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Comparative Analysis of PVA-bonded Oil Palm Trunk and Rubberwood Composite Boards with NaCl and $CaCO_3$ Additives

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ABSTRACT

This study investigates composite boards fabricated from oil palm trunk (OPT) and rubberwood (RW) using polyvinyl alcohol (PVA) as a binder with sodium chloride (NaCl) and calcium carbonate ($CaCO_3$) as additives. Mechanical testing showed maximum bending strengths of 5.94 MPa (OPT) and 5.34 MPa (RW) at 10% PVA loading, while internal bonding values peaked at 0.97 MPa (RW). Dimensional stability improved with fillers, reducing thickness swelling by up to 25% compared to control boards. Flame retardancy was significantly enhanced, with LOI values exceeding 26% for all formulations containing NaCl and $CaCO_3$, classifying them as self-extinguishing. Thermogravimetric analysis confirmed improved thermal stability, with decomposition temperatures reaching ~543 °C in filler-modified boards. These findings highlight that integrating NaCl and $CaCO_3$ with PVA not only improves flame resistance but also enhances durability and thermal performance, demonstrating the potential of OPT and RW as sustainable raw materials engineered wood products.

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1. INTRODUCTION

In the achievement of a low-carbon and sustainable future, convergence of scientific innovation, technological advancement, and social responsibility has become a global imperative. One of the promising solutions is to turn agricultural residues into high-value-added products for environmental and economic resilience. OPT and RW, two abundant by-products of Southeast Asia's agro-industrial complex, have great

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potential as renewable raw materials for engineered wood products. The strategic application of such biomass feedstocks minimizes waste generation and supports local economies via sustainable material creation (Lamaming et al., 2015; Yusof et al., 2020).

OPT, recovered from aged oil palm plantations, and RW, derived from latex-deficient rubber trees, have been researched in depth to discover their mechanical suitability for application in plywood, composites, and fiberboards. Their use aligns with circular economy principles by extending the value chain of crops and reducing dependence on primary forest resources (Karim et al., 2020; Ratnasingam et al., 2015). However, moving away from conventional wood adhesives, particularly formaldehyde-based resins, is critical for ensuring low-emission manufacturing processes. Here, polyvinyl alcohol (PVA) has also been identified as a safe, non-toxic binder that aligns with green chemistry principles and improves indoor air quality (Shakir et al., 2017; Li et al., 2017).

For further reinforcing the safety and functionality of composite materials, NaCl and $CaCO_3$ are incorporated in the present research as functional additives. NaCl exhibits flame retarding and thermal buffering action, while $CaCO_3$ enhances the mechanical strength and thermal insulation of the composite (Rajaei et al., 2014; Tao et al., 2019). Synergistic use of such additives in combination with PVA is a sign of science-based design to develop innovative biomaterials that meet evolving requirements for fire safety, environmental sustainability, and material durability.

This work thus highlights the intersection of science, technology, and society, demonstrating that biomass from a local source can be upcycled into fire-resistant particleboards with minimal environmental impact. Through the use of agricultural residues, renewable binders, and nontoxic additives, we envision being part of sustainable building material options that align with global efforts in carbon reduction, resource preservation, and human health.

2. EXPERIMENTAL

OPT particles were sourced from Encore Agriculture Industries Sdn. Bhd. Selangor, Malaysia, while RW particles were obtained from a plywood manufacturer in Penang. Both materials were initially milled into coarse particles with an approximate size of 10 mm. These were then screened using a four-tier sieving system, and the final retained particles used for board fabrication were in the range of 0.5–2 mm, consistent with standard particleboard dimensions (Zhang et al., 2018; Juda et al., 2023). $CaCO_3$ and NaCl were purchased from ChemAr and QRec, respectively. PVA and citric acid were supplied by R & M Chemicals. All reagents were analytical grade and used without further purification.

The OPT and RW particles were blended with additives in different proportions: 10% or 20% PVA, 10% or 20% $CaCO_3$, and up to 30% NaCl, as shown in Table 1. The NaCl content was capped at 30% because higher salt loadings have been reported to compromise mechanical integrity by weakening particle bonding, similar to the effects observed with other inorganic fillers in lignocellulosic composites (Tao et al., 2019; Wang et al., 2022). This upper limit is consistent with previous findings that excessive mineral additives cause brittleness and reduced bending strength. In addition, 10% citric acid was incorporated as a cross-linking agent for PVA, as suggested by Birck et al. (2014), who reported that such a formulation enhances crosslinking efficiency. Control boards containing 100% OPT and 100% RW were also fabricated. The composites were hot-pressed at 160 °C for 20 minutes to a target density of 700 kg/m^2 (Wahab et al., 2018). In total, twelve types of particleboard were produced (Table 1), with three replicates prepared for each formulation to ensure experimental reliability.

Table 1. Formulation for composite board making.

Materials	Particles		Addition		
	OPT (%)	RW (%)	PVA (%)	$CaCO_3$ (%)	NaCl (%)
A1	100	0	0	0	0
B1	0	100	0	0	0

Materials	**Particles**		**Addition**		
	OPT (%)	**RW (%)**	**PVA (%)**	**$CaCO_3$ (%)**	**NaCl (%)**
A2	90	0	10	0	0
B2	0	90	10	0	0
A3	60	0	10	0	30
B3	0	60	10	0	30
A4	40	0	10	20	30
B4	0	40	10	20	30
A5	50	0	10	10	30
B5	0	50	10	10	30
A6	40	0	20	10	30
B6	0	40	20	10	30

*OPT- Oil Palm Trunk, RW-Rubberwood, PVA- Polyvinyl alcohol, CaCO3- Calcium carbonate, NaCl-Sodium chloride

2.1. BENDING TEST AND INTERNAL BONDING TEST (IB)

The bending test was done according to Japanese Industrial Standard JIS A 5908-2003 (2003) using an Instron machine model 4204. A central point load was applied at a crosshead speed of 10 mm/min across an effective span of 150 mm. The test specimens measured 50 mm × 200 mm, and four replicates were prepared for each particleboard type. Internal bonding testing was also carried out by the Japanese Industrial Standard (JIS A 5908-2003) (2003) using the same type of Instron machine, model 4204, as the bending test machine. A sample specimen was strapped to the 50 mm x 50 mm block and then secured in the machine. The tension load was applied vertically on the face of the board with a tension loading speed of 2 mm/min. Subsequently, the maximum load (P') was recorded at the breaking point of the perpendicular tensile strength of the board. Four test samples were prepared to determine internal bonding performance.

2.2. DIMENSIONAL STABILITY TEST

The thickness swelling (TS) and water absorption (WA) tests of the composite board were determined based on the percentage increase in thickness and weight after water immersion, relative to their initial values (Zuo et al., 2018). These tests were conducted by soaking the composite boards in water, after which TS and WA were measured following the Japanese Industrial Standard JIS A 5908-2003. Specimens with dimensions of 50 mm × 50 mm × 10 mm were oven-dried at 105 ± 2 °C until constant weight, then immersed in distilled water at room temperature (25 ± 2 °C) for 24 h. After immersion, samples were surface-dried and re-weighed, and the thickness was re-measured. Four replicates were tested for each board.

2.3. LIMITED OXYGEN INDEX TEST (LOI)

The flammability of the composite boards was evaluated using the Limited Oxygen Index (LOI) test, following ASTM D2863 with a Fire Testing Technology LOI apparatus. Rectangular specimens (80 mm × 10 mm × 5 mm) were positioned vertically in the sample holder, and the minimum oxygen concentration required to sustain combustion was recorded. All tests were performed in a controlled atmosphere, and 15 replicate specimens of each board were prepared to ensure accuracy.

2.4. THERMOGRAVIMETRIC ANALYSIS TEST

TGA was conducted with a Shimadzu TGA-50, heating the samples from room temperature to 920 °C at 20 °C/min under nitrogen flow. Weight loss profiles were obtained as a function of temperature and analyzed using the Freeman–Carroll method (Hatakeyama & Quinn, 2006).

2.5. FOURIER TRANSFORM INFRARED (FTIR) ANALYSIS

FTIR spectra were recorded using a Perkin Elmer spectrometer at 2 cm^{-1} resolution with 15 scans, employing the KBr pellet method at a 1:100 sample-to-KBr ratio.

3. RESULTS AND DISCUSSION

3.1. EVALUATION OF MECHANICAL PROPERTIES AND DIMENSIONAL STABILITY

The bending strength results of all samples are presented in Fig. 1. Among the OPT composite boards, sample A2 exhibited the highest bending strength, while sample B2 recorded the highest value for RW. Specifically, the mixture of OPT with 10% PVA reached 5.94 MPa, whereas RW with 10% PVA showed 5.34 MPa. Lamaming et al. (2015) reported that PVA addition enhances the mechanical performance of composite boards. The lowest bending strength values were obtained from A1 (100% OPT, 0.40 MPa) and B1 (100% RW, 0.97 MPa). As shown in Fig. 1, the bending strength decreased with the incorporation of $CaCO_3$ and NaCl. According to Hongzhen et al. (2017), excessive $CaCO_3$ (>10%) weakens intermolecular forces, destabilizes the internal structure, and reduces bending strength.

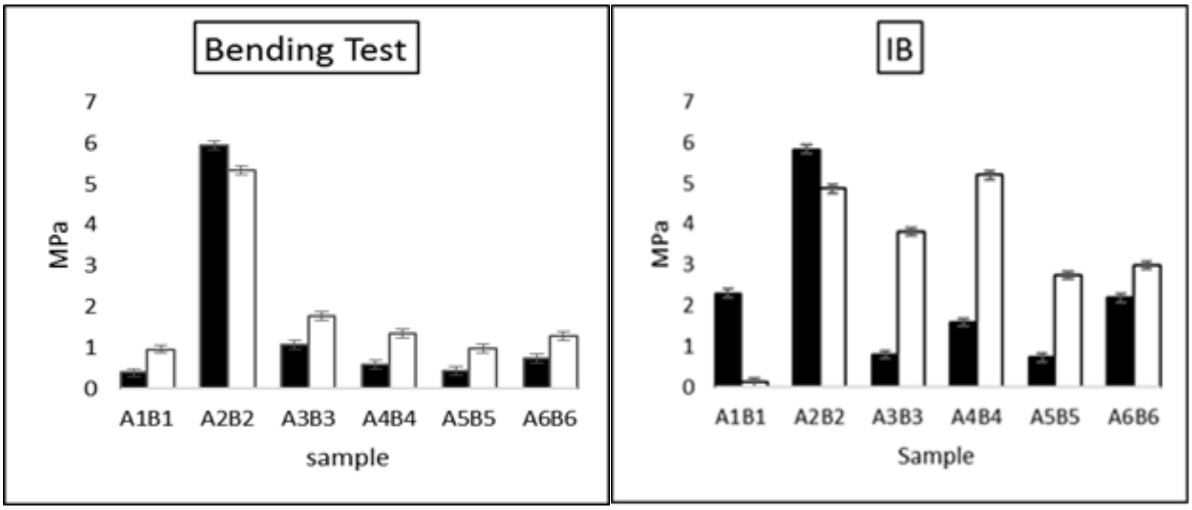

Figure 1. Bending test and internal bonding (IB) test result of comparative study of OPT and RW particleboards.

The ANOVA results for bending strength in Table 2 revealed significant differences among particleboard formulations for both OPT and RW ($p < 0.001$). This indicates that variations in PVA, $CaCO_3$, and NaCl contents had a measurable influence on the bending performance of the composites. For OPT-based boards, the between-group variance ($F = 12.523$) was notably higher than the within-group variance, confirming that formulation played a dominant role in determining flexural strength. Similarly, RW composites also showed significant treatment effects ($F = 5.546$), though the lower F value suggests that RW was less sensitive to additive changes compared with OPT. These findings highlight that the mechanical properties of the boards are strongly dependent on binder and filler composition, consistent with previous studies reporting that filler loading can either enhance or weaken stress transfer across the particle–matrix interface.

The Duncan post-hoc test shown in Table 3 further clarified which formulations differed significantly. For OPT, sample A2 clustered in a distinct subset with the highest bending strength, confirming the positive role of moderate PVA content in improving matrix cohesion. In contrast, formulations with high $CaCO_3$ and NaCl loadings (A3, A5, A6) fell into subsets associated with lower bending values, suggesting that excessive filler disrupted interfacial bonding. For RW, a similar pattern was observed, where B2 produced the highest bending strength, while filler-heavy formulations (B3, B4, B6) yielded lower values. These results demonstrate that PVA alone significantly enhances bending properties through hydrogen bonding interactions, whereas high mineral filler contents tend to dilute the effectiveness of the binder. Collectively, the ANOVA and post-hoc outcomes validate the experimental observations and confirm that formulation optimization is critical for achieving the desired balance between strength and functionality.

Table 2. ANOVA for the Bending Test of OPT and RW particleboard with different ratio

Bending Test		**Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
	Between Groups	94.692	5	18.938	12.523	<.001
OPT	Within Group	63.516	42	1.512		
	Total	158.208	47			
	Between Groups	62.918	5	12.584	5.546	<.001
RW	Within Groups	95.290	42	2.269		
	Total	158.208	47			

Table 3. Duncan Post-Hoc for Bending Test

Bending Test		**Subset for alpha= 0.05**	
OPT	**N**	**1**	**2**
A1	4	.5325	
A2	4		6.0525
A3	8	1.1025	
A4	4	1.9471	
A5	24	.8437	
A6	4	.5600	
Sig.		.106	1.000
RW			
B1	4	.9300	
B2	4		5.4900
B3	4	1.7225	
B4	24	1.6558	
B5	8	1.2900	
B6	4	.9600	
Sig.		.461	1.000

*Means for groups in homogeneous subsets are displayed.
a. Uses Harmonic Mean Sample Size = 5.143

Figure 1 also presents the internal bonding (IB) performance of OPT and RW composites. The highest IB for OPT was observed in A2 (OPT + 10% PVA), while B4 (RW + 10% PVA, 20% $CaCO_3$, and 30% NaCl) showed the highest IB for RW composites. The lowest IB was recorded in B1 (control RW, 0.13 MPa). Overall, the addition of $CaCO_3$ and NaCl reduced IB in both OPT and RW, likely due to the higher $CaCO_3$ content. The decline in IB is attributed to changes in particle composition, where $CaCO_3$ partially covered the OPT particle surfaces, limiting the adhesive bonding of PVA. Similar findings were reported in $CaCO_3$-filled pine flake composites with phenol–formaldehyde resin (Tao et al., 2019). In general, RW particleboards exhibited higher IB than OPT particleboards, which is consistent with the findings of Lee et al. (2018).

The performance variations can be attributed not only to the filler content but also to interfacial interactions between PVA and the lignocellulosic particles. PVA, rich in hydroxyl (–OH) groups, forms hydrogen bonds with hydroxyl groups present on cellulose and hemicellulose surfaces of both OPT and RW. This molecular interaction improves adhesion and stress transfer across the matrix, explaining the enhanced internal bonding observed at moderate PVA levels, consistent with recent reports of hydrogen bonding and physical entanglement effects in PVA–wood systems (Liu et al., 2024; Huang et al., 2024; Chen et al., 2024). However, excessive filler loading (NaCl or $CaCO_3$) disrupts this interaction by occupying surface sites and reducing effective contact between PVA and wood particles, thereby lowering mechanical strength.

The ANOVA results for internal bonding in Table 4 demonstrated statistically significant differences among formulations for both OPT and RW composites ($p < 0.001$). The F values 10.319 for OPT and 6.680 for RW indicate that binder and filler ratios had a strong influence on tensile strength perpendicular to the board surface. Similar to the bending test, OPT appeared more sensitive to additive variation than RW, suggesting that the lower density and higher porosity of OPT fibers amplified the effects of PVA and mineral fillers.

The Duncan post-hoc analysis shown in Table 5 revealed that A2 had the highest internal bonding strength, confirming that moderate PVA addition optimizes interfacial adhesion. In contrast, formulations with excessive fillers for A3 and A6 exhibited the lowest IB, reflecting poor particle binder contact. For RW composites, B2 and B5 formed distinct subsets with the highest IB values, whereas B1 showed the weakest bonding. These results emphasize the role of PVA as a hydrogen-bonding binder while demonstrating that excessive mineral loading diminishes adhesion by masking hydroxyl-rich wood surfaces.

Table 4. ANOVA for the IB of OPT and RW particleboard with different ratio

IB		**Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
OPT	Between Groups	80.814	5	16.163	10.319	<.001
	Within Group	65.788	42	1.566		
	Total	146.601	47			
RW	Between Groups	64.938	5	12.988	6.680	<.001
	Within Groups	81.663	42	1.944		
	Total	146.601	47			

Table 5. Duncan Post-Hoc for IB

IB		**Subset for alpha= 0.05**			
OPT	**N**	**1**	**2**	**3**	**4**
A1	4	2.40125	2.40125		
A2	4			5.75750	
A3	4	.84750			
A4	24		3.39333		
A5	8	2.07250	2.07250		
A6	4	.71500			
Sig.		.053	.117	1.00	
RW					
B1	4	.51500			
B2	4				4.83750
B3	4		3.78500	3.78500	3.78500
B4	24		2.31104		
B5	8			4.29375	4.29375
B6	4		2.63500	2.63500	
Sig.		1.000	.116	.078	.261

*Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 5.143

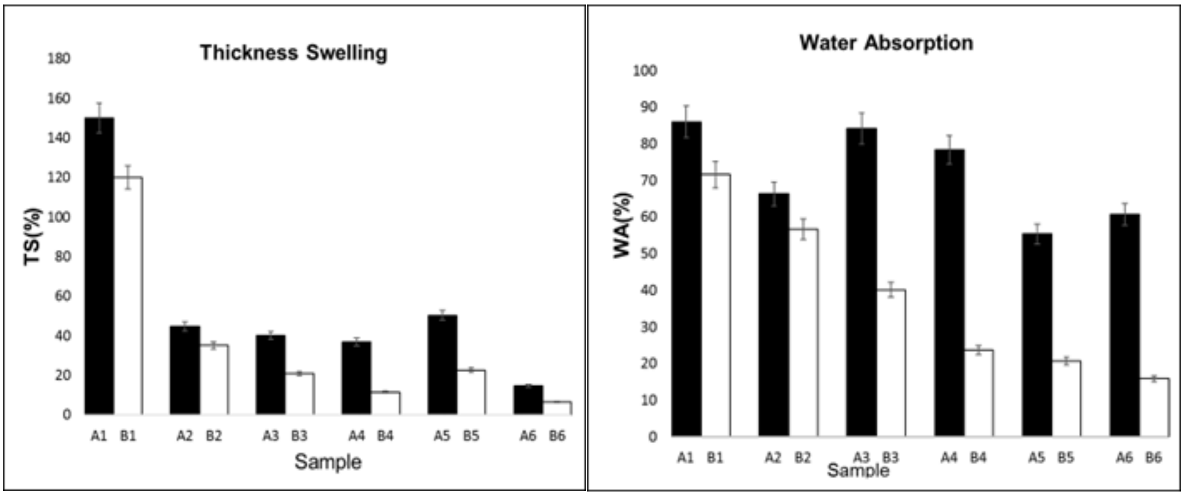

Figure 2. Thickness swelling (TS) and water absorption (WA) results of a comparative study for OPT and RW particleboards

Dimensional stability, typically evaluated through thickness swelling (TS) and water absorption (WA), is a crucial property influencing the service life of particleboards under environmental exposure. As shown in Fig. 2, both WA and TS of OPT and RW particleboards decreased with the incorporation of PVA, $CaCO_3$, and NaCl. Srivabut et al. (2018) reported that such reductions occur because chemical fillers act as barriers that limit water penetration into the boards. This modification therefore enhances the durability of both OPT and RW based composites. Swelling occurs when water molecules diffuse into the cell wall, and the extent of swelling is directly related to the quantity of water absorbed (Younis, 2017). Figure 2 further indicates that RW particleboards exhibit better dimensional stability than OPT boards, consistent with findings by Lee et al. (2018). Wahab et al. (2018) also explained that the porous structure of OPT particles promotes water uptake, leading to higher WA, which in turn results in swelling and greater TS.

The ANOVA results for TS and WA confirmed highly significant differences among board types for both OPT and RW ($p < 0.001$). For TS in Table 6, OPT had a higher F value (11.280) compared with RW (7.516), indicating stronger treatment effects in OPT-based boards. Similarly, for WA in Table 8, the influence of formulation was more pronounced in RW boards (F = 56.757) than in OPT (F = 13.265), highlighting that dimensional stability improvements depend not only on additive type but also on intrinsic wood characteristics.

Duncan post-hoc tests in Tables 7 and 9 showed that boards containing fillers and PVA for A5 and B5 exhibited significantly lower TS and WA values compared with control boards for A1 and B1. Particularly, B5 recorded the lowest water uptake, reflecting the effectiveness of mineral fillers in reducing porosity and limiting water penetration. Conversely, controls and low-PVA boards absorbed more water and swelled extensively, demonstrating the crucial role of both binder and filler in enhancing dimensional stability. These results validate that filler incorporation, when optimized, can act as a hydrophobic barrier, thereby prolonging the service life of the boards under humid conditions.

Table 6. ANOVA for the TS of OPT and RW particleboard with different ratio

TS		**Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
OPT	Between Groups	48535.129	5	9707.026	11.280	<.001
	Within Group	36143.965	42	860.571		
	Total	84679.094	47			
RW	Between Groups	39987.441	5	7997.488	7.516	<.001
	Within Groups	44691.653	42	1064.087		
	Total	84679.094	47			

Table 7. Duncan Post-Hoc for TS

TS		**Subset for alpha= 0.05**		
OPT	**N**	**1**	**2**	**3**
A1	4		149.2500	
A2	4	44.5700		
A3	4	40.4250		
A4	24	35.9121		
A5	8	25.8825		
A6	4	50.4800		
Sig.		.239	1.000	
RW				
B1	4			119.000
B2	4	35.4625	35.4625	
B3	4	20.9575	20.9575	
B4	24		56.0817	
B5	8	8.8425		
B6	4	22.3675	22.3675	
Sig.		.241	.122	1.000

*Means for groups in homogeneous subsets are displayed.
a. Uses Harmonic Mean Sample Size = 5.143

Table 8. ANOVA for the WA of OPT and RW particleboard with different ratio

WA		**Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
OPT	Between Groups	16495.192	5	3299.038	13.265	<.001
	Within Group	10445.663	42	248.706		
	Total	26940.855	47			
RW	Between Groups	23467.672	5	4693.534	56.757	<.001
	Within Groups	3473.183	42	82.695		
	Total	26940.855	47			

Table 9. Duncan Post-Hoc for WA

WA		**Subset for alpha= 0.05**			
OPT	**N**	**1**	**2**	**3**	**4**
A1	4			86.2475	
A2	4		66.4550	66.4550	
A3	4			84.3525	
A4	24	38.0633			
A5	8		69.7213	69.7213	
A6	4	55.2700	55.2700		
Sig.		.087	.173	.072	

WA		Subset for alpha= 0.05			
OPT	N	1	2	3	4
RW					
B1	4				71.4850
B2	4			56.1225	
B3	4		40.5225		
B4	24				71.9612
B5	8	19.7463			
B6	4	20.7575			
Sig.		.859	.1000	1.000	.933

*Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 5.143

3.2. EVALUATION OF LIMITED OXYGEN INDEX (LOI)

The Limited Oxygen Index (LOI) test is commonly used to evaluate the flammability and flame retardancy of materials. It is regarded as one of the key screening and quality control techniques in flame-retardant research and development (Birck et al., 2014). A higher LOI value indicates that a material is more resistant to ignition and combustion (Zhang et al., 2018). Figure 3 presents the LOI results for a comparative study of OPT and RW particleboards.

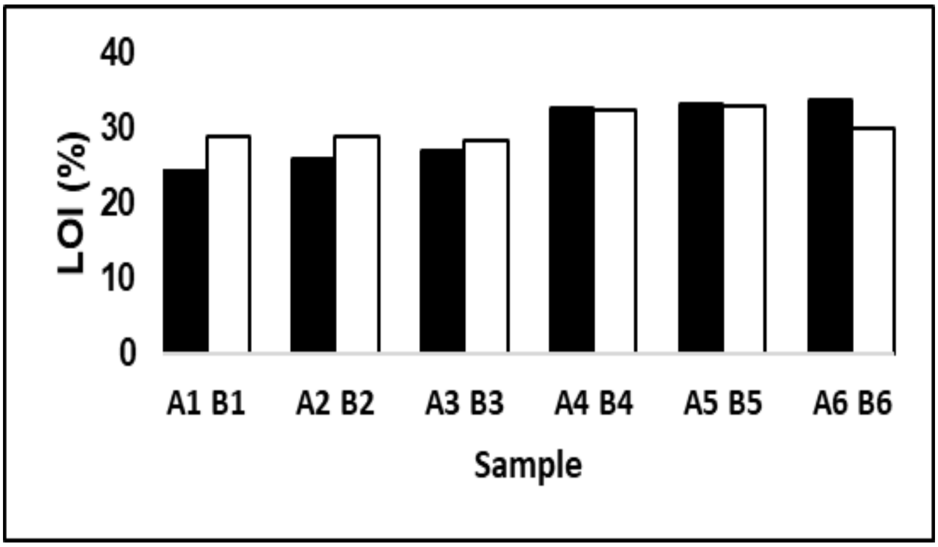

Figure 3. Limited Oxygen Index (LOI) result for comparative study between OPT and RW particleboards

As shown in Fig. 3, the LOI of OPT particleboards increased with the addition of $CaCO_3$ and NaCl fillers. The highest value was obtained for sample A6, which consisted of OPT with 20% PVA, 10% $CaCO_3$, and 30% NaCl. Wang et al. (2017) reported that $CaCO_3$ enhances flame retardancy by delaying ignition, reducing the heat of combustion, and improving the overall fire resistance of particleboards. While OPT boards generally exhibited higher LOI improvements with additive incorporation, RW-based boards also demonstrated notable flame-retardant enhancement, achieving values above 27%, comparable to OPT. The slightly lower values in RW composites may reflect differences in density and inherent lignin content, which influence char formation during combustion. Compared with conventional flame-retardant systems such as ammonium polyphosphate, borates, and halogen-free mineral fillers, the NaCl/$CaCO_3$ approach demonstrates competitive LOI values above 26% while maintaining lower toxicity and cost (Rajaei et al., 2017; Schirp & Su, 2016). While APP- or phosphorus-based systems often yield higher LOI values, they may involve higher cost or environmental concerns, highlighting the novelty of adopting NaCl as a low-cost, sustainable alternative in wood composites.

The ANOVA results for LOI in Table 10 revealed a clear distinction between OPT and RW composites. OPT boards showed significant differences among formulations ($F = 42.882$, $p < 0.001$), indicating that NaCl and $CaCO_3$ loadings had a strong influence on flame resistance. By contrast, RW composites exhibited no significant differences ($p = 0.206$), suggesting a more uniform flame-retardant performance across formulations. This discrepancy highlights the stronger responsiveness of OPT to additive incorporation, likely due to its more porous structure and higher moisture affinity.

The Duncan post-hoc test in Table 11 identified A6 as having the highest LOI, indicating that it falls into a distinct subset with superior flame-retardant performance. In contrast, A1 showed the lowest value, underscoring the necessity of filler incorporation for fire safety. For RW, although differences were not statistically significant, a gradual increase in LOI with higher filler content was observed, with B5 and B6 showing slightly better fire resistance than B1. Overall, the statistical analysis validates that mineral fillers, particularly in OPT boards, substantially enhance flame retardancy, positioning NaCl/$CaCO_3$ systems as viable, eco-friendly alternatives to conventional halogenated flame retardants.

Table 10. ANOVA for the LOI of OPT and RW particleboard with different ratio

LOI		**Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
OPT	Between Groups	391.792	5	78.358	42.882	<.001
	Within Group	76.746	42	1.827		
	Total	468.538	47			
RW	Between Groups	71.590	5	14.318	1.515	.206
	Within Groups	396.948	42	9.451		
	Total	468.538	47			

Table 11. Duncan Post-Hoc for LOI

LOI		**Subset for alpha= 0.05**			
OPT	**N**	**1**	**2**	**3**	**4**
A1	4	23.9400			
A2	4		25.7725		
A3	4		27.3000		
A4	24			30.2871	
A5	8				33.2763
A6	4				33.7650
Sig.		1.000	.077	1.00	.565
RW		Subset for alpha= 0.05			
B1	4	28.2800			
B2	4	28.9225	28.9225		
B3	4	29.1725	29.1725		
B4	24	29.5550	29.5550		
B5	8	31.1438	31.1438		
B6	4				
Sig.		.191	.059		

*Means for groups in homogeneous subsets are displayed.
b. Uses Harmonic Mean Sample Size = 5.143

3.3. EVALUATION OF THE THERMAL STABILITY OF PARTICLEBOARD

Thermogravimetric analysis (TGA) is a widely applied technique for assessing the thermal stability of materials and identifying the decomposition behavior of polymers within composite systems, such as OPT and RW-based particleboards (Younis, 2017). Figures 4a and 4b display the thermogravimetric (TG) weight-loss curves and derivative thermogravimetric (DTG) profiles, respectively, for comparative particleboards made from OPT and RW. In this evaluation, the specimens were subjected to a controlled increase in temperature to assess their heat resistance and decomposition patterns.

As shown in Fig. 4a, the TGA curves of both OPT and RW composites revealed two distinct stages of weight loss occurring between 50–150 °C and 200–250 °C. The first stage corresponds to the evaporation of moisture and volatile compounds (Lamaming et al., 2015), while the second stage reflects polymer decomposition leading to carbonaceous char formation (Zuo et al., 2018). For both OPT and RW particleboards bonded with PVA, weight loss began around 200 °C, with complete decomposition observed at approximately 543 °C, consistent with Schirp and Su (2016). This behavior is expected, as PVA undergoes dehydration at the onset of thermal degradation, producing unsaturated compounds (Younis, 2017).

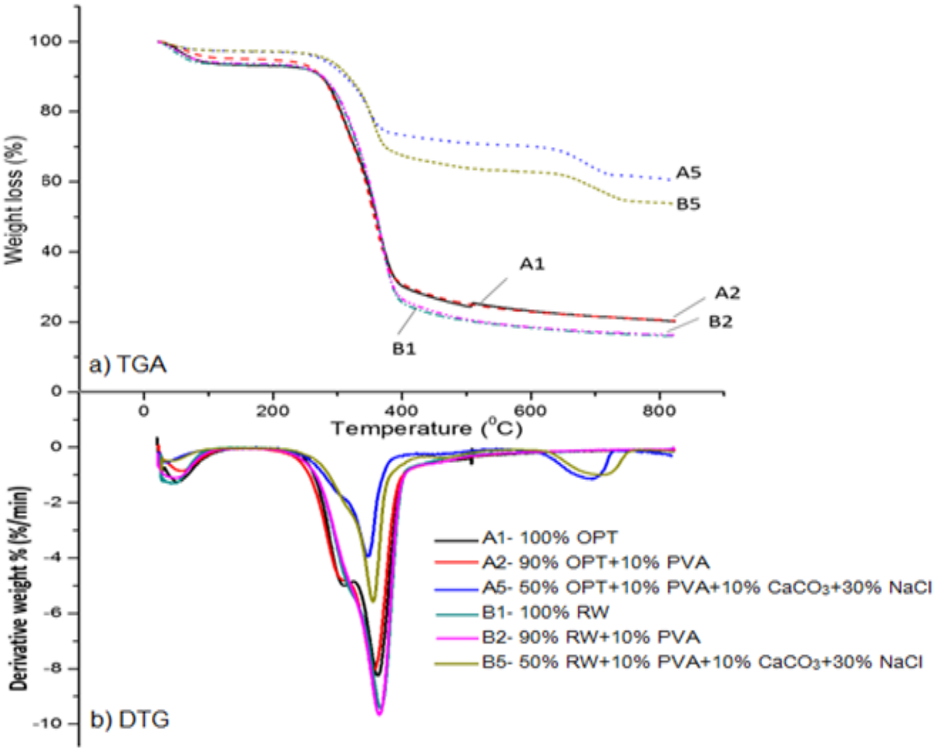

Figure 4. a) Thermogravimetric (TG) and, b) derivative thermogravimetric (DTG) curves of selected comparative particleboard of OPT and RW.

Moreover, particleboards containing 10% PVA, 10% $CaCO_3$, and 30% NaCl (samples A5 and B5) demonstrated greater thermal resistance. This improvement can be attributed to the decomposition of $CaCO_3$ into carbon dioxide at elevated temperatures, which contributes to thermal stabilization (Schirp & Su, 2016). Each additive displayed a distinct degradation pathway (Jiang et al., 2017), and Lamaming et al. (2017) further noted that the incorporation of inorganic materials enhances crystallinity, thereby improving thermal stability. The DTG results presented in Fig. 4b provide a detailed view of mass loss across distinct temperature ranges (Amini et al., 2013). In both OPT and RW composites, the addition of $CaCO_3$ and NaCl shifted decomposition onset to higher temperatures. However, RW composites consistently retained slightly higher residual mass at 600 °C compared to OPT, suggesting greater thermal stability, likely due to their denser microstructure and lower porosity.

3.4. EVALUATION IN FUNCTIONAL GROUP

Figure 5 shows the FTIR spectra of OPT and RW particleboards. A broad band near 3415 cm^{-1} corresponds to O–H stretching vibrations, characteristic of hydroxyl groups in cellulose and hemicellulose. Absorption bands between 2800–3000 cm^{-1} reflect C–H stretching vibrations associated with polysaccharides and lignin, while peaks around 1104–1110 cm^{-1} and 1155–1159 cm^{-1} indicate cellulose contributions from both crystalline and amorphous domains (Lee et al., 2018). The pronounced O–H band also supports hydrogen bonding between PVA and lignocellulosic surfaces, which underpins the enhanced dimensional stability and bonding strength observed at moderate PVA contents. In $CaCO_3$-filled boards, carbonate-related bands further suggest its contribution to flame retardancy, as thermal decomposition releases CO_2 that dilutes flammable volatiles and delays ignition.

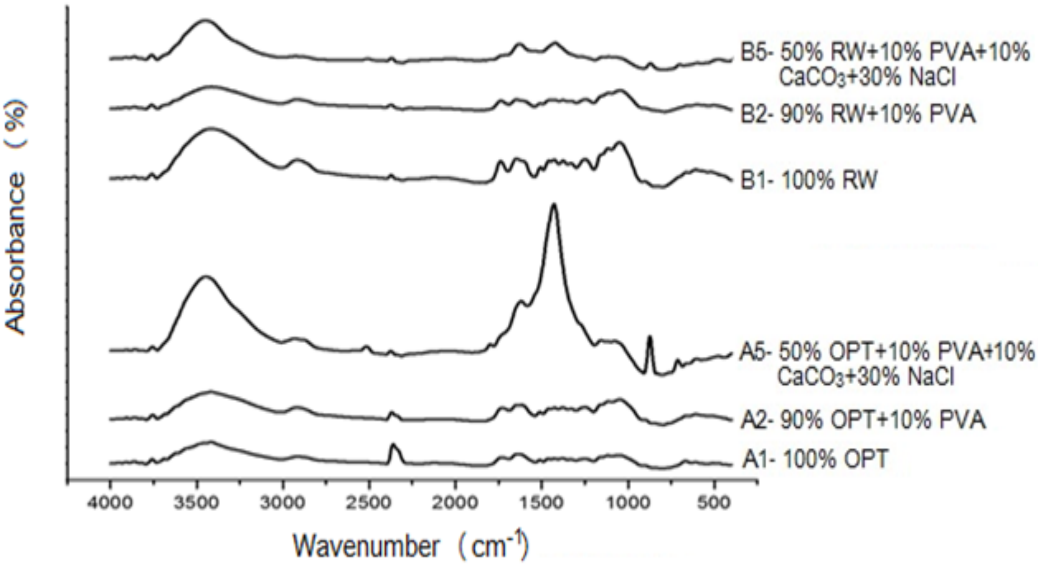

Figure 5. FTIR spectra of selected particleboards from OPT and RW

4. CONCLUSION

This study confirms the feasibility of producing flame-retardant particleboards from OPT and RW using PVA as a formaldehyde-free binder and $CaCO_3$/NaCl as eco-friendly additives. All formulations, except the OPT control, achieved LOI values above 26%, classifying them as self-extinguishing. OPT composites generally exhibited higher flame resistance, whereas RW boards showed superior internal bonding and dimensional stability, reflecting the influence of inherent material properties. These results confirm the viability of both biomass types as sustainable feedstocks for engineered wood products. Future work should focus on optimizing additive ratios to balance flame retardancy with mechanical performance, thereby supporting the development of low-emission, value-added materials for a circular, carbon-conscious economy.

AUTHOR CONTRIBUTIONS

Madihan Yusof: Conceptualization, Writing- Origional Draft Preparation; Junidah Lamaming: Data Curation, Supervision; Mohamad Saiful Sulaiman: Software, Validation; Ros Syazmini Mohd Ghani: Writing-Reviewing and Editing; Sofiyah Mohd Razali: Methodology, Validation.

COMPETING INTERESTS

The author(s) has/have no competing interests to declare.

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DATA AVAILABILITY STATEMENT

The datasets generated and analyzed during the current study are available from the corresponding author.

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