

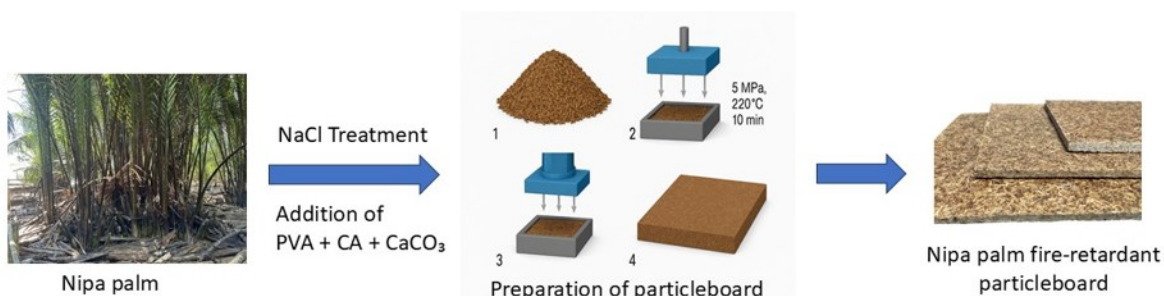
# Physicochemical and Fire-resistant Properties of Optimized Nipa Palm-based Flame-retardant Composite

Junidah Lamaming <sup>a,\*</sup>, Madihan Yusof <sup>b</sup>, Muhamad Saiful Sulaiman <sup>b</sup>, Nurjannah Salim <sup>c</sup>, Ros Syazmini Mohd Ghani <sup>b</sup> and Pei Yi Lee <sup>a</sup>

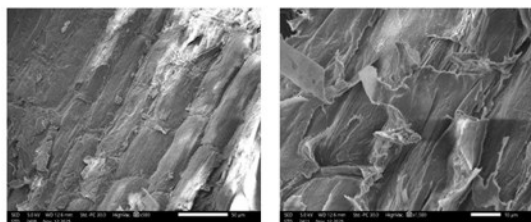
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DOI: 10.15376/biores.21.3.6679-6690

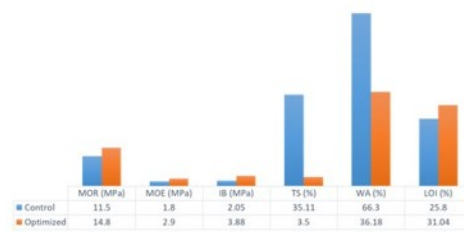
## GRAPHICAL ABSTRACT



Nipa Palm Fire-Retardant Particleboard Properties



Morphological using FESEM



Mechanical properties

# Physicochemical and Fire-resistant Properties of Optimized Nipa Palm-based Flame-retardant Composite

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Increasing demand for bio-based fire-retardant products requires abundant agricultural waste. The nipa palm, found in Malaysian estuaries, especially Sarawak, is an important, underutilized lignocellulosic resource. This study investigates the physicochemical and fire-retardant properties of a composite made from nipa palm biomass. Polyvinyl alcohol (PVOH) was crosslinked with citric acid and reinforced with calcium carbonate to produce the composite with the nipa particles. Microstructural and compositional analyses were performed utilizing scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDX), while mechanical characteristics, dimensional stability, and fire performance were rigorously investigated. The improved composite met JIS A 5908 (2003) structural particleboard standards with a modulus of rupture of 14.8 MPa, an internal bond strength of 3.88 MPa, and a modulus of elasticity of 2.9 GPa. The SEM images showed a compact, uniform cross-section with minimal voids and strong fiber-matrix adhesion. The EDX demonstrated the consistent distribution of CaCO<sub>3</sub> within the composite matrix. Synergistic interactions between PVOH–citric acid crosslinking and mineral filler reinforcement increased flame resistance and char formation in the limiting oxygen index fire analysis. This research showed nipa palm biomass to be a sustainable feedstock for high-performance fire-retardant particleboards. The work offers insight into eco-friendly interior binder systems.

DOI: 10.15376/biores.21.3.6679-6690

*Keywords:* Reinforced composite; Fire resistant board; Lignocellulosic biomass characterization; Mechanical properties; Nipa palm

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## INTRODUCTION

In Malaysia, the nipa palm grows widely along coastal and estuarine regions, with notable concentrations observed in the state of Sarawak. Sarawak's extensive mangrove forest spans roughly 0.09 million hectares (Rozainah and Aslezaeim 2010), serving as a significant and sustainable resource for the Nipa palm. The local abundance offers an economic opportunity for the valorization of fronds and empty fruit bunches (EFB), which are frequently treated as waste.

The chemical composition of nipa palm biomass is crucial for its application as a composite reinforcement and as a potential source of char-forming agents for fire retardancy. The raw material that contains cellulose (28.9 to 45.6 wt%), hemicellulose

(21.8 to 26.4 wt%), and lignin (19.4 to 33.8 wt%), which are known to influence char production and thermal stability, is mixed into a polymer matrix. The ash concentration is high (5.1 to 11.7 wt%), mostly made up of Na, K, and Ca. These elements can act as catalytic sites during thermal degradation and char formation (Tamunaidu and Saka 2011).

The incorporation of natural lignocellulosic fibers into polymer composites intrinsically elevates fire susceptibility due to their higher cellulose and hemicellulose content, which decompose swiftly under heat and facilitate flame propagation. As a result, extensive research has concentrated on enhancing the fire performance of palm-based and other agricultural biomass composites *via* chemical modification, polymer crosslinking, and the integration of inorganic fillers (Yusof *et al.* 2020; Suriani *et al.* 2021; Yusof *et al.* 2025). Previous studies have mostly focused on oil palm wastes, especially oil palm empty fruit bunch (OPEFB), due to their abundance and favorable fiber morphology. These composites often utilized conventional inorganic flame retardants, such as magnesium hydroxide ( $Mg(OH)_2$ ) and aluminum hydroxide ( $Al(OH)_3$ ), which function primarily by endothermic decomposition and the dilution of combustible gases. Suriani *et al.* (2021) reported significant reductions in burning rates, reaching as low as 11.47 mm/min at 20 wt% fiber loading, in OPEFB composites containing magnesium hydroxide. Meanwhile, Soni and Sinha (2023) explored the effect of flame-retardant additives of magnesium hydroxide and aluminum hydroxide on hemp fiber-based epoxy, and discovered that the lowest horizontal burning rate of produced composites was recorded as 11.6 mm/min with the greatest LOI was 25.3%. Both investigations demonstrate the efficacy of mineral fillers in suppressing flame spreading.

Recent research has focused on hybrid and more sustainable fire-retardant systems that combine bio-degradable polymer matrices, such as polyvinyl alcohol (PVOH), with organic crosslinkers and inorganic fillers to achieve enhanced mechanical reinforcement and improved thermal stability. The PVOH is notably attractive due to its significant char-forming ability, good hydrogen bonding potential with lignocellulosic fibers, and compatibility with green crosslinkers like citric acid. Upon crosslinking, PVOH produces a thermally stable network that limits polymer chain mobility and enhances condensed-phase flame retardancy through the creation of a protective char layer (Wen *et al.* 2025; Yusof *et al.* 2025). The incorporation of mineral fillers, such as calcium carbonate ( $CaCO_3$ ), improves fire resistance by functioning as a heat sink, emitting  $CO_2$  during thermal decomposition, and strengthening the char structure, which diminishes heat release and mass loss rates (Yusof *et al.* 2025).

Despite the increasing interest in fire-retardant lignocellulosic composites, there is still insufficient data on the utilization of nipa palm (*Nypa fruticans*) as a sustainable feedstock for fire-retardant particleboard, especially in combination with green binder systems. Current research on palm-derived fire-retardant composites has predominantly concentrated on oil palm byproducts and conventional inorganic flame retardants, whereas comprehensive studies on nipa palm particles are notably lacking, despite their prevalence in coastal and mangrove environments. Furthermore, while PVOH crosslinked with citric acid has demonstrated improvements in interfacial bonding, mechanical strength, and char formation in various lignocellulosic systems, its efficacy in nipa-based composites, particularly in conjunction with calcium carbonate ( $CaCO_3$ ) as a multifunctional filler and fire-retardant additive remains unreported. The lack of comprehensive investigations that integrate mechanical performance, microstructural analysis (scanning electron microscopy (SEM)), elemental composition (energy-dispersive X-ray spectroscopy (EDX)), and fire-retardant properties limits the understanding of the relation between structure, properties,

and fire resistance in nipa particleboards. Addressing such shortcomings is essential for promoting the sustainable utilization of nipa palm biomass and for developing sustainable, fire-resistant particleboards that comply with industrial and regulatory standards, which this study aims to further investigate.

## EXPERIMENTAL

### Materials

The nipa particles were obtained from local nipa plantation near Mukah, Sarawak and were ground to achieve a fine particle size of approximately 10 to 20 mm. Calcium carbonate ( $\text{CaCO}_3$ ) and sodium chloride ( $\text{NaCl}$ ) were procured from ChemAr and QRec, respectively. Polyvinyl alcohol (PVOH) and citric acid were supplied by R & M Chemicals. All the chemicals were used as received and were of analytical grade.

### Sample Preparation and Composite Making

The nipa particles were subsequently screened using a four-level screener to isolate particles ranging from 10 mm to 20 mm in size. These particles were treated with  $\text{NaCl}$  by immersion in 10%  $\text{NaCl}$  solutions for 6 h, following the optimized method described by Yusof *et al.* (2025). After treatment, the particles were oven-dried at  $103 \pm 2$  °C to remove excess water. The dried particles were then mixed with 20% PVOH and 4%  $\text{CaCO}_3$ .  $\text{CaCO}_3$  filler improves structural densification, thermal stability, and char formation in composites, while  $\text{NaCl}$  pretreatment improves fiber surface by removing impurities and improving particle–binder interaction, promoting better matrix interfacial bonding. The aqueous PVOH solution was prepared by dissolving the PVOH (10 g) powder in deionized water at 80 °C under constant stirring until fully dissolved (Ngadiman *et al.* 2015). Subsequently, 10% (1 g) citric acid was added to the PVOH solution to facilitate crosslinking, enhancing its performance as a binder. The crosslinked PVOH and  $\text{CaCO}_3$  were then blended with nipa particles. The size of the composite board was 300 mm × 300 mm × 10 mm, and the target board density was 1 kg/m<sup>3</sup>. Composite boards were hot-pressed for 10 min at a temperature of  $220 \pm 2$  °C, achieving a final thickness of 0.5 cm. After pressing, the composite boards were trimmed to the desired dimensions. A sample without  $\text{NaCl}$  treatment was studied as a control.

### Characterization

#### *Scanning electron microscopy*

The composite samples were morphologically analyzed utilizing field emission scanning electron microscopy (FESEM) model JEOL JSM-IT500HR (JEOL Ltd.). The internal bonding strength samples were utilized for test specimens measuring 1 cm × 1 cm × 1 cm. The specimens were dried in an oven at  $103 \pm 2$  °C and thoroughly cleaned to eliminate any contaminants prior to imaging. The samples were coated with a 20-nm thick layer of gold utilizing a sputter coater to enhance conductivity. A LEO Supra 50 VP scanning electron microscope, linked to a computer for image processing and acquisition, was employed for imaging. Images from the SEM were analyzed from multiple angles and evaluated based on surface morphology.

### *Mechanical testing*

An Instron Universal Testing Machine, model 4204, was utilized to conduct the bending test in accordance with JIS A 5908 (2003). A loading rate of 10 mm/min was employed for the test. The bending test specimens included an effective span of 150 mm and dimensions of 50 mm × 200 mm. Four test specimens were created for each particleboard type to evaluate its bending capabilities.

Internal bonding tests were conducted using the same Instron 4204 machine employed for the bending test, in compliance with JIS A 5908 (2003). Each specimen was affixed to a 50 mm × 50 mm block before being positioned in the testing device. A vertical tensile force was applied to the specimen's surface at a loading rate of 2 mm/min. The maximum load (P') at which the perpendicular tensile strength of the board failed was noted as the internal bonding (IB) strength. Four samples were utilized as duplicates for the internal bonding test.

### *Dimensional stability test*

The composite board was assessed for thickness swelling (TS) and water absorption (WA) by determining the ratio of its post-immersion thickness and weight to its initial thickness and weight, respectively. The experiments involved submerging the composite board in water for 24 h, followed by the recording of measurements. All processes were conducted in accordance with JIS A 5908 (2003). Four replicates were conducted for the assessment of TS and WS, respectively.

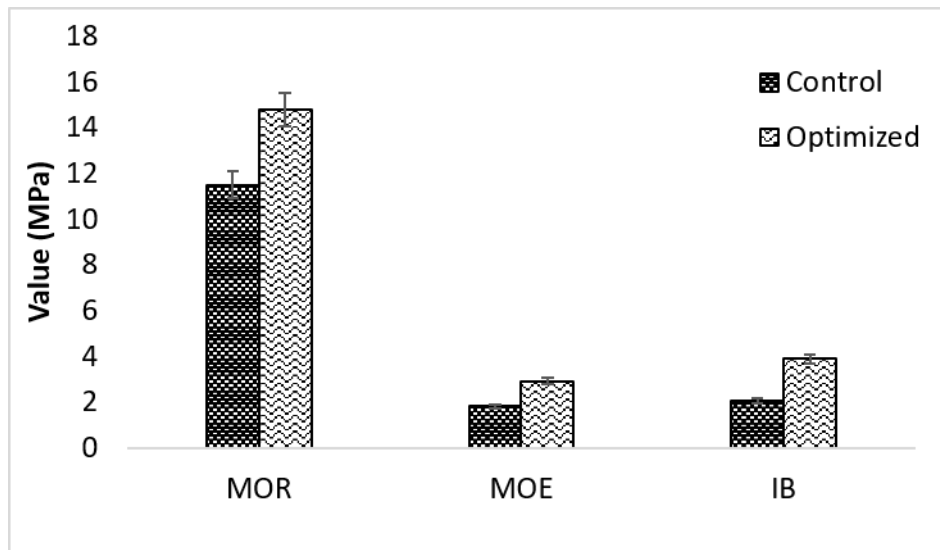
### *Limited oxygen index*

The Limited Oxygen Index (LOI) test was performed to assess the flammability of composite boards by identifying needed oxygen concentration in air necessary for combustion (Korobeinichev *et al.* 2023). The test utilized Fire Testing Technology LOI equipment in accordance with the ASTM D2863-00 (2000) standard. All procedures were conducted under regulated environmental conditions in compliance with the designated oxygen index testing procedure. Every sample measured 8 cm × 1 cm × 0.5 cm, in accordance with the ASTM D 2863-00 (2000) standard.

## **RESULTS AND DISCUSSION**

### **Mechanical Properties**

As shown in Fig. 1, the optimized particleboard greatly improved the mechanical properties of the fire-retardant composite boards made from nipa palm particles. The optimized formulation achieved a Modulus of Rupture (MOR) of 14.8 MPa, an Internal Bond strength of 3.88 MPa, and a Modulus of Elasticity (MOE) of 2.9 GPa, indicating notable enhancements relative to the control board. The values satisfy or surpass the minimum criteria established in JIS A 5908 (2003) for particleboards meant for structural and semi-structural applications, hence indicating the technical feasibility of the produced composite. The enhancement is mainly ascribed to the synergistic effects of PVOH–citric acid crosslinking and CaCO<sub>3</sub> addition, which together improve interfacial adhesion and load transfer efficiency (Jia *et al.* 2025).



**Fig. 1.** Mechanical strength of control and optimized fire-retardant nipa palm particleboard crosslinked with PVOH and citric acid

The SEM cross-sectional pictures offer direct microstructural data corroborating the observed mechanical trends. The optimized boards display fracture surfaces characterized by a dense and uniform morphology, minimal voids, restricted fiber pull-out, and comprehensive matrix covering of the nipa particles (Fig. 3c through 3f). Citric acid facilitates esterification processes between the hydroxyl groups of PVOH and the lignocellulosic components of nipa fibers, leading to a chemically crosslinked network that inhibits fiber debonding under stress. Comparable morphological changes from porous to consolidated structures have been seen in citric acid-crosslinked lignocellulosic composites and are closely associated with enhancements in MOR, MOE, and IB strength (Jiang *et al.* 2025; Yusof *et al.* 2025).

The EDX analysis supports the SEM findings by verifying the consistent distribution of calcium (Ca) throughout the optimized composite matrix, in addition to prominent carbon (C) and oxygen (O) peaks linked to PVOH and nipa fibers. The uniform Ca signal signifies efficient distribution of  $\text{CaCO}_3$ , which serves a dual function as a micro-filler and a fire-retardant addition. From a mechanical perspective,  $\text{CaCO}_3$  particles fill micro-voids and function as stress-transfer routes at the polymer–fiber interface, thus improving internal bonding strength and rigidity. This method elucidates the nearly doubled interfacial bond strength seen in the optimized boards and corresponds with other research indicating that mineral fillers substantially enhance interfacial cohesion in bio-based composites when adequately distributed (Budiyanoro *et al.* 2018; Yusof *et al.* 2025).

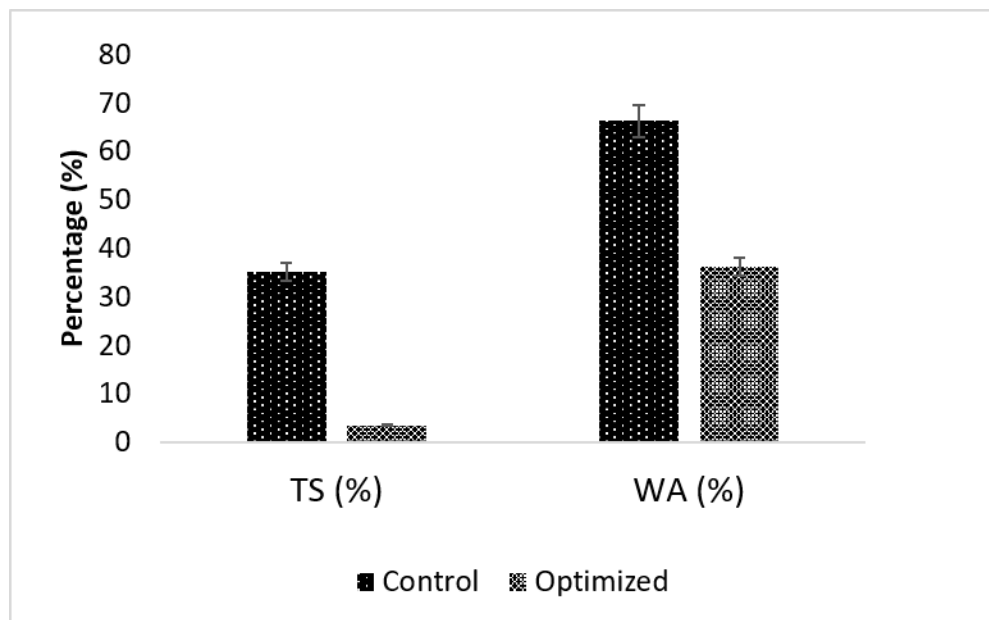
The performance trends identified in this study align with recent research on agricultural waste-derived composites with eco-friendly binder methods. Yusof *et al.* (2025) recorded similar improvements in MOR (15 to 17 MPa) and IB strength ( $> 3.5$  MPa) for fire-resistant boards produced from oil palm trunk particles utilizing a PVOH-citric acid- $\text{CaCO}_3$  formulation. Although there are variations in biomass source and fiber structure, the consistency of performance across systems highlights the flexibility and applicability of this binder synergy. The additional NaCl pre-treatment performed to nipa particles in this work likely enhanced fiber surface cleanliness and lowered hygroscopicity, hence promoting effective crosslinking and dimensional stability. The SEM, EDX, and mechanical findings collectively elucidate a definitive structure–composition–property

interaction, indicating that the optimized nipa-based composite may be created to meet industrial performance needs with sustainable materials.

### Dimensional Stability

The optimized nipa palm particleboard demonstrated a notable improvement in dimensional stability with respect to the control sample, as shown in Fig. 2. The control board exhibited a thickness swelling (TS) of 35.1% and a water absorption (WA) of 66.3%, indicating a highly porous structure with considerable infiltration of water routes. The optimized board exhibited a notable reduction in TS to 3.5% and WA to 36.1%. The TS value of the optimized composite exceeds the 12% maximum limit specified by the JIS A 5908 standard, affirming its suitability for practical applications. The notable decrease in TS and WA is due to the enhanced interfacial bonding facilitated by the PVOH–citric acid crosslinked network, which creates a more cohesive polymer matrix surrounding the nipa particles. This crosslinked structure minimizes the accessibility of hydrophilic sites and restricts water diffusion into the particleboard structure.

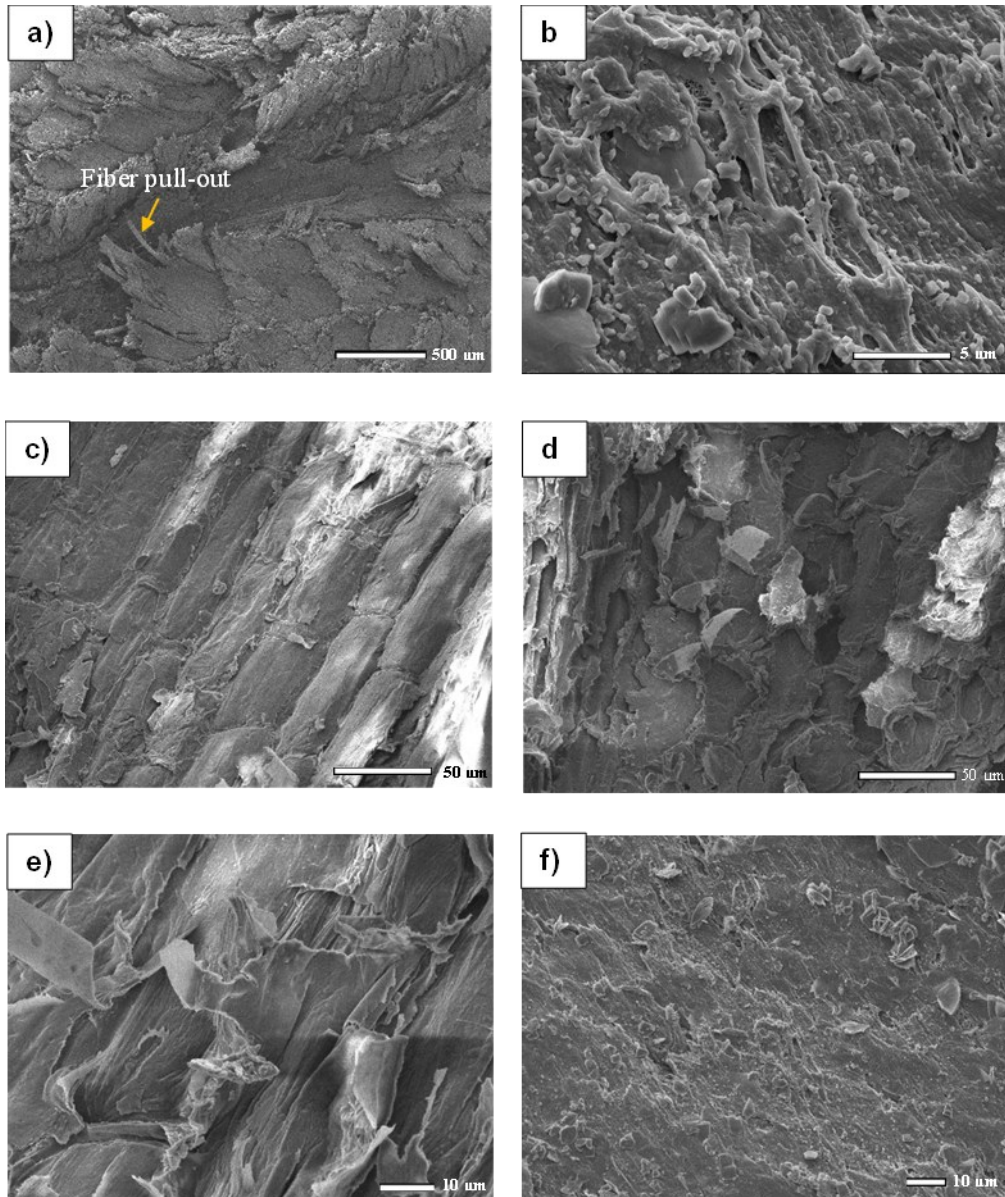
The enhancements in dimensional stability are considerably supported by the SEM morphological findings and mechanical results. The SEM images of the optimized composite displayed a dense and well-integrated microstructure with minimized voids and robust particle-matrix adhesion, while the control board exhibited increased porosity and inter-particle gaps. The use of  $\text{CaCO}_3$  filler enhanced pore filling and structural densification, hence limiting water penetration and swelling. Similar correlations between improved matrix bonding, reduced porosity, and lower TS and WA values have been widely reported in polymer-bonded lignocellulosic composites (Yusof *et al.* 2020, 2025). The synergistic effects of PVOH–citric acid crosslinking and  $\text{CaCO}_3$  reinforcement provide an integrated structure that improves mechanical strength and dimensional stability by reducing moisture infiltration and fiber expansion inside the composite matrix.



**Fig. 2.** TS and WA of control and optimized fire-retardant nipa palm particleboard crosslinked with PVOH and citric acid

### Morphological Analysis

Cross-sectional SEM micrographs (Fig. 3) show microstructural variations between the control and optimized fire-retardant nipa palm particleboard. The fracture surface on the control board (Fig. 3a and 3b) appears rough and heterogeneous, with visible cracks, inter-particle gaps, and fiber pull-out. These characteristics imply a poor interfacial contact between nipa palm particles and the binder, permitting moisture intrusion and stress concentration under load. Porous and weakly bonded morphologies have been observed in untreated lignocellulosic particleboards, which are frequently linked with low mechanical strength and dimensional instability (Jawaid and Abdul Khalil 2011; Hosseini *et al.* 2023).



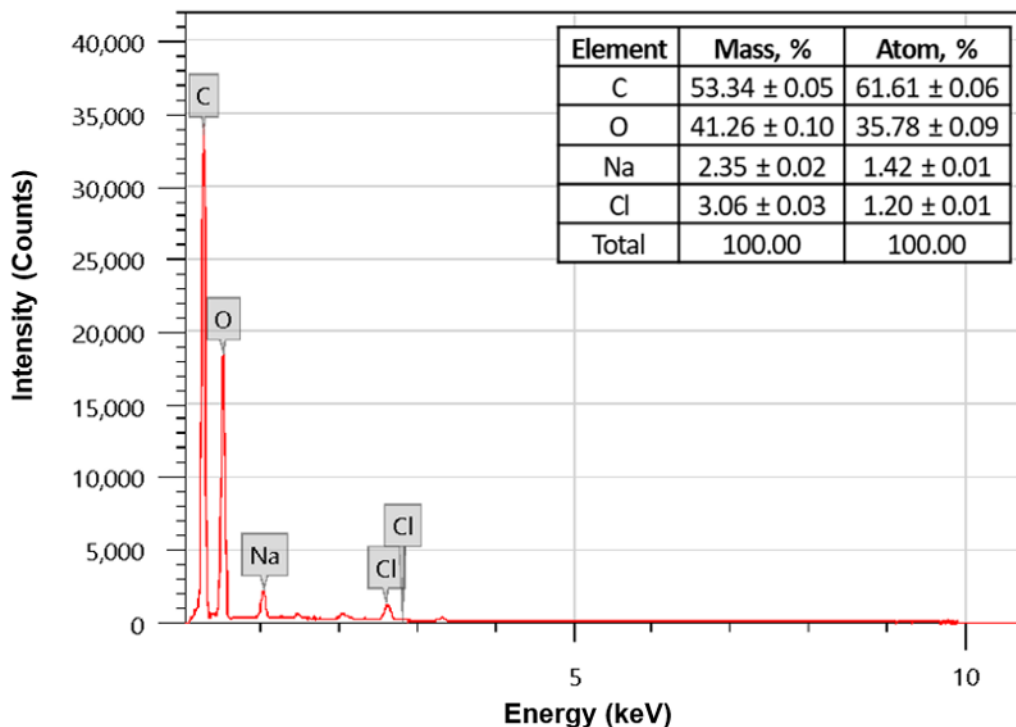
**Fig. 3.** FESEM micrographs of a-b) control; and c-f) the optimized fire-retardant nipa palm particleboard crosslinked with PVOH and citric acid

Figure 3c to 3f shows that the improved composite with PVOH and 4 wt% CaCO<sub>3</sub> had a denser and more consistent microstructure. The particles were well immersed in the PVOH matrix, with low void content and increased particle-matrix adhesion. CaCO<sub>3</sub> particles were evenly distributed and fill micro-pores and interstitial gaps, resulting in a compact structure with efficient stress transfer. The smoother fracture surfaces and reduced fiber pull-out indicated strong interfacial interactions, which were likely facilitated by hydrogen bonding between PVOH hydroxyl groups and the cellulose-rich nipa fibers (Ching *et al.* 2015; Majumdar *et al.* 2023; Jia *et al.* 2025).

Overall, the SEM results confirm the optimized fire-retardant board's higher tensile strength and dimensional stability. Combining PVOH crosslinking and CaCO<sub>3</sub> filler improves interfacial bonding, load distribution, and reduces internal porosity, preventing moisture infiltration. Similar improvements in mechanical performance and water resistance have been widely reported in mineral-filled, polymer-modified lignocellulosic composites, confirming that the microstructural densification observed here is a contributor to the superior macroscopic properties of the optimized nipa palm particleboard (Suteja and Hidayatullah 2024). The PVOH matrix infiltration into fiber surfaces, uniform CaCO<sub>3</sub> dispersion, and the absence of porosity or interfacial gaps provide a structural basis for the observed enhancements in tensile strength and dimensional stability, corroborating trends seen in similar PVOH-reinforced natural fiber composites reported in the literature.

### Elemental Analysis

The EDX analysis (Fig. 4) validates the compositional changes that are able to account for the enhanced microstructure evident in the SEM cross-sectional images of the optimized fire-retardant nipa palm composite.



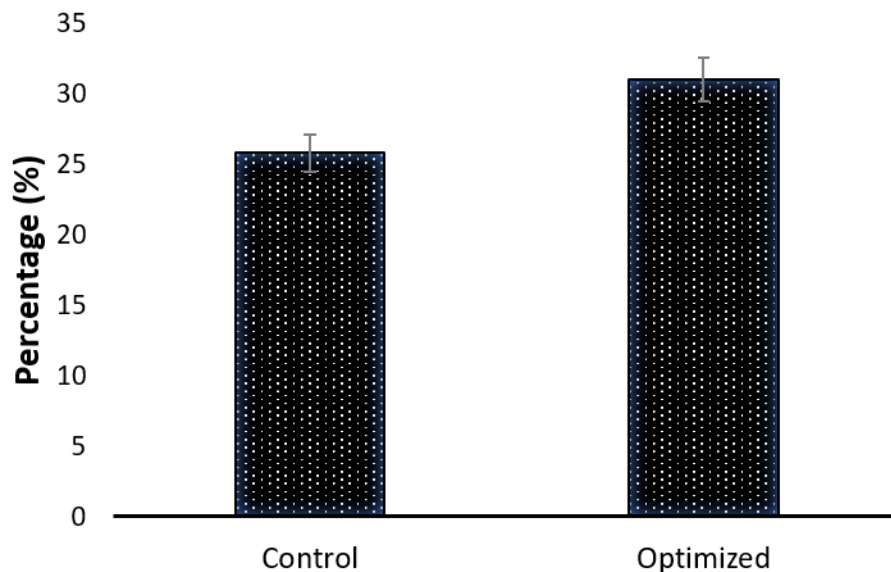
**Fig. 4.** EDX spectra for the optimized fire-retardant nipa palm particleboard crosslinked with PVOH and citric acid

The optimized composite displays clear and evenly distributed calcium (Ca) signals in conjunction with C and O, hence validating the effective integration of  $\text{CaCO}_3$  inside the PVOH-bonded matrix. The consistent Ca distribution throughout the examined regions aligned with the SEM images, which reveal pore filling, smoother fracture surfaces, and a more compact interior structure. This uniform distribution of  $\text{CaCO}_3$  indicates efficient filler-matrix interaction, with  $\text{CaCO}_3$  particles serving as micro-reinforcements and void-blocking agents, thus improving load transfer and limiting moisture penetration paths.

The compositional evidence from the EDX results strongly supports the morphological interpretation acquired from the SEM. The presence of organic elements (C, O) from nipa fiber, Na and Cl from NaCl, and PVOH alongside inorganic Ca from  $\text{CaCO}_3$  validates the formation of a hybrid organic-inorganic composite system. This synergy elucidates the noted enhancements in tensile strength, dimensional stability, and fire-retardant efficacy, as mineral fillers, such as  $\text{CaCO}_3$ , are recognized for their potential to boost char formation, thermal stability, and structural density in lignocellulosic composites. The SEM and EDX investigations collectively indicate a definitive structure-composition property relationship for the improved fire-retardant nipa palm particleboard.

### LOI Analysis

The LOI analysis demonstrated a substantial improvement in the material's fire-resistant properties following optimization. As shown in Fig. 5, the control sample exhibited an LOI of 25.8%, whereas the optimized sample, incorporating calcium carbonate,  $\text{CaCO}_3$  with PVOH synergy, achieved a higher LOI of 31.04%. This increase of approximately 5.2% indicates a transition from a slow-burning material to one that exceeds the critical 30% threshold, effectively classifying it as a self-extinguishing material. The addition of  $\text{CaCO}_3$  likely enhances the thermal stability and char formation of the matrix, thereby restricting the oxygen supply required for combustion and improving the overall fire retardancy.



**Fig. 5.** LOI of control and optimized fire-retardant nipa palm particleboard crosslinked with PVOH and citric acid

These findings are consistent with reported research on bio-composite materials, reinforcing the efficacy of mineral additives in enhancing fire resistance. A similar trend was observed by Yusof *et al.* (2020, 2025) in their studies on fire-resistant boards utilizing oil palm trunk particles, where optimized formulations yielded comparable improvements in LOI values. The alignment with the findings suggests that the synergistic interaction observed in this study is a reliable mechanism for improving the fire safety of biomass-based composites, confirming that the optimization strategy successfully elevates the material's performance to meet high fire-retardant standards.

## CONCLUSIONS

1. Particles from the nipa palm (*Nypa fruticans*) can be effectively transformed into fire-retardant particleboards *via* a sustainable PVOH–citric acid–CaCO<sub>3</sub> formulation, with mechanical properties and dimensional stability that meet JIS A 5908 (2003) standards.
2. The optimized fire-retardant nipa palm particleboard shows dense particle packing, strong PVOH-mediated interfacial bonding, uniform CaCO<sub>3</sub> dispersion, and reduced porosity. The compact microstructure and cohesive fracture behavior explain the improved tensile strength and dimensional stability compared to the control board.
3. The combined effects of PVOH crosslinking and mineral filler reinforcement enhance char formation and flame suppression, indicating the great potential of eco-friendly binder systems for sustainable construction materials.

## ACKNOWLEDGMENTS

The authors are grateful for the support of the financial aids from Universiti Malaysia Sarawak (UNI/F07/CATALYST/86420/2025) and Wacana Ilmu UNIMAS.

## Conflict of Interest

No conflict of interest.

## Use of Generative AI

ChatGPT was used to rephrase and improve the clarity of the manuscript text with all content reviewed and verified by the authors.

## REFERENCES CITED

- ASTM D635-03. (2003). “Standard test method for rate of burning and/or extent and time of burning of plastic in a horizontal position,” ASTM International, West Conshohocken, PA, USA.
- ASTM D2863-00. (2000). “Standard test method for measuring the minimum oxygen concentration to support candlelike combustion of plastics (oxygen index),” ASTM International, West Conshohocken, PA, USA.
- Budiyantoro, C., Osiati, H., Kamiel, B. P., and Fikri, M. L. S. (2018). “The effect of CaCO<sub>3</sub> filler component on mechanical properties of polypropylene,” *IOP Conf.*

- Ser.- Mater. Sci. Eng.* 432, article 012043. <https://doi.org/10.1088/1757-899X/432/1/012043>
- Ching, Y. C., Rahman, A., Ching, K. Y., Sukiman, N. L., and Chuah, C. H. (2015). "Preparation and characterization of polyvinyl alcohol-based composite reinforced with nanocellulose and nanosilica," *BioResources* 10(2), 3364-3377. <https://doi.org/10.15376/biores.10.2.3364-3377>
- Hosseini, S. B., Gaff, M., Li, H., and Hui, D. (2023). "Effect of fiber treatment on physical and mechanical properties of natural fiber-reinforced composites: A review," *Rev. Adv. Mater. Sci.* 62, article 20230131. <https://doi.org/10.1515/rams-2023-0131>
- Jawaid, M., and Abdul Khalil, H. P. S. (2011). "Cellulosic/synthetic fibre reinforced polymer hybrid composites: A review," *Carbohydr. Polym.* 86(1), 1-18. <https://doi.org/10.1016/j.carbpol.2011.04.043>
- Jia, D., Xu, L., Pan, D., Xiao, Y., Zhang, Y., Yuan, Y., and Wang, W. (2025). "Flame-retardant polyvinyl alcohol materials: Mechanisms, design strategies, and multifunctional applications," *Polymers* 17(19), article 2649. <https://doi.org/10.3390/polym17192649>
- Jiang, K., Wang, J., Fan, D., Chu, F., and Chen, Y. (2025). "Citric acid-mediated lignocellulosic fiber bonding for sustainable materials: Multiscale insights into molecular cross-linking and physical interlocking," *ACS Sustain. Chem. Eng.* 13(50), 21568-21578. <https://doi.org/10.1021/acssuschemeng.5c08884>
- JIS A 5908:2015 (2015). "Particleboards," Japanese Standards Association, Tokyo, Japan.
- Korobeinichev, O. P., Sosnin, E. A., Shaklein, A. A., Karpov, A. I., Sagitov, A. R., Trubachev, S. A., Shmakov, A. G., Paletsky, A. A., and Kulikov, I. V. (2023). "The effect of flame-retardant additives DDM-DOPO and graphene on flame propagation over glass-fiber-reinforced epoxy resin under the influence of external thermal radiation," *Molecules* 28(13), article 5162. <https://doi.org/10.3390/molecules28135162>
- Majumdar, R., Mishra, U., Mahata, N., Shah, M. P., Mondal, A., and Bhunia, B. (2023). "Preparation, characterization, and performance evaluation of composite films of polyvinyl alcohol/ cellulose nanofiber extracted from *Imperata cylindrica*," *Chemosphere* 337, article 139370. <https://doi.org/10.1016/j.chemosphere.2023.139370>
- Ngadiman, N. H. A., Noordin, M. Y., Kurniawan, D., Idris, A., Shakir, A. S. A. (2015). "Influence of polyvinyl alcohol molecular weight on the electrospun nanofiber mechanical properties," *Procedia Manuf.* 2, 568-572. <https://doi.org/10.1016/j.promfg.2015.07.098>
- Rozainah, M.Z., and Aslezaeim, N. (2010). "A demographic study of a mangrove palm, *Nypa fruticans*," *Sci. Res. Essays* 5 (24), 3896-3902. <https://doi.org/10.5897/SRE.9000004>
- Soni, P., and Sinha, S. (2023). "Fiber and future: Unleashing the power of industrial hemp waste through epoxy composites," *Polym. Compos.* 45(1), 413-423. <https://doi.org/10.1002/pc.27786>
- Suriani, M. J., Radzi, F. S. M., Ilyas, R. A., Petru, M., Sapuan, S. M., and Ruzaidi, C. M. (2021). "Flammability, tensile, and morphological properties of oil palm empty fruit bunches fiber/pet yarn-reinforced epoxy fire retardant hybrid polymer composites," *Polymers* 13(8), article 1282. <https://doi.org/10.3390/polym13081282>

- Suteja, and Hidayatullah, S. (2024). “Physical, mechanical and thermal properties of PVOH biocomposite reinforced waru fiber nanocellulose–CaCO<sub>3</sub> powder,” *SJME Kinematika* 10(2), article 810. <https://doi.org/10.20527/sjmekinematika.v10i2.810>
- Tamunaidu, P., and Saka, S. (2011). “Chemical characterization of various parts of nipa palm (*Nypa fruticans*),” *Ind. Crop. Prod.* 34(3), 1423-1428. <https://doi.org/10.1016/j.indcrop.2011.04.020>
- Wen, C., Xu, D., and Wang, Q. (2025). “Preparation of bio-based flame-retardant poly(vinyl alcohol) foams with improved cell structure and mechanical performance,” *Eur. Polym. J.* 223, article 113670. <https://doi.org/10.1016/j.eurpolymj.2024.113670>
- Yusof, M., Lamaming, J., Hashim, R., Yhaya, M., Sulaiman, O., and Selamat, M. (2020). “Flame retardancy of particleboards made from oil palm trunk-poly(vinyl) alcohol with citric acid and calcium carbonate as additives,” *Constr. Build. Mater.* 263(1), 1-8. <https://doi.org/10.1016/j.conbuildmat.2020.120906>
- Yusof, M., Sulaiman, S., Ghani, R. S. M., and Razali, S. M. (2025). “Innovative biobased composites from oil palm trunk: Enhancing mechanical and flame-retardant properties through optimized additive treatments,” *J. Renew. Mater.* 13(10), 2059-2075. <https://doi.org/10.32604/jrm.2025.02025-0101>

Article submitted: February 3, 2026; Peer review completed: March 7, 2026; Revised version received: March 13, 2026; Accepted: April 20, 2026; Published: June 5, 2026.  
DOI: 10.15376/biores.21.3.6679-6690