δ = 1.7 N/mm^2, p = 0.001), and 1.5% WV + hot water (Δ = 1.9 N/mm^2, p = 0.001). These findings confirm that the 1.3% NaOH treatment severely compromised bond integrity, likely due to over-delignification or fiber damage caused by alkaline degradation.

Table 5: Tukey's HSD post hoc test for pairwise comparisons of internal bond (IB) strength across treatment groups

Group 1	Group 2	Mean Diff.	*p*-adj
Control	1.3% WV + NaOH	1.0	0.001
1.0% WV + Hot Water	1.3% WV + NaOH	1.7	0.001
1.5% WV + Hot Water	1.3% WV + NaOH	1.9	0.001
1.0% WV + Hot Water	1.0% WV + Acetic Acid	1.2	0.001
1.5% WV + Hot Water	1.0% WV + Acetic Acid	1.4	0.001
1.5% WV + Hot Water	1.3% WV + Acetic Acid	0.9	0.045
1.0% WV + Hot Water	1.3% WV + Acetic Acid	0.7	0.045

Among the most effective treatments, 1.5% WV + hot water and 1.0% WV + hot water showed significantly higher IB strengths than the 1.0% WV + acetic acid group, with mean differences of 1.4 and 1.2 N/mm^2, respectively (both p = 0.001). This highlights the superior performance of hydrothermal treatment in enhancing resin-fiber adhesion, possibly through improved fiber swelling and matrix compatibility.

Notably, even the 1.3% WV + acetic acid group, which had moderate performance, was statistically outperformed by 1.5% WV + hot water (Δ = 0.9 N/mm^2, p = 0.045) and 1.0% WV + hot water (Δ = 0.7 N/mm^2, p = 0.045). Though these differences are smaller, they underscore the consistent advantage of hot water pretreatment at elevated WV concentrations.

In summary, the post hoc analysis reinforces the earlier ANOVA findings by confirming that hot water pre-treatment, particularly at 1.5% WV, provides a statistically significant improvement in IB strength over both the control and chemically treated groups. These results support the suitability of hydrothermal methods as a cleaner, more consistent approach for improving bonding performance in OPT-based composite panels.

The statistical analysis of IB strength data confirmed that the choice of pre-treatment and antifungal agent concentration significantly influences the IB performance of OPT-based particleboards. Among all treatments, 1.5% WV (hot water) demonstrated the best performance, achieving the highest IB strength with acceptable variability. This treatment approach holds promise for enhancing the structural integrity of particleboards in applications requiring high adhesive bonding performance. Conversely, alkaline treatments, particularly at intermediate concentrations, were detrimental to bonding performance and should be applied with caution or avoided where IB is a key specification.

3.4 Thermal Properties

Thermal analysis was performed using TGA to assess the thermal stability and decomposition behavior of OPT particleboards subjected to different pre-treatment methods. Distinct thermal degradation patterns were observed, reflecting variations in structural composition and influence of chemical modifications introduced during pre-treatment (Fig. 8). The initial stage of thermal degradation, occurring between 30°C and 150°C (Fig. 8a–d), corresponds to the evaporation of free and bound moisture within the fibers. Among the samples, NaOH-treated fibers (Fig. 8d) had the lowest weight loss in this temperature range, suggesting a reduced hydrophilic nature. This was likely due to the removal of extractives and hemicellulose, which are rich in polar hydroxyl (–OH) groups that contribute to water absorption [43].

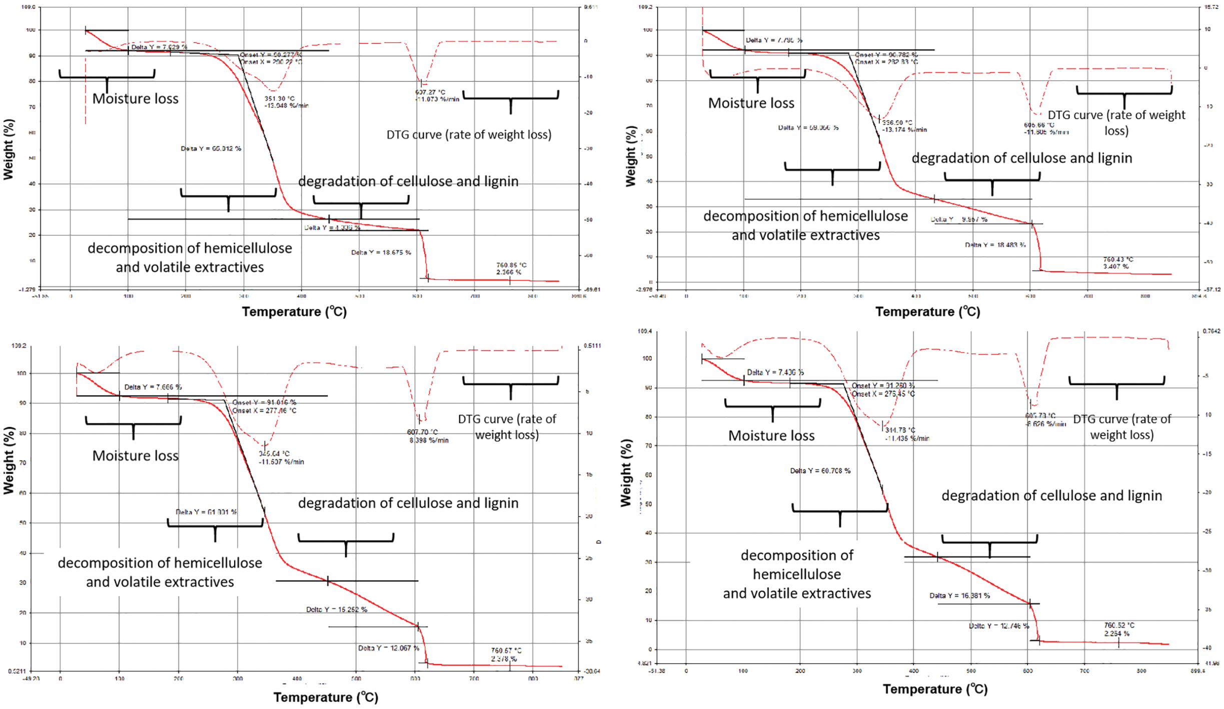

Figure 8: TGA analysis of OPT particleboards subjected to different pre-treatment methods (**a**) hot water (**b**) 1.0% WV acetic acid (**c**) 1.3% WV acetic acid (**d**) 1.5% WV NaOH

The second degradation stage, occurring between 200°C and 350°C, was primarily attributed to the decomposition of hemicellulose and volatile extractives. Due to its amorphous structure and lower molecular weight, hemicellulose decomposes at lower temperatures than cellulose [44]. The TGA curves showed that NaOH-treated samples had a higher onset temperature for degradation in this region compared to untreated and hot water-treated fibers, indicating enhanced thermal stability. This suggested that NaOH effectively eliminated thermally unstable hemicellulose, thereby preserving the more stable cellulose component.

The most substantial mass loss was observed in the 350°C to 600°C range, corresponding to the degradation of cellulose and lignin. Cellulose typically decomposes between 350°C and 450°C, while lignin degrades over a broader range up to 600°C due to its complex aromatic structure [45]. Notably, NaOH and acetic acid-treated samples had higher onset temperatures for mass loss than untreated fibers, indicating that these chemical treatments enhanced thermal resistance. The shift in peak decomposition temperatures further supported improved structural integrity, which is beneficial for applications requiring higher thermal performance [46]. The pre-treatment method significantly influenced the thermal behavior of the particleboards. NaOH treatment notably improved fiber stability by selectively removing hemicellulose and partially degrading lignin, resulting in a cellulose-enriched matrix with higher thermal resistance. This was reflected in both the elevated onset temperatures and the reduced rate of mass loss. Acetic acid treatment also enhanced thermal stability, although less than NaOH treatment, as it retained more lignin while still reducing the hemicellulose fraction. In contrast, hot water-treated fibers showed thermal degradation patterns like those of untreated fibers, indicating that hot water alone did not substantially modify the thermal characteristics [47].

In addition to pre-treatment effects, varying the loading of antifungal agents, both commercial and WV, influenced the thermal performance of the particleboards. Higher concentrations of antifungal additives (1.3% and 1.5%) tended to enhance thermal stability as reflected in increased onset degradation temperatures and greater residual char. This suggested that the antifungal agents may have contributed to cross-linking or structural reinforcement, which enhanced the composite's resistance to thermal degradation [48]. WV contains organic acids and phenolic compounds that could interact with fiber constituents and resin, leading to the formation of thermally stable structures [49]. However, the thermal enhancement was less pronounced at lower concentrations (1.0%), indicating that a minimum threshold of additive was required to achieve noticeable improvements. These findings implied that optimizing antifungal agent loading not only contributed to microbial resistance but also positively impacted the thermal behavior of particleboards.

Residual weight observed between 700°C and 800°C provided insights into the char formation capacity of the samples, a critical parameter in evaluating fire resistance [50]. NaOH-treated samples retained a higher proportion of char residue compared to other treatments, suggesting improved thermal decomposition and formation of more stable carbonaceous structure. Enhanced char formation contributes to improved flame retardancy by creating a protective barrier that slows down further degradation. Therefore, NaOH-treated particleboards may be more suitable for applications demanding superior thermal resistance and fire safety. Thermal stability of pre-treated OPT particleboards showed that optimized chemical pre-treatment and antifungal additive loading can significantly enhance the thermal performance of particleboards, enabling their use in environments subjected to elevated temperatures and humidity. These findings supported the development of sustainable, thermally stable engineered wood products from oil palm trunk residues, offering a viable alternative to traditional timber materials with added environmental benefits.

The influence of antifungal agents on particleboard performance can be attributed to the chemical activity of their active compounds, which interact with both the resin matrix and lignocellulosic fibers during hot pressing. The commercial antifungal used in this study, although proprietary, is commonly composed of quaternary ammonium compounds and phenolic derivatives, known for their surface-active and antimicrobial properties. These molecules can interact electrostatically with the negatively charged hydroxyl and carboxyl groups of cellulose and lignin, reducing surface polarity and enhancing compatibility with the UF resin. This modification improves resin wetting, fiber–matrix adhesion, and consequently the mechanical strength of the boards.

In contrast, the WV contains naturally derived bioactive compounds, primarily acetic acid, phenolic compounds (e.g., guaiacol, cresol, catechol), and carbonyl compounds (e.g., acetone, furfural). These components can react with or hydrogen-bond to fiber hydroxyl groups and UF resin functional groups, leading to partial esterification ($-OH + CH_3COOH \rightarrow -OCOCH_3 + H_2O$) and improved interfacial bonding. The phenolic constituents also contribute to cross-linking reactions and increased thermal stability, while the weak organic acids reduce hydrophilicity by decreasing the number of free hydroxyl sites. Together, these chemical interactions strengthen the adhesive interface, reduce moisture absorption, and enhance the mechanical and dimensional stability of the particleboards.

Therefore, the improvement observed in the physical and mechanical properties of the treated boards arises not only from enhanced biological resistance but also from the chemical modification of fiber surfaces and improved resin curing behavior induced by the active compounds in the antifungal agents.

4 Conclusions

This study demonstrated that appropriate pre-treatment and antifungal modification can significantly enhance the performance of particleboards produced from OPT particles. Chemical pre-treatments improved fiber surface roughness and reduced the presence of extractives, leading to better resin penetration and bonding efficiency. Among the antifungal additives, WV showed a more pronounced effect than the commercial antifungal due to its reactive bioactive components, which promote partial esterification and hydrogen bonding with both the lignocellulosic fibers and the urea–formaldehyde resin matrix. These interactions improved interfacial adhesion, dimensional stability, and thermal resistance of the boards. Overall, the combination of optimized pre-treatment and bio-based antifungal additives contributes to the development of durable, eco-friendly particleboards suitable for sustainable wood composite applications.

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