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# Innovative Biobased Composites from Oil Palm Trunk: Enhancing Mechanical and Flame-Retardant Properties through Optimized Additive Treatments

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**ABSTRACT:** This study investigates the development of an oil palm trunk (OPT) high-performance flame-retardant composite derived from an inexpensive and sustainable biomass source, processed using sodium chloride (NaCl) as a low-cost flame retardant, polyvinyl alcohol (PVA) as an adhesive, and calcium carbonate (CaCO<sub>3</sub>) as an additive. The work aims to address the inherent flammability of OPT and to enhance its mechanical performance, dimensional stability, and fire resistance in an environmentally friendly and cost-effective manner. Results indicate that a 10% NaCl treatment optimally improves the performance of the composite, increasing bending strength (MOR) from 5.95 to 12.61 MPa and internal bonding strength (IB) from 2.05 to 4.18 MPa. Dimensional stability was significantly enhanced, thickness swelling (TS) and water absorption (WA) being reduced by 43.8% and 51.3%, respectively. Flame retardancy was significantly enhanced, achieving an Underwriters Laboratories (UL-94) V-0 rating and a limiting oxygen index (LOI) value of 33.57%. Higher NaCl concentrations exceeding 10% led to reduced mechanical performance and flame retardancy, likely due to disruption of matrix-fiber interactions or the formation of voids. Compared to halogenated or phosphorus type flame retardants, the NaCl had an advantageous cost, ecology and processing ease, along with the removal of toxic emissions. Synergistic effects of NaCl, PVA, and CaCO<sub>3</sub> contributed to reduced water absorption, enhanced dimensional stability, and improved fire resistance, making this composite a viable green product for applications where flame retardation is required. This study provides new insights into the utilization of agricultural waste products to develop eco-friendly flame-retardant composite materials, contributing to environmental sustainability and the production of fire-safe engineered wood products.

**KEYWORDS:** Limited oxygen index; calcium carbonate; polyvinyl alcohol; engineered wood product

## 1 Introduction

Fire risks represent a significant hazard across various industries, including construction, packaging, and furniture manufacturing, particularly when dealing with lignocellulosic materials such as wood and agricultural waste. It has been reported that combustible products contribute to approximately 30% of building fires, highlighting the urgent need for the development of next-generation flame-retardant (FR) technologies [1].



Oil palm trunk (OPT), a highly renewable biomass material abundant in tropical regions such as Indonesia and Malaysia, holds substantial potential for sustainable product development. Although these compositions are advantageous for mechanical strength, their high cellulose and lignin content make them highly combustible, limiting their usage in flame-retardant applications [2]. While OPT offers clear environmental advantages, its inherent flammability remains a major constraint. Conventional flame-retardant approaches often involve synthetic chemicals, particularly halogenated compounds, which, despite their effectiveness, pose serious environmental and health risks [3,4]. As of this, scientists are now turning more to inorganic and bio-based options to attain fire resistance without disrupting ecological harmony [5].

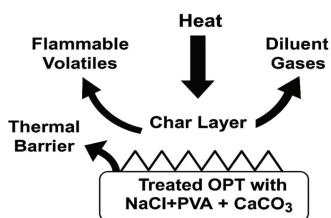
In contrast, NaCl is a benign, low-cost, and abundant inorganic salt that enhances flame retardancy primarily through char formation and suppression of flammable volatiles [6]. Its simple treatment process, non-toxic nature, and compatibility with bio-based adhesives such as PVA make it a more environmentally responsible alternative. Moreover, the absence of hazardous emissions during thermal degradation positions NaCl as a safer choice in indoor applications or consumer products. This study explores NaCl as a viable substitute for conventional flame retardants in oil palm trunk composites, offering comparative benefits in performance, processability, cost-effectiveness, and ecological impact. Furthermore, while some studies explore borax or boric acid as flame retardants, NaCl offers advantages in terms of availability, cost, and salt-induced charring mechanisms that may be particularly suited to the porosity and cellular structure of OPT. The rationale for selecting NaCl over other agents lies in its benign nature, compatibility with hydrophilic binders, and prior evidence of effective flame-retardant behavior in agricultural fibers [6].

Other components, such as calcium carbonate ( $\text{CaCO}_3$ ) and polyvinyl alcohol (PVA) also play critical roles in composite formulation.  $\text{CaCO}_3$ , commonly used in fire-resistant systems, enhances thermal stability by releasing  $\text{CO}_2$  during decomposition, thereby reducing oxygen availability for combustion [7,8]. PVA, a widely used binder in wood composites, provides excellent interfacial adhesion, though it has limited thermal stability [9]. To address this, researchers have explored the integration of inorganic fillers like boric acid and phosphorus compounds in PVA-based composites to improve fire resistance. Consequently, recent research has increasingly focused on inorganic and bio-based alternatives that achieve fire resistance while maintaining ecological integrity [5].

Conventional flame retardants, particularly halogenated and phosphorus-based compounds, are widely recognized for their high flame-inhibiting efficiency, however, their application raises critical concerns related to toxicity, environmental persistence, and disposal challenges. Halogenated systems can emit corrosive and carcinogenic gases during combustion, while phosphorus-based additives, although less toxic, often require complex synthesis and high production costs [4,5].

Despite these advances, several limitations persist in the existing research. While phosphorus-based intumescent systems have demonstrated efficacy in promoting char formation and reducing heat release rates, research on NaCl-based flame-retardant especially in biomass composite is limited [10]. Additionally, many flame-retardant applications involve complex chemical processes, which increase production costs and introduce environmental concerns [11]. Most existing studies also focus on conventional wood species, whereas the distinctive porosity and lower density of oil palm trunk require targeted research to optimize flame-retardant performance [11].

To address these gaps, this study hypothesizes that NaCl-treated oil palm trunk composites, when combined with PVA and  $\text{CaCO}_3$ , will exhibit enhanced fire retardancy and mechanical performance comparable to that of conventional flame-retardant systems, while offering environmental and cost benefits. This study introduces a novel, high-performance flame-retardant composite by applying NaCl treatment to OPT, utilizing PVA as an adhesive and  $\text{CaCO}_3$  as an additive, and Fig. 1 shows the schematic of the proposed oil palm trunk flame-retardant composite board.



**Figure 1:** Schematic of the proposed oil palm trunk flame retardant composite boards

NaCl concentrations of 10%, 20%, and 30% were selected to investigate the threshold beyond which performance declines, based on preliminary optimization studies and literature indicating a nonlinear effect of salt loading on composite properties [6,12]. The novelty of this work lies in the optimization of NaCl-based treatment for OPT and the comparative evaluation against synthetic flame-retardant systems in terms of cost, performance, and environmental impact.

The aim is to contribute to sustainability by transforming OPT waste into a value-added product. In contrast to previous studies predominantly centered on synthetic flame retardants, this work proposes an eco-friendly, cost-effective strategy for improving flame resistance using agricultural waste-derived materials. The results are expected to generate new knowledge on sustainable fire-retardant technologies for biomass-derived composites, enhancing fire safety in engineered wood products and supporting the advancement of sustainable material development.

## 2 Experimental

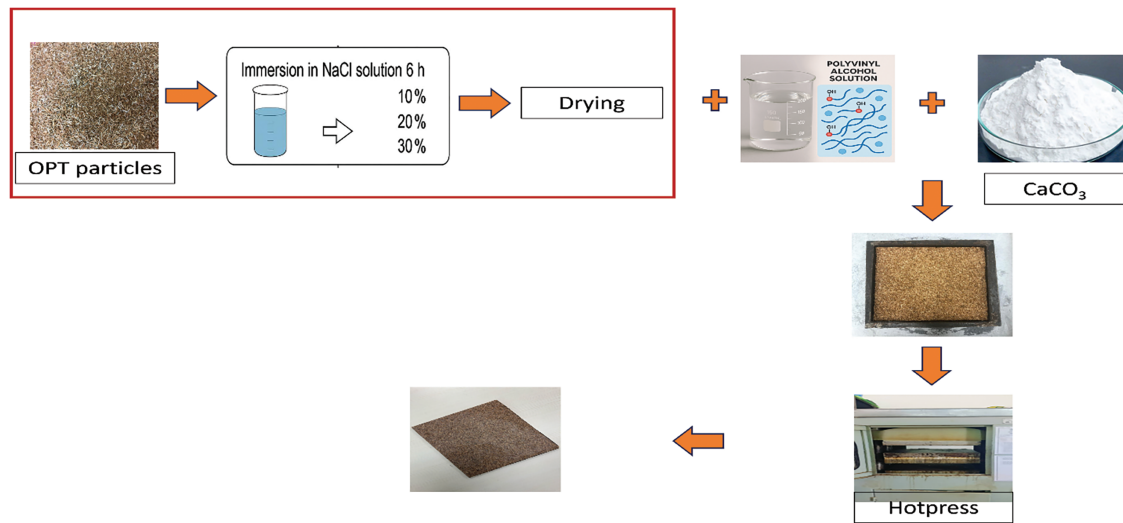
### 2.1 Materials

The OPT particles were obtained from Encore Agriculture Industries Sdn. Bhd., Kuala Lumpur, Malaysia, while the rubberwood (RW) was sourced from a plywood factory P. W Plywood in Penang, Malaysia. Both OPT and RW were ground to achieve a fine particle size of approximately 10 mm.  $\text{CaCO}_3$  and NaCl were procured from ChemAr in Selangor, Malaysia, and QRec in Negeri Sembilan, Malaysia, respectively. PVA and citric acid were supplied by R&M Chemicals from Penang, Malaysia. All the chemicals were used as received and were of analytical grade.

### 2.2 Methods

#### 2.2.1 Sample Preparation and Composite Making

The OPT was subsequently screened using a four-level screener to isolate particles ranging from 10 to 20 mm in size. These particles were treated with NaCl by immersion in 10%, 20%, and 30% NaCl solutions for 6 h, following the method described by Das and Sarmah [12]. After treatment, the particles were oven-dried at  $105^\circ\text{C}$  to remove excess water. The dried particles were then mixed with 20% PVA and 4%  $\text{CaCO}_3$ . The aqueous PVA solution was prepared by dissolving the PVA powder in deionized water at  $80^\circ\text{C}$  under constant stirring until fully dissolved [13]. Subsequently, 10% citric acid was added to the PVA solution to facilitate crosslinking, enhancing its performance as a binder. The crosslinked PVA and  $\text{CaCO}_3$  were then blended with OPT particles. The size of the composite board was  $300\text{ mm} \times 300\text{ mm} \times 10\text{ mm}$ , and the target board density was  $1\text{ kg/m}^3$ . Composite boards were hot-pressed for 10 min at a temperature of  $220 \pm 2^\circ\text{C}$  [14], achieving a final thickness of 0.5 cm. After pressing, the composite boards were trimmed to the desired dimensions. Fig. 2 shows the process of preparing the composite boards.



**Figure 2:** Schematic diagram outlining the preparation of oil palm trunk flame-retardant composite boards

### 2.2.2 Bending Test and Internal Bonding Test

The bending test was conducted using an Instron Universal Testing Machine, model 4204 from Instron Company, Norwood, CT, USA, in accordance with the JIS A 5908-2003 [15]. The test was performed under a concentrated loading rate of 10 mm/min. Specimens for the bending test measured 50 mm × 200 mm, with an effective span of 150 mm. For each particleboard type, four test samples were prepared to determine bending performance.

Internal bonding tests were also carried out following the JIS A 5908-2003 standard [15], using the same Instron 4204 machine employed in the bending test. Each specimen was adhered to a block with dimensions of 50 mm × 50 mm and positioned in the testing machine. A vertical tensile load was applied to the surface of the board at a loading speed at 2 mm/min. The maximum load (P') at which the perpendicular tensile strength of the board failed was recorded as the internal bonding strength. Four samples were replicates for the internal bonding test.

### 2.2.3 Dimensional Stability Test

The composite board was evaluated for thickness swelling (TS) and water absorption (WA) by calculating the ratio of its thickness and weight after water immersion to its initial thickness and weight, respectively. The tests were conducted by submerging the composite board in water for 24 h, and subsequent measurements were recorded. All procedures were performed by the JIS A 5908-2003 [15]. Four replicates were done for testing TS and WS, respectively.

### 2.2.4 Limited Oxygen Index Test (LOI)

The Limited Oxygen Index (LOI) test was conducted to evaluate the flammability of composite boards by determining the minimum oxygen concentration in air required to sustain combustion [16]. The test was performed using Fire Testing Technology LOI equipment, manufactured by Firetesting Technology Company, West Sussex, UK, following the ASTM D 2863-00 standard [17]. All procedures were carried out under controlled environmental conditions in accordance with the specified oxygen index testing protocol. Each specimen measured 8 cm × 1 cm × 0.5 cm, consistent with the ASTM D 2863-00 [17] standard.

### 2.2.5 UL-94

The UL 94 flammability test was conducted to assess the flammability characteristics of plastic materials, including flame-retardant composites, commonly used in the electronics and construction industries. This test quantitatively evaluates ignitability and flame propagation in vertically mounted specimens exposed to a small ignition source. The procedure, originally formulated by Underwriters Laboratories Inc., was performed in accordance with ASTM D 635-03 [18].

During testing, the burner was adjusted to produce a blue flame with an inner cone height of 20 mm and a flame power rating of 50. The flame was applied on the bottom edge of each vertically mounted specimen, with the burner positioned approximately 10 mm below the lower rim. Each sample was exposed to the flame for 10 s, repeated five times to ensure consistent combustion assessment. Five replicate specimens were prepared for each flame-retardant composite type, with dimensions of 12.5 cm × 1.3 cm × 0.5 cm.

### 2.2.6 Thermogravimetric Analysis Test

Thermogravimetric analysis (TGA) was performed using a Shimadzu TGA-50 thermogravimetric analyzer, manufactured by Shimadzu, Nishinokyo, Japan. Sample was heated from ambient temperature to 920°C at a constant rate of 20°C min<sup>-1</sup> under a nitrogen atmosphere. The TGA data were recorded as weight percentage loss relative to temperature. The thermal degradation behavior and kinetics were analyzed using the Freeman-Carroll method [19].

### 2.2.7 Study of Morphological

Scanning electron microscopy (SEM) was employed as part of the morphological characterization of the composite samples. Test specimens measuring 1 cm × 1 cm × 1 cm were prepared from the internal bonding strength samples. Before imaging, the specimens were thoroughly cleaned to remove any contaminants and oven-dried at 105°C. To enhance conductivity, the samples were coated with a thin layer of gold (approximately 20 nm in thickness) using a POLARON 515 sputter coater. Imaging was carried out using a LEO Supra 50 variation pressure (VP) scanning electron microscope manufactured by Carl Zeiss, Oberkochen, Germany, which was connected to a computer for image acquisition and processing. SEM images were evaluated based on surface morphology and analyzed from various preferred angles.

### 2.2.8 Fourier Transform Infrared (FTIR) Analysis

Fourier transform infrared analysis (FTIR) was performed to study the chemical structure of organic molecules, and to detect potential structural changes. Spectra were viewed using a Perkin-Elmer Spectrometer supplied by Perkin Elmer Company from Bridgeport, USA. The spectra of the samples were obtained by averaging 15 scans with a wavenumber range between 4000 cm<sup>-1</sup> and 650 cm<sup>-1</sup> with a resolution of 2 cm<sup>-1</sup>. Each piece was mixed with KBr and pressed into a disk with a ratio of 1:100. In infrared spectroscopy, the radiation of infrared light (IR) is passed through the piece.

### 2.2.9 Analytical Statistics

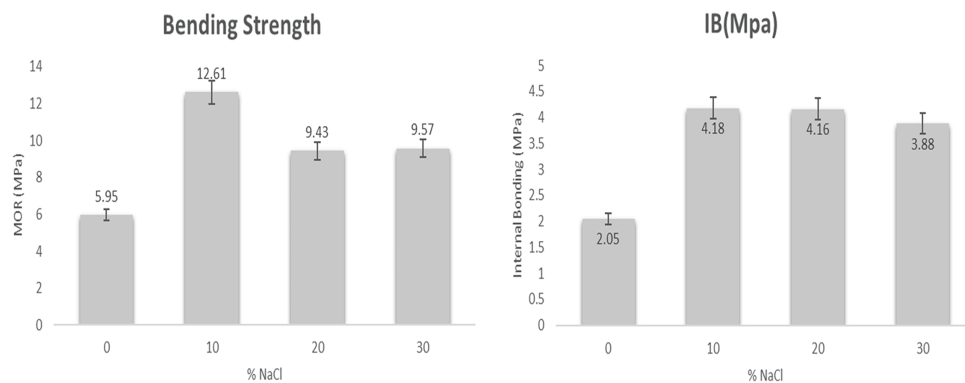
The IBM SPSS Statistics version 23 (SPSS Inc. Chicago, IL, USA) was used to analyze the data. The data were analyzed by the researchers using a single-factor, completely randomized design. Composite board properties were evaluated through Analysis of variance (ANOVA), as well as Duncan's multiple range test, with *p*-values ≤ 0.05 being statistically significant.

### 3 Results and Discussion

#### 3.1 Evaluation of Mechanical Properties and Dimensional Stability

Fig. 2 illustrates the bending strength (MOR) of the bio-based composite board derived from oil palm trunk (OPT), demonstrating a significant improvement as the NaCl content increases from 0% to 10%. The MOR value rises from 5.95 to 12.61 MPa, reflecting a substantial enhancement in mechanical properties through 10% NaCl treatment [20,21]. According to JIS A 5908-2003 [15], widely used in the evaluation of wood-based composites, the minimum MOR of composite board (Type 8) is 8.0 MPa. The standard also offers a span-to-thickness ratio of 15:1 for bending tests. As a result, the board demonstrates potential mechanical performance for non-structural applications such as wall cladding, furniture panel, and interior components. This improvement is attributed to the synergistic effects of NaCl and the inherent structure of OPT particles, which contribute to enhancing structural integrity and resistance to bending stresses. However, beyond this optimal concentration, the MOR begins to decline, falling to 9.57 MPa at 20% NaCl and further to 9.43 MPa at 30% NaCl. These results suggest that while moderate NaCl treatment reinforces the composite, excessive NaCl may disrupt the matrix-fiber interactions or induce void formation, thereby compromising structural integrity [22,23]. The optimal 10% NaCl concentration thus achieves a balance between improved flame retardancy and mechanical performance, underscoring the potential of bio-based materials such as OPT for high-performance applications.

Similarly, Fig. 3 presents the internal bonding (IB) strength of the composite board, following a comparable trend. As the NaCl content increases from 0% to 10%, IB strength rises markedly from 2.05 to 4.18 MPa, indicating enhanced interfacial adhesion and resistance to internal stresses. This enhancement is likely due to the combined effects of NaCl, PVA, and  $\text{CaCO}_3$ , which interact to reinforce the internal structure of the composite. However, as NaCl content exceeds 10%, IB strength decreases slightly to 4.16 MPa at 20% and further to 3.88 MPa at 30%. This decline highlights the necessity of optimizing additive concentrations to avoid weakening adhesion and structural stability. Similar trends have been reported in other bio-based composites, where the addition of flame-retardant or reinforcing agents enhances mechanical properties only up to a certain threshold, beyond which performance deteriorates due to matrix interference [23]. Overall, the results confirm that 10% NaCl represents the optimal concentration for maximizing the internal bonding strength of the OPT-based composite, offering a well-balanced performance in terms of both mechanical strength and fire resistance.

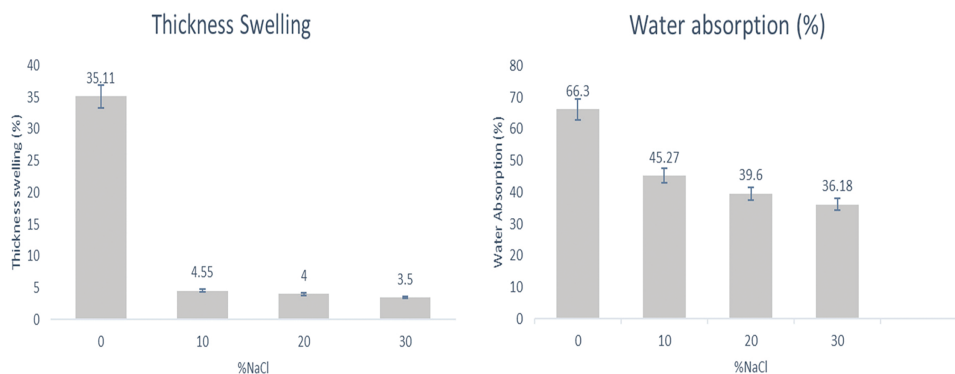


**Figure 3:** Bending strength and internal bonding strength from oil palm trunk flame retardant composite boards



These findings emphasize the vital role of renewable components such as OPT particles, PVA adhesive, and  $\text{CaCO}_3$  additive in fabricating high-performance composites. By effectively integrating bio-based resources and optimizing treatment conditions, this study demonstrates a sustainable pathway for improving the mechanical and flame-retardant characteristics of bio-based materials. Such an approach contributes to the broader objective of developing environmentally friendly alternatives to conventional synthetic composites.

Fig. 4 presents the physical properties of the OPT composite board, focusing on TS and WA, which are the key indicators of dimensional stability and moisture resistance in bio-based products. The TS values show a substantial reduction with increasing NaCl concentration from 0% to 10%, with values decreasing from 35.11% to 4.55%. This marked improvement highlights the efficacy of NaCl treatment in enhancing the dimensional stability of OPT-based composites. These results align with prior studies on bio-based materials, in which inorganic salt treatments reduced swelling and improved composite integrity. For example, Lòpez et al. [24] demonstrated that the incorporation of NaCl into thermoplastic-reinforced wood particleboards significantly reduced swelling, while Song et al. [25] found that salt-based treatments improved dimensional stability of lignocellulosic composites. Similarly, Hafidz et al. [26] reported that alkaline treatments on oil palm fibers led to micropore contraction and capillary collapse, reducing both thickness swelling and water uptake.



**Figure 4:** Thickness swelling and water absorption from oil palm trunk flame-retardant composite boards

WA results further substantiate the benefits of NaCl treatment in enhancing the performance of OPT composites. As NaCl content increases from 0% and 30%, WA significantly decreases from 66.3% to 36.18%. This trend can be attributed to the synergistic interaction among the OPT particles, PVA adhesive, and  $\text{CaCO}_3$  additive. NaCl likely alters the composite's internal structure and surface chemistry, acting as a cross-linking agent that reduces hydrophilicity and inhibits water uptake [22]. The reduction in WA becomes more pronounced at higher NaCl concentrations, confirming NaCl's crucial role in enhancing water resistance [20,21]. Additionally, PVA, a bio-based adhesive, further contributes through its strong film-forming ability, which acts as a moisture barrier [27]. The synergistic effect between NaCl and PVA enhances this barrier function, resulting in lower water absorption. Moreover,  $\text{CaCO}_3$ , a naturally occurring mineral, decreases porosity and improves mechanical cohesion, further restricting pathways for water infiltration [28].

Collectively, the interaction of NaCl, PVA, and  $\text{CaCO}_3$  represents a clear expression of individual and synergistic contributions to reducing moisture uptake and improving dimensional stability. By leveraging agricultural waste such as OPT and incorporating sustainable additives, this study presents a promising approach to developing high-performance, eco-friendly composites. These results not only validate the

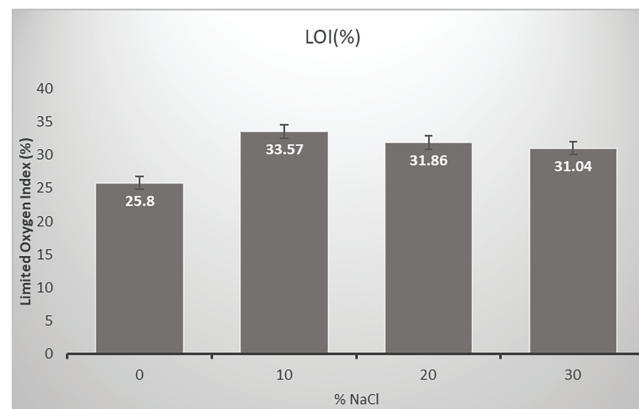
potential of agricultural waste-derived materials but also demonstrate their applicability in industries requiring moisture-resistant and dimensionally stable bio-based composites.

### 3.2 Evaluation on Limited Oxygen Index

Table 1 presents the classification of materials based on their flammability, where substances requiring oxygen concentrations below 20.95% are categorized as highly flammable, while those with LOI values of 28% or higher are considered to possess strong flame-retardant characteristics. Fig. 5 illustrates the LOI results for OPT flame-retardant composite boards treated with varying concentrations of NaCl. The LOI measures the minimum oxygen concentration required to sustain combustion, with higher values indicating superior flame retardant performance.

**Table 1:** Specimen classification according to LOI value (ASTM D 2863: 2013)

Oxygen concentration (%)	Sample classification
<20.95	Highly flammable
=20.95	Marginally stable
21 up to 28	Slow rate burning
29 up to 100	Self-extinguish
>100	Non-flammable



**Figure 5:** LOI from oil palm trunk flame retardant composite boards

A significant increase in LOI is observed as the NaCl content increases from 0% to 10%, rising from 25.8% to 33.57%. This notable improvement underscores the efficacy of NaCl in enhancing the flame retardancy of bio-based OPT composites [21]. The enhancement is likely attributed to the role of NaCl as a flame inhibitor, which promotes char formation, facilitates the release of non-combustible gases during thermal decomposition, and contributes to the formation of a protective barrier that insulates the substrate from heat and oxygen exposure [29].

However, beyond the 10% NaCl threshold, a decline in LOI is observed, with values decreasing to 31.86% at 20% NaCl and further to 31.04% at 30% NaCl. This reduction suggests that while moderate NaCl incorporation enhances fire resistance, excessive concentrations may negatively impact composite performance. The decline is likely due to the disruption of matrix-fiber interactions or the formation of microvoids within the composite, which may undermine its structural coherence and thermal barrier



effect [30]. These findings indicate that a 10% NaCl concentration provides the optimal balance between flame retardancy and mechanical integrity in OPT-based composites. This trend is consistent with observations in other bio-based systems, where flame-retardant effects are enhanced up to a critical concentration, beyond which material performance may deteriorate due to structural instability [31].

The contribution of bio-based components such as OPT particles, PVA, and  $\text{CaCO}_3$  is also critical to the observed flame-retardant performance. PVA, a bio-derived adhesive, improves interfacial bonding and film formation, while  $\text{CaCO}_3$  enhances thermal stability and reduces porosity, further contributing to the flame-retardant properties of the composite [27,28]. By utilizing renewable resources and optimizing additive formulations, this study offers a sustainable strategy for enhancing fire safety in bio-based materials. These findings support the development of eco-friendly alternatives to synthetic composites and demonstrate the potential of agricultural waste-derived materials in applications requiring reliable flame retardancy.

### 3.3 Evaluation of UL-94 Test

The categorization of flammability in the UL-94 vertical burning test is defined by the V-0, V-1, and V-2 classifications, as outlined in Table 2. The corresponding results presented in Tables 3 and 4 demonstrate a clear enhancement in flame-retardant performance with the increasing concentrations of NaCl in the OPT composite. At 0% NaCl, the composite achieves a V-1 rating, indicating that it self-extinguishes within 30 s but may emit flaming droplets during combustion.

In contrast, the addition of NaCl at 10%, 20%, and 30% consistently enables the composite to attain a V-0 rating, which is the highest classification in the UL-94 standard. A V-0 rating indicates that the material self-extinguishes within 10 s and does not produce flaming drips, reflecting excellent flame-retardant behaviour. This improvement can be attributed to the role of NaCl as both a char-forming agent and flame inhibitor. During thermal decomposition, NaCl likely facilitates the release of non-combustible gases that dilute flammable volatiles and interrupt the combustion process. Simultaneously, it contributes to the formation of a thermally stable protective barrier that limits oxygen and heat access to the composite substrate [29]. Previous studies have similarly reported the efficacy of inorganic salts such as NaCl in improving flame retardancy in natural fiber composites by enhancing thermal stability and suppressing flame spread [32]. The consistent achievement of V-0 with NaCl loadings as low as 10% emphasizes the efficiency of NaCl in delivering high flame retardant performance. These findings are consistent with earlier research on the role of inorganic flame retardants in augmenting the fire resistance of lignocellulosic products [33]. In general, these findings underscore the critical function of NaCl in enhancing the fire safety of OPT composites, validating their potential in environments where stringent flame retardant standards are required.

**Table 2:** UL94 fire testing rating and criteria [34]

Sample classified for the following criteria	V-0	V-1	V-2
After flame time for each specimen $t_1$ or $t_2$	$\leq 10$ s	$\leq 30$ s	$\leq 30$ s
Total after flame for any set ( $t_1$ plus $t_2$ for five specimens)	$\leq 50$ s	$\leq 250$ s	$\leq 250$ s
After flame/glow time to each specimen after the second application ( $t_1 + t_2$ )	$\leq 30$ s	$\leq 60$ s	$\leq 60$ s
After the flame glow of any specimen up to the clamp			
Cotton indicator ignited by flaming drips	No	No	No
	No	No	Yes

**Table 3:** UL94 fire testing rating for oil palm flame-retardant composite board

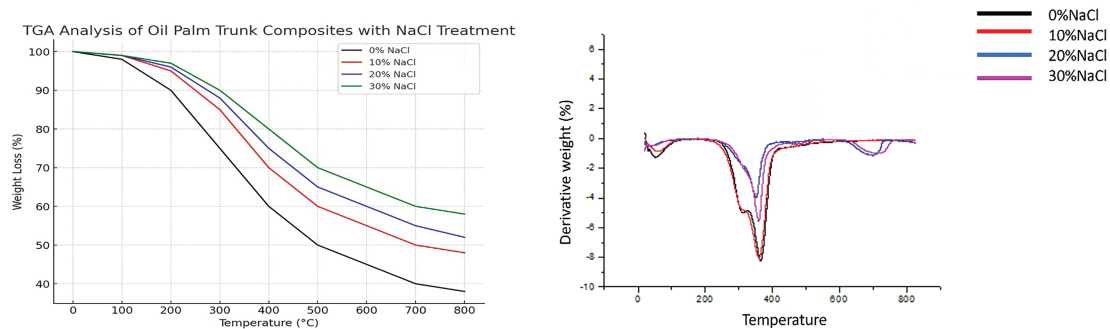
Sample classified for the following criteria	0% NaCl	10% NaCl	20% NaCl	30% NaCl
After flame time for each specimen $t_1$ or $t_2$	$\leq 30$ s	$\leq 10$ s	$\leq 10$ s	$\leq 10$ s
Total after flame for any set ( $t_1$ plus $t_2$ for five specimens)	$\leq 240$ s	$\leq 37$ s	$\leq 42$ s	$\leq 46$ s
After flame/glow time to each specimen after the second application ( $t_1 + t_2$ )	$\leq 58$ s	$\leq 24$ s	$\leq 25$ s	$\leq 29$ s
After the flame glow of any specimen up to the clamp				
Cotton indicator ignited by flaming drips	No	No	No	No
	No	No	No	No

**Table 4:** UL-94 test result from oil palm trunk flame retardant composite boards

NaCl (%)	UL-94
0%	V-1
10%	V-0
20%	V-0
30%	V-0

### 3.4 Evaluation of Thermal Stability of Composite

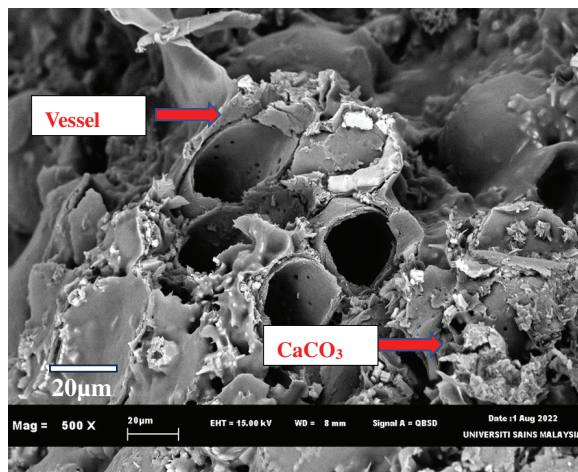
Thermogravimetric analysis (TGA) was employed to assess the thermal stability and decomposition behaviour of OPT composite boards treated with varying concentrations of NaCl. Fig. 6 presents the weight loss (%) as a function of temperature for the different NaCl-treated samples. The data indicate that increasing NaCl concentration enhances the thermal stability of the composites. The untreated sample (0% NaCl) exhibits the highest weight loss at lower temperatures, indicating early onset of thermal degradation and poor thermal resistance. In contrast, the composite treated with 10% NaCl demonstrates improved thermal stability, characterised by delayed degradation and a higher residual mass at elevated temperatures. Samples treated with 20% and 30% NaCl exhibit further enhancement in thermal resistance, consistent with findings from previous studies on salt-treated lignocellulosic composites [27].

**Figure 6:** TGA and DTG of oil palm trunk flame retardant composite boards

The derivative thermogravimetric (DTG) curve shows distinct thermal degradation profiles with a prominent peak between approximately 300°C to 400°C corresponding to the decomposition of major lignocellulosic components, hemicellulose and cellulose [27]. The most significant rate of weight loss was observed in the 0% NaCl, which proves that lower thermal stability than the treated sample. Increasing the NaCl content, especially at 20% and 30%, resulted in less intense DTG peaks that slightly shifted towards higher temperatures, interfering with a slowing down of the thermal decomposition process. This can be attributed to the flame-retardant nature of NaCl, which would facilitate the formation of a protective char layer during thermal degradation and halt volatile emission. Typically, the 30% NaCl sample had the lowest derivative weight loss, confirming enhanced thermal stability. In general, DTG curves demonstrate that the thermal resistance of oil palm trunk composite boards is improved by the NaCl treatment to be more suitable for applications where thermal durability and fire resistance are required. The improved thermal performance is attributed to the role of NaCl in reducing the evolution of volatile organic compounds, promoting the formation of a protective barrier over the lignocellulosic matrix, and enhancing char development during decomposition. Salts such as NaCl are known to facilitate the formation of carbonaceous char, which serves as an insulating layer that retards heat transfer and minimizes combustion [35].

### 3.5 Evaluation of Morphological

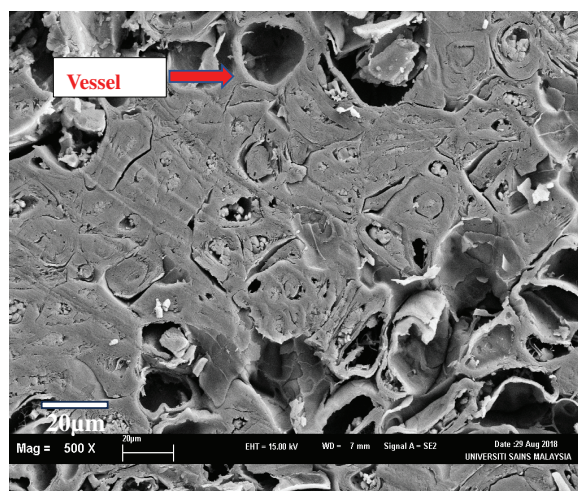
The scanning electron microscopy (SEM) micrographs offer detailed insights into the microstructural differences between OPT composite treated with 10% NaCl and those left untreated. As shown in Fig. 6, the NaCl-treated composite exhibits a denser and smoother surface morphology compared to the untreated sample. NaCl treatment appears to reduce surface porosity and improve the overall structural integrity of the composite. This is evident from the reduced presence of voids and the enhanced surface smoothness in the treated sample. The increased compactness likely contributes to the improvements in mechanical strength and reduced water absorption previously reported (Fig. 7) [20].



**Figure 7:** SEM from OPT with 10% NaCl with 500× magnification

In contrast, Fig. 8 illustrates the untreated OPT composite, which displays a rougher surface with a higher degree of porosity. The abundance of voids and surface irregularities indicates weak interfacial bonding and poor structural cohesion, which can negatively affect both mechanical performance and dimensional stability. These microstructural deficiencies correspond with the lower bending strength (MOR) and IB values observed in untreated composites. The smoother and more homogenous surface of the NaCl

sample, on the other hand, suggests improved adhesion between the matrix and the fibers, contributing to superior resistance against both bending and internal stresses [22].



**Figure 8:** SEM from OPT with 0% NaCl with 500× magnification

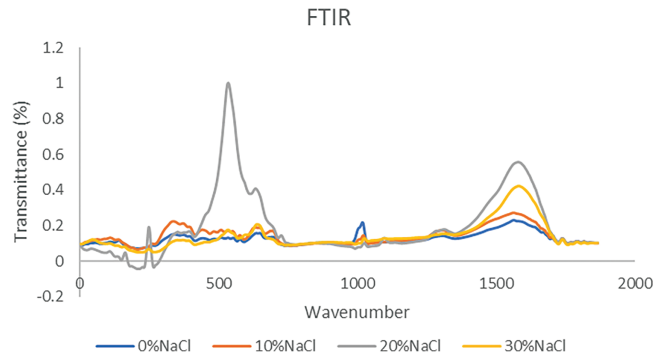
Additionally, the SEM observations align with the results of the WA and TS tests. The reduced porosity in the 10% NaCl-treated composite limits the pathway for water ingress, resulting in enhanced dimensional stability. This suggests that NaCl may alter both the inner structure and surface properties of the OPT particles, potentially acting as a crosslinking agent that decreases hydrophilicity while enhancing flame resistance [27]. The synergistic interaction among NaCl, PVA adhesive, and  $\text{CaCO}_3$  is further validated by the superior performance in flame retardancy tests. Specifically, the 10% NaCl-treated composites achieved the highest LOI value and consistent V-0 ratings in the UL-94 test [29,32].

Overall, the SEM micrographs visually confirm the beneficial effects of NaCl treatment on the microstructure of OPT composites, which underlie the observed enhancement in mechanical, dimensional, and flame-retardant properties. These findings are consistent with prior research demonstrating how inorganic fillers such as NaCl and  $\text{CaCO}_3$  can significantly improve the structural and functional performance of lignocellulosic composites [33]. The 10% NaCl treatment is identified as the optimal formulation, offering an effective balance between flame retardancy and mechanical performance, and thus presents a promising strategy for the development of high-performance, sustainable OPT-based composites.

### 3.6 FTIR Analysis

The FTIR analysis of composite boards of oil palm trunk treated with different concentrations reveals the chemical modification presented in Fig. 9. Characteristic lignocellulosic peaks were observed in all samples, such as a broad absorption band  $3300\text{ cm}^{-1}$  (O–H stretching),  $2900\text{ cm}^{-1}$  (C–H stretching), and peaks at around  $1730$  and  $1600\text{ cm}^{-1}$  corresponding to C=O stretching in hemicellulose and aromatic skeletal vibrations in lignin, respectively. Notably, the 20% NaCl-treated sample displayed significantly higher transmittance intensities across the fingerprint region ( $400\text{--}1500\text{ cm}^{-1}$ ), particularly at  $\sim 500$  and  $\sim 1500\text{ cm}^{-1}$ , indicating deeper chemical interactions or structural reorganization. This can be taken to imply partial crystallization of the NaCl-induced reorganization of the polymeric network that enhances the rigidity or thermal response of the composite. The changes also indicate potential alterations in hydrogen bonding and NaCl biopolymer interactions, supporting improvements in fire resistance and thermal stability as observed in DTG analysis. The findings are consistent with current studies on the role of inorganic salts in modifying

the physicochemical structure and flame retardancy of lignocellulosic composites [27,34,36]. The inclusion of NaCl not only alters the chemical environment but can also enhance composite durability for thermal and structural applications.



**Figure 9:** FTIR spectra of oil palm trunk composite boards

### 3.7 Statistical Analysis of ANOVA

The ANOVA results in Table 5 clearly show that different NaCl treatment ratios significantly affected all properties of the oil palm trunk composite board, including TS, WA, MOR, IB, and LOI. For all response variables, the  $p$ -values are less than 0.001, indicating statistically significant differences among the treatment groups at the 0.005 significance level. For TS, ANOVA shows a very high F-value, demonstrating a strong impact of NaCl treatment ratio on the dimensional stability of the composite board. Similarly, for WA, a higher F-value confirms that NaCl treatment plays a significant role in reducing moisture absorption within the composite structure.

**Table 5:** Analysis of Variance (ANOVA) of oil palm trunk composites board with different ratio of NaCl treatment

Response: NaCl Ratio (%)	Df	Sum Sq	Mean Sq	F value	Prob > F
TS	3	2870.977	956.992	4559.186	<0.001**
WA	3	2190.133	730.044	9945.263	<0.001**
MOR	12	92.401	30.800	203.906	<0.001**
IB	3	11.902	3.967	60.646	<0.001**
LOI	12	140.582	46.861	316.515	<0.001**

Note. \*\*Significant with  $p < 0.005$

The mechanical properties for MOR and IB also showed significant variation with NaCl treatments. This indicates that the NaCl content affects bending strength and internal bonding in the composite. This may be either by changing fiber-matrix interaction or reinforcement of the fiber due to NaCl, depending upon concentration. While for LOI showed a highly significant treatment effect with F-value of 316.515. It means that the flammability characteristics of the composite are altered by the addition of NaCl. Overall, ANOVA results confirm that the variation of NaCl ratio significantly affects the physical, mechanical and flame retardant properties of oil palm trunk composite boards. The finding emphasize the importance of optimizing NaCl concentration to enhance the performance characteristics of bio-based composite for panelling or structural applications.

### 3.8 Aging Behaviour and Environmental Durability

Although this study demonstrates enhancements in flame retardancy, mechanical properties, and dimensional stability of the treated OPT composite with NaCl at different concentrations, there remains a genuine concern over long-term durability under environmental stress conditions for real-world applications. Exposure to cyclic humidity, UV radiation, and thermal cycling can lead to structural degradation and loss of fire resistance. The hydrophilicity of NaCl and PVA may result in salt leaching or binder degradation over time, causing interfacial bonding loss and weakening of composite integrity. UV exposure can also cause polymer chain scission or surface degradation with a negative influence on appearance, as well as mechanical stability. Accelerated aging tests like moisture absorption-desorption, thermal aging, and UV exposure, therefore, ought to be incorporated in future investigations to evaluate the long-term performance of the material. In particular, prolonged moisture contact can alter salt distribution and reduce adhesion between OPT fibers and PVA–CaCO<sub>3</sub> matrix. These works are essential to confirm environmental reliability and functional durability of the composite, particularly in exterior building or outdoor furnishing use. Such durability experiments integrated into the paper will provide more in-depth insight into lifecycle performance and guide the material's industrial-scale usage.

### 3.9 Limitations and Future Work

While this study presents encouraging results in enhancing OPT composites using NaCl, PVA, and CaCO<sub>3</sub>, several limitations warrant attention for future development. The current evaluation was confined to initial mechanical, physical, and flame-retardant properties, without assessing long-term durability under environmental aging conditions such as UV exposure, humidity cycling, or thermal fluctuations. These factors are essential for predicting the composite's real-world performance, particularly in outdoor or semi-exposed applications. Industrial scalability also poses significant challenges. The NaCl immersion process, while effective at the laboratory scale, may be inefficient for large-scale production due to extended drying times, high water consumption, and the risk of uneven salt distribution. Furthermore, although PVA enhances adhesion and environmental compatibility, its relatively high cost may limit feasibility for mass production. Uniform dispersion of CaCO<sub>3</sub> and consistent matrix-fiber interaction across large panels also require further process optimization. To ensure commercial viability, future research should focus on pilot-scale production trials, automation of the treatment and forming steps, and comprehensive life cycle and techno-economic assessments. Environmental impact studies, particularly concerning NaCl leaching and end-of-life disposal, are also necessary to support the material's sustainability claims and industrial adoption. To ensure responsible material development, future studies should incorporate comprehensive life-cycle assessments (LCA) to quantify the environmental footprint of the composite, from raw material extraction to end-of-life management. This includes evaluating salt leaching behavior, eco-toxicity thresholds, and potential impacts under various disposal and recycling pathways. Incorporating such analyses will be essential for validating the composite's sustainability and aligning its application with environmental regulations and circular economy principles.

## 4 Conclusion

The fabrication of flame-retardant OPT composites with NaCl, PVA, and CaCO<sub>3</sub> exemplifies a green and sustainable alternative to conventional petroleum-based composites. By optimizing the NaCl treatment conditions, this study successfully enhances the mechanical, thermal, and flame-retardant properties of OPT-based composites, while simultaneously addressing the environmental concerns associated with synthetic flame retardants. The results underscore the significance of advanced treatment strategies and processing techniques in improving the compatibility of biomass-derived reinforcements with polymer matrices.



The synergistic interactions among NaCl, PVA, and CaCO<sub>3</sub> are shown to improve structural integrity, dimensional stability, and flame resistance, validating the approach of integrating bio-based additives for performance enhancement. Moreover, the investigation of interfacial bonding and microstructural features highlights the critical role of material design in the development of high-performance bio-composites. This research makes a valuable contribution to the growing field of hybrid composites based on lignocellulosic materials and biopolymers, supporting the advancement of sustainable material technologies. As industries increasingly prioritize environmental responsibility, the findings provide a foundational framework for the development of next-generation biomass-based thermoset and thermoplastic composites and offering cost-effective, high-performance, eco-friendly alternatives for diverse industrial applications.

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