
Research article

Role of phosphorus-based fire retardant in enhancing the fire retardancy of waste-based and natural fiber composites

Neni Surtiyeni^{1,*}, Efa Latiffah¹ and Nurul Hidayati Fithriyah²

¹ Department of Physics, Faculty of Mathematics and Natural Science, Institut Teknologi Bandung, Jalan Ganesa 10, Bandung 40132, Indonesia

² Department of Chemical Engineering, Faculty of Engineering, Universitas Muhammadiyah Jakarta, Jalan Cempaka Putih Tengah XXVII, Jakarta 10510, Indonesia

* **Correspondence:** Email: nenis@itb.ac.id.

Abstract: This study provides a preliminary investigation into the feasibility of incorporating phosphorus-based fire retardants (PFRs) into waste-based and natural-fiber composite boards using mixing and surface-coating approaches. The combination of epoxy polymer (EP) and PFR has been widely applied in the electronics, transportation, and construction industries. PFR functions via gas-phase radical quenching and condensed-phase char promotion, thus slowing the combustion rate. The primary challenge lies in identifying the most effective method for incorporating PFR into the composites. Two approaches were investigated: The mixing method, which involves blending PFR with other composite components, and the coating method, which involves applying PFR to the surface of the composite using a suitable polymer adhesive. The thermoplastic polymer polyvinyl alcohol (PVA) was able to bind PFR powder to the surface of wooden boards but was ineffective on composite board surfaces. In contrast, thermoset polymers such as urea-formaldehyde (UF) and EP successfully adhered PFR to the surface of composite boards. Fire retardancy tests demonstrated that the mixing method offered a simple and effective approach for fabricating fire-retardant composite boards (peak temperature was reached 2.5 times longer), while EP was identified as a more effective adhesive for surface coating (1.6 higher residual mass compared to UF). Both methods are viable for further development in the production of fire-retardant composites. To achieve optimal fire performance, the critical mass optimization of PFR is required. Notably, exceeding this critical mass (1.5 g of PFR/EP coat on waste-based composite boards) can paradoxically increase the combustion rate rather than suppress it.

Keywords: composite board; fire retardant; municipal solid waste; natural fiber; phosphorus

1. Introduction

Municipal solid waste (MSW) management is a major problem in developing countries, such as Indonesia, where landfills are the dominant method, with only a small portion of plastic waste entering the recycling industry. On the other hand, population growth has led to a sharp increase in the demand for wood for furniture, construction, packaging, and other purposes. The development of particle board (PB) industry from sawdust has given rise to innovations in processing MSW into composite boards as a wood substitute [1–3]. Industrial PBs relies heavily on the development of adhesive technology, which is dominated by environmentally harmful formaldehyde-based adhesives. Composite boards have been successfully produced from waste leaves, plastic, paper, fabric, and polyvinyl acetate (PVAc) adhesives with mechanical strength equivalent to that of Albizia wood (AW). Composite boards are added with fire retardant (FR) to improve fire retardancy, thus requiring a longer burning time. In addition to significantly reducing waste, composite boards can be used as a wood-replacing building material for simple houses [3–6].

A fundamental understanding of combustion mechanisms is essential for the development of effective fire retardancy properties. The combustion process is described by the fire tetrahedron, which comprises four critical elements: fuel, oxygen, heat, and chain reactions. Fire initiation begins with pyrolysis, an endothermic process wherein flammable materials decompose when exposed to heat from ignition sources such as a lit cigarette or faulty electrical equipment. This heat induces thermal degradation of the combustible substrate, resulting in the release of gases, heat, light, and smoke. The emitted gases act as fuel when they encounter sufficient atmospheric oxygen. The exothermic nature of the combustion reaction feeds thermal energy back into the system, accelerating further substrate degradation. The release of gas and heat drives flame propagation through chain reactions, which persist as long as the energy output exceeds the energy required for degradation. Fire retardation can be achieved by incorporating fire-retardant chemicals [4,7].

FR function by disrupting one or more elements of the fire tetrahedron, thereby impeding the combustion process. This can involve isolating the fuel source, reducing heat, limiting oxygen availability, or interrupting chain reactions. Based on their interaction with the substrate, FR are categorized into additive and reactive types. Additive FRs interact physically with the substrate, whereas reactive FRs chemically bond with the polymer matrix. The fire retardancy mechanism may operate in either the gas phase or the condensed phase. Certain FR, such as clay-based materials, function exclusively in the condensed phase, while halogen-based FR (e.g., bromine and chlorine compounds) act in the gas phase [4,7].

Halogen-based FRs, such as decabromodiphenyl ether and hexabromocyclododecane, are highly effective because they inhibit flame propagation by scavenging reactive radicals in the gas phase. However, their decomposition can release hazardous and corrosive gases, such as HCl and HBr, and may generate toxic by-products under incomplete combustion conditions. These environmental and health concerns have led to increasing restrictions on their use. Boron-based FRs are generally more environmentally friendly and exhibit low toxicity, but their high water solubility can cause leaching in humid environments, reducing long-term fire retardancy performance. In addition, boron compounds often provide limited fire retardancy when used alone and usually require synergistic additives. For

these reasons, phosphorus-based FRs (PFRs) were selected in this study. PFRs offer a dual-action fire retardancy mechanism by functioning in the gas and condensed phases. In the gas phase, phosphorus-containing species ($\text{PO}\bullet$, $\text{PO}_2\bullet$, and $\text{HPO}_2\bullet$) suppress combustion by disrupting free-radical chain reactions of $\text{H}\bullet$ and $\text{OH}\bullet$. Furthermore, in the condensed phase, they promote the formation of a stable protective char layer that acts as a barrier against heat transfer, oxygen diffusion, and the release of flammable volatiles. This combined mechanism provides high FR efficiency while maintaining broader applicability, lower toxicity, and better environmental compatibility than conventional halogen-based systems. Consequently, PFRs are widely regarded as one of the most promising and sustainable FR solutions for polymer and bio-based composite materials [7–10].

Global FR consumption spans multiple sectors, including plastics, rubber, textiles, adhesives, and wood, with the majority (approximately 65%) used in plastics. However, the application of FR to wood and lignocellulosic materials is limited. Application methods for wood include impregnation and surface coating [11]. In the impregnation method, FRs are introduced into the wood during production, resulting in deeper penetration and retained efficacy even if the surface is damaged. However, this method is cost-intensive due to the high-pressure injection processes involved. The coating method, either intumescent or non-intumescent, involves applying FRs to the wood surface. It is more economical and straightforward but may lose effectiveness if the coating is physically compromised [3,4]. Combinations of PFRs and epoxy are widely utilized as plasticizers in polymer composites for use in electronics, construction, and transportation industries [12].

Recent research has successfully created environmentally friendly and sustainable plywood that has superior cohesive bonds, water resistance, and fire retardancy by using chitosan-based biomass adhesives. The adhesive's superior performance is achieved through synergistic physicochemical cross-linking of chitosan dissolved in phytic acid, glycerol triglycidyl ether, and polyacrylamide, which forms a three-dimensional interpenetrating network structure. Fire-resistant wood modification is obtained through the impregnation process of sodium silicate and aluminum hydroxide, which is a synergistic fire-retardant system. Furthermore, the use of (3-aminopropyl) triethoxysilane for the reaction process between the adhesive and the wood substrate. Biomass adhesives can also be made from a mixture of chitosan and polyacrylic acid. To improve fire-resistant properties, the adhesive can also be mixed with ammonium polyphosphate [13,14].

In this study, we report a series of treatment steps applied to waste-based composite boards (WCB) to enhance their fire retardancy properties. PFRs were incorporated into the composite material. The first step involved identifying effective methods to integrate PFRs into the waste composite. Two approaches were employed: (1) incorporating PFRs as fillers during board fabrication and (2) applying surface coatings using adhesive polymers. For the coating approach, selecting a polymer with appropriate compatibility was essential. Subsequently, different PFR mass ratios were tested to determine the optimal quantity yielding the lowest combustion rate. Finally, the fire resistance of the untreated composite boards was compared to various wood-based panels to evaluate the key factors influencing the fire retardancy behavior of natural fiber composites.

2. Materials and methods

PFR powder was characterized using JEOL JSM-6510 scanning electron microscopy (SEM), operated at an accelerating voltage of 15.0 kV, integrated with Energy dispersive X-ray spectroscopy (EDS) function for elemental analysis.

The WCB consisted of plant waste, plastic, textile, and paper, with PVAc serving as the binder. The plant waste component comprised various leaves and vegetables. Plastic components were obtained from different types of post-consumer plastic packaging waste. The textile component consisted of a mixture of cotton and polyester fibers, while the paper component was derived from discarded newspapers and magazines. All waste materials were collected from a typical housing neighborhood in Bandung, West Java, Indonesia. The PVAc adhesive used in this study was commercially available under the FOX trademark and produced by PT. Aica Indria, Indonesia. PFR powder, yellow colored, was supplied by the Bandung Fire and Rescue Department, West Java, Indonesia.

Plant waste was categorized as coarse (GL) or fine (GS). GL was produced using a composting machine, whereas GS was obtained by milling GL for 15 h. The average size of GL particles ranged from 2 to 7 cm, while SEM analysis revealed that GS had an average particle size of approximately 50 μm [2]. The plastic, paper, and textile components were cut into pieces with dimensions ranging from 75 to 150 mm^2 . The mass composition of WCB constituents was adopted from another study, in which the WCB achieved a mechanical strength of 60 MPa. The composition consisted of 10.2 wt% PVAc, 16.9 wt% GL, 13.6 wt% GS, 8.5 wt% paper, 3.4 wt% plastic, 3.4 wt% textile, and 44 wt% water, with a total waste mass of 26 g [2].

PFR was incorporated using two methods, namely mixing and coating. In the mixing method, the composite fabrication began by dissolving PVAc in 13 mL of distilled water for 10 min until a homogeneous solution was obtained. PFR was then added to the PVAc solution and stirred until homogeneous before being mixed with all waste components. The mixture was stirred for 15 min and subsequently dried under a halogen lamp (Philips TN-0450 VATLUX, 220/240 V, 50/60 Hz, maximum 500 W) positioned approximately 14 cm above the sample for 15 min to reduce its moisture content. The mixture was then transferred into a stainless-steel cylindrical mold with an inner diameter of 25 mm and hot-pressed under a load of 2 tons at 125 $^{\circ}\text{C}$ for 30 min, followed by an additional pressing stage for 30 min at room temperature. The samples were subsequently conditioned in ambient air for at least 4 days.

The fire retardancy test for WCB containing PFR was conducted using a Bunsen burner in an open environment. Cylindrical composite specimens (25 mm in diameter and 25 mm in height) were positioned 5 cm above the flame tip. The initial flame temperature was approximately 150 $^{\circ}\text{C}$, measured using an infrared temperature recorder placed at a distance of 23 cm. The elapsed combustion time (t) and temperature (T) were continuously recorded. Experiments were performed twice for composite boards without PFR and with 2 g of PFR [2].

For the coating method, WCB were first fabricated using the same composition as in the mixing method. The mixture of WCB components was then transferred into a rectangle stainless-steel mold (approximately $16.8 \times 10.8 \text{ cm}^2$) and consolidated by hot pressing under a 5-ton load at 250 $^{\circ}\text{C}$ for 60 min. Following hot pressing, the composite was kept in the mold at room temperature for 24 h to ensure complete cooling and dimensional stability. The composite board was then removed from the mold and conditioned by air drying under ambient laboratory conditions for at least 4 days. After that, the composite board was coated with PFR material and PVAc solution. However, the PFR–PVAc mixture did not adhere effectively to the WCB surface because the WCB is heterogeneous, non-porous, and lacks sufficient surface functional groups. These characteristics result in low surface energy and poor interfacial compatibility, preventing PVAc from forming a strong and durable bond with the substrate. Therefore, two thermosetting polymers, namely epoxy (EP) and urea formaldehyde (UF), were employed as alternative binders for the PFR. The EP system consisted of epoxy resin (Bakelit

Korea, distributed by PT Brataco, Indonesia) and an epoxy hardener (Gabriel Phenoxies Inc., USA/Canada, distributed by PT Brataco, Indonesia). UF was also supplied by PT Brataco, Indonesia. The epoxy resin and hardener were thoroughly mixed before being applied to the composite surface and subsequently dried under ambient conditions. The epoxy resin and hardener were mixed at a 1:1 ratio. PFR readily dispersed within the EP adhesive system. The coating process was conducted using a painting-like approach and repeated until the entire amount of PFR had been uniformly distributed over the composite surface. The interval between successive coatings was approximately 10 min. After coating, the composite boards were air-dried for several days. The coated surfaces remained wet and glossy despite being air-dried for five days. Using EP system as the binder, the amount of PFR material was varied to observe the combustion delay performance. The PFR loading varied from 0.5 to 3.0 g at intervals of 0.5 g.

Subsequently, UF was investigated as an alternative PFR binder. Brown UF powder was dissolved in water, mixed with PFR, and coated onto the surface of the WCBs before drying under ambient conditions for subsequent combustion testing. Air-drying a single thin coating layer required only a few hours, whereas multiple coating layers required up to one day, with each subsequent layer applied only after the preceding layer had completely dried. Using UF adhesive, the amount of PFR material was also varied from 0.5 to 3.0 g at intervals of 0.5 g.

The combustion test apparatus for PFR-coated composite boards was further improved by placing the Bunsen burner inside a partially enclosed box equipped with air inlet and outlet openings. In the previous setup, the Bunsen burner was operated in an open environment, resulting in unstable flames due to fluctuating airflow conditions. The enclosure was constructed from steel plates, aluminum, and glass, forming a cubical chamber with dimensions of $33 \times 33 \times 50 \text{ cm}^3$. To improve temperature measurement accuracy, a thermocouple was employed, with its sensing tip positioned beneath the composite specimen. The thermocouple continuously recorded temperature and time throughout the combustion process. Furthermore, changes in the composite appearance during combustion were recorded using an Olympus μ -7030 digital camera. Combustion tests on PB and AW samples coated with PFR were also carried out in a closed chamber.

Fire retardancy characterization was also performed using thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC). Preliminary evaluation of the fire-retardant material was conducted on AW using PVA adhesive and a roll-press coating method. The wood is a cellulosic material rich in hydroxyl groups, enabling the formation of a dense network of strong intermolecular hydrogen bonds with the hydroxyl groups of PVA. TGA/DSC analysis were performed on three specimens: AW with 0, 2, and 4 g of PFR.

Additional fire retardancy tests were conducted to determine the most suitable polymer binder for attaching PFR to WCBs. WCB containing an identical amount of PFR were prepared using EP or UF adhesive, and without PFR coating for comparison. Furthermore, combustion rates were compared among prepared WCB, natural AW, and commercial PB to evaluate the fire retardancy characteristics of the developed composite material. All specimens were uniformly coated with 2 g of PFR/EP. The composite board specimens used in this comparison had a rectangular geometry with a surface area of approximately 38 cm^2 . The measured parameters included temperature variation, combustion time, and visual changes on the specimen surface during burning.

This study was designed as a preliminary study aimed at identifying the feasibility of applying PFR to composite boards and obtaining initial trends regarding the effect of PFR mass addition on fire retardancy performance. Therefore, the mass ranges were selected using relatively coarse intervals as

an initial screening approach, not as a final formulation optimization process. The differences in mass ranges in each section of the study reflected the characteristics of each PFR addition method and aimed to identify potential working ranges for further research.

3. Results and discussion

According to the EDX analysis shown in Table 1, P_2O_5 oxide-equivalent was the dominant component in the PFR powder, representing 92.58 wt% of the overall composition. Other components identified were Na_2O (1.07% m/m), MgO (3.34% m/m), Al_2O_3 (1.26% m/m), SiO_2 (1.01% m/m), and FeO (0.73% m/m). FR materials containing P_2O_5 (Phosphorus pentoxide) are halogen-free, harmless, and less likely to form toxic gases because some of the phosphorus is locked into the charcoal [12].

Table 1. EDX results of commercial PFRs.

Element	Energy (keV)	Mass (%)	Error (%)	Mol (%)	Compound	Compound mass (%)	Cation	K
O	-	55.08	-	-	-	-	-	-
Na K	1.04	0.80	0.58	2.19	Na_2O	1.07	0.24	1.45
Mg K	1.25	2.02	0.61	10.47	MgO	3.34	0.58	3.50
Al K	1.49	0.67	0.70	1.56	Al_2O_3	1.26	0.17	1.29
Si K	1.74	0.47	0.85	2.13	SiO_2	1.01	0.12	1.06
P K	2.01	40.4	1.02	82.36	P_2O_5	92.58	9.09	91.50
Fe K	6.40	0.57	2.70	1.28	FeO	0.73	0.07	1.20
Total	-	100.00	-	100.00	-	100.00	10.28	-

Combustion tests were conducted to compare the heating rates of WCB containing 0 g (without PFR) and 2 g of PFR. Both samples were subjected to combustion, and their temperatures were recorded as a function of time, as illustrated in Figure 1a. It was observed that the composite without PFR exhibited a more rapid temperature increase compared to the PFR-containing sample. The WCB without PFR reached a temperature of 400 °C in approximately 120 s, whereas the PFR-containing WCB required approximately 300 s to reach the same temperature. Furthermore, visual inspection revealed that the composite without PFR attained a similar burn color within 4.26 min, while the sample containing 2 g of PFR required approximately 19 min to reach the same degree of charring. Video recordings indicated that in the sample without PFR, the combustion reaction occurred slightly above the surface of the material (Figure 1b). This phenomenon is attributed to the release of flammable gases during combustion, which escape from the material and react with ambient oxygen to produce flames at elevated temperatures. In contrast, the combustion reaction in the PFR-containing sample occurred within the vapor phase above the material, as evidenced by the absence of visible flame on the composite surface (Figure 1c). These results confirm that the presence of PFR effectively delays the combustion process in both the gas and condensed phases [15].

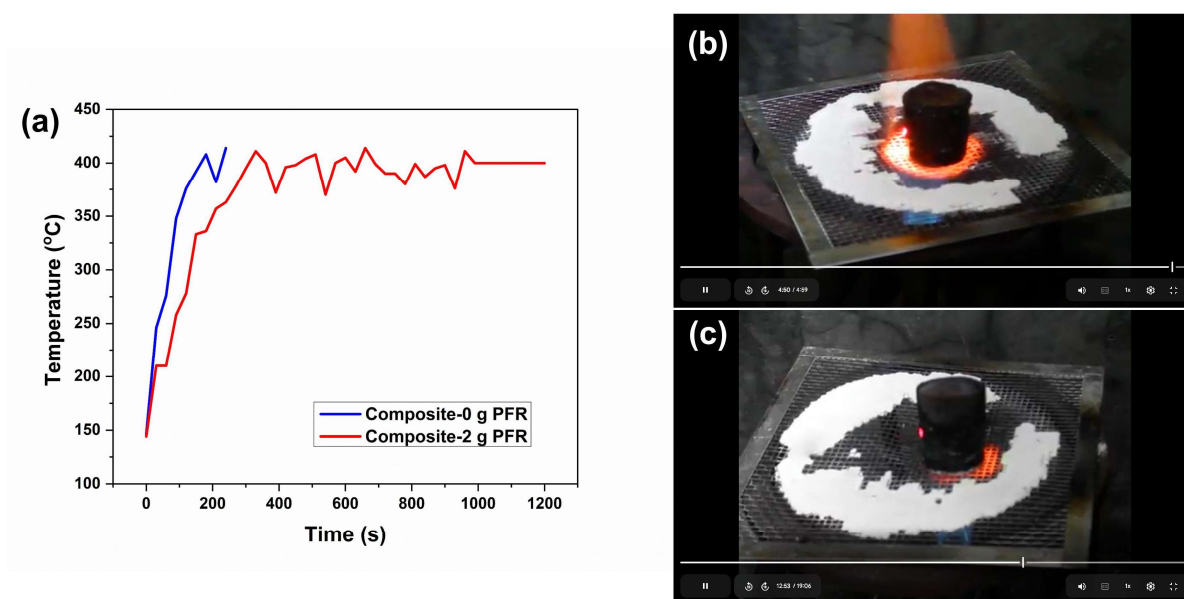


Figure 1. Combustion process: (a) temperature rises of WCB containing 0 and 2 g of PFR; (b) observation of WCB containing 0 g of PFR; and (c) observation of WCB containing 2 g of PFR.

Mechanism of chained combustion reactions of hydrocarbon fuel, for example ethane, in gas phase is presented in Table 2. There are hydrocarbon branches and hydroxyl branches of the chain reactions, which mainly produce $\text{H}\cdot$ and $\text{HO}\cdot$ radicals for further chain reactions [4].

Table 2. Mechanism of chained combustion reactions of hydrocarbon fuel, for example ethane, in gas phase [4,16].

Stage	Reaction
Initiation	$\text{C}_2\text{H}_6 \rightarrow \text{C}_2\text{H}_5\cdot + \text{H}\cdot$
	$\text{C}_2\text{H}_5\cdot + \text{O}_2 \rightarrow \text{C}_2\text{H}_5\text{OO}\cdot$
	$\text{H}\cdot + \text{O}_2 \rightarrow \text{HO}_2\cdot$
Propagation: a. Hydrocarbon Branches	$\text{C}_2\text{H}_5\text{OO}\cdot + \text{C}_2\text{H}_6 \rightarrow \text{C}_2\text{H}_4 + \text{H}_2\text{O} + \text{HO}\cdot$
	$\text{C}_2\text{H}_5\text{OO}\cdot \rightarrow \text{CH}_3\text{CHO} + \text{HO}\cdot$
b. Hydroxyl Branches	$\text{HO}\cdot + \text{H}_2 \rightarrow \text{H}_2\text{O} + \text{H}\cdot$
	$\text{H}\cdot + \text{O}_2 \rightarrow \text{O}\cdot + \text{HO}\cdot$
	$\text{O}\cdot + \text{H}_2 \rightarrow \text{HO}\cdot + \text{H}\cdot$
	$\text{HO}_2\cdot \rightarrow \text{inactive species (wall reaction)}$
Termination	$2\text{C}_2\text{H}_5\cdot \rightarrow \text{C}_4\text{H}_{10}$

The decomposition reaction mechanism of PFR in slowing the combustion rate [9] is as follows from Eqs 1–7.





During high-temperature combustion, solid fuels decompose to produce flammable gases (such as $\text{H}\bullet$ and $\text{OH}\bullet$ radicals), non-flammable gases (smoke), and char. The $\text{H}\bullet$ and $\text{OH}\bullet$ radicals are highly reactive and tend to bond with oxygen, triggering combustion and promoting flame spread [4]. This PFR powder is a mixture of monoammonium phosphate ($\text{NH}_4\text{H}_2\text{PO}_4$) and ammonium sulfate ($(\text{NH}_4)_2\text{SO}_4$), with a predominant monoammonium phosphate content. When a material containing PFR undergoes combustion, reactive $\text{H}\bullet$ and $\text{OH}\bullet$ radicals derived from flammable gases interact with phosphorus atoms. This reaction reduces the concentration of these radicals, thereby slowing the combustion process and limiting flame propagation [4,7]. At temperatures around 250 °C, ammonium polyphosphate decomposes to release ammonia (NH_3) and generate phosphoric acid (H_3PO_4), which catalyzes the dehydration and carbonization of the carbon-rich components within the composite. As thermal degradation progresses, H_3PO_4 undergoes condensation reactions to form polyphosphoric acid and phosphorus pentoxide (P_2O_5), a strong dehydrating agent that further promotes the formation of a stable carbonaceous char layer. This phosphorus-rich char acts as an effective thermal and mass transfer barrier by reducing heat transfer, limiting oxygen diffusion, and suppressing the release of volatile combustible products, thereby delaying oxidation and flame propagation. Consequently, the combustion process is significantly slowed, resulting in enhanced fire resistance of the composite material [7,17–20].

The results of TGA of AW coated with 0, 2, and 4 g of PFR using PVA as the adhesive, are shown in Table 3 and Figure 2. The comparison of the samples' mass degradation due to the rise of temperature between 30–600 °C, at a rate of 10 °C/min. The AW-0 g PFR exhibited two distinct mass degradation events, as indicated by the black curve in Figure 2. The first and most significant mass loss occurred between 220 and 350 °C, within a time interval of 21 to 30 min, resulting in a mass reduction of 72.32%. This degradation is attributed to the thermal decomposition of primary wood polymers, namely hemicellulose, cellulose, and lignin. The second mass loss, amounting to only 8.44%, occurred over the temperature range of 420 to 530 °C, corresponding to a time interval of 38 to 51 min. This secondary degradation is associated with the decomposition of residual material.

Table 3. TGA results of AW coated with 0, 2, and 4 g of PFR.

PFR mass (g)	Δm_1 (%)	T_1 range (°C)	t_1 range (min)	Δm_2 (%)	T_2 range (°C)	t_2 range (min)	Δm_3 (%)	T_3 range (°C)	t_3 range (min)	Residual mass (%)
0	0.00	50–220	0–20	72.32	220–350	21–30	8.44	420–530	38–51	19.24
2	0.00	50–170	0–13	36.47	170–320	14–27	32.05	470–558	43–52	31.48
4	15.00	50–180	0–15	37.60	180–350	16–31	24.42	400–600	36–57	22.98

Note: Δm is mass loss, T range is temperature range at which mass loss occurs, t range is the time interval over which mass loss occurs, and the numbering 1, 2, 3 indicates the stages of mass loss in the sample.

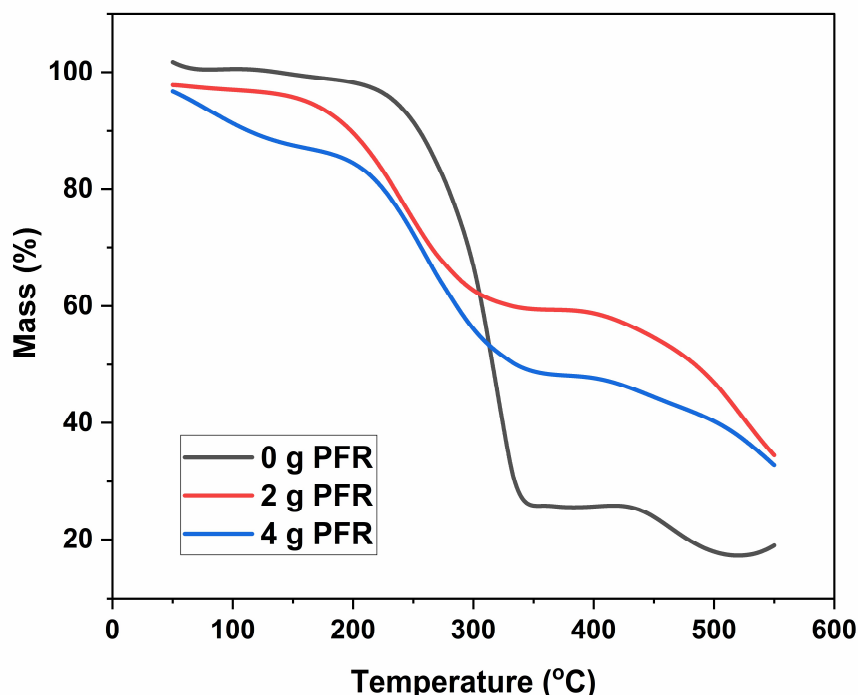


Figure 2. Effect of PFR coating mass (0, 2, and 4 g) on the degradation of AW.

During the thermal degradation of these three major organic polymers, volatile gases composed primarily of hydrogen, carbon, oxygen, and other minor components present in the wood matrix were released. In addition to gas evolution, char formation also occurred, comprising carbonaceous compounds and tar, such as levoglucosan [9]. The total residual mass after combustion at 600 °C for 51 min was 19.24%. The decomposition of each wood component took place at different temperature intervals, depending on the activation of energy required for each constituent, as summarized in Table 4.

The AW-2 g PFR exhibited two distinct stages of mass degradation, as indicated by the red curve in Figure 2. The first degradation event accounted for a 36.47% mass loss, occurring within the temperature range of 170 to 320 °C and a time interval from 14 to 27 min. This initial degradation is attributed to the decomposition of the coating material, which is a mixture of PVA adhesive and PFR. The coating forms a thermally protective barrier through the phosphorus-based fire retardancy mechanism. PVA melts at approximately 220 °C [21] whereas PFR containing P_2O_5 decomposes around 340 °C [22]. The second stage of degradation resulted in a 32.05% mass loss between 470 and 558 °C, corresponding to a time span of 43 to 52 min. This stage reflects the complete decomposition of the coating material. The total residual mass after combustion up to 600 °C over 52 min was 31.48%.

Table 4. The decomposition process that occurs in wood [23,24].

Temperature range	The decomposition process that occurs in wood
>100 °C	Evaporation of water vapor
160–200 °C	Decomposition of hemicellulose, cellulose, lignin, and the release of water vapor
200–225 °C	Water vapor release
225–275 °C	Wood burning process
280–500 °C	Volatile gases and carbon charcoal are formed; the wood structure begins to break down
>500 °C	Production of volatile gases and formation of carbon char

The AW-4 g PFR exhibited three distinct degradation stages, as shown by the blue curve in Figure 2. The first degradation occurred below 180 °C during the initial 15 min of combustion, resulting in a 15% mass loss due to the evaporation of coating materials. The second stage, with a 37.60% mass loss, took place between 180 and 350 °C over a period of 16 to 31 min, likely corresponding to the initial decomposition of the polymeric adhesive within the coating. The third degradation stage led to a 24.42% mass loss in the temperature range of 400 to 600 °C, over a duration of 36 to 57 min, indicating complete breakdown of the coating material. The total residual mass after 57 min at 600 °C was 22.98%. Among the tested samples, the AW-0 g PFR exhibited the lowest residual mass. In general, a higher PFR content is expected to yield a greater residual mass. However, the sample coated with 4 g of PFR produced a smaller residue compared to the AW-2 g PFR. This anomaly may be attributed to increased mass loss due to the evaporation of coating materials at temperatures below 180 °C in the higher-PFR sample. While minor mass loss (approximately 7%) was also observed in the 2 g PFR sample below 180 °C, it was included in the first degradation stage. A greater residual mass indicates better thermal stability of the wood composite.

The results of DSC characterization of AW with coatings of 0, 2, and 4 g of PFR with PVA adhesive are shown in Figure 3 and Table 5. AW-0 g exhibited two endothermic degradation events corresponding to hemicellulose/cellulose decomposition and residual char oxidation. Coating with 2 g PFR introduced a low-temperature endotherm (coating evaporation, ~145 °C) and a significantly increased high-temperature enthalpy (4323.78 J/g), indicating robust char formation. However, increasing the loading to 4 g reduced the total residual mass (from 31.48 to 22.98%) and required higher enthalpy (6462.24 J/g) to overcome the protective layer, suggesting overloading leads to a dense, non-insulating glassy layer that cracks under thermal stress.

An increase in PFR loading from 2 to 4 g leads to a shift in the temperature range of all three peaks. For the 2 g PFR sample, the maximum temperatures ($T_{\max}$) of the three peaks were 145, 250, and 525 °C, respectively, while for the 4 g PFR sample, the $T_{\max}$ values were 153, 273, and 561 °C. The enthalpy of the third peak, indicating the effectiveness of PFR in inhibiting combustion, increased sharply from 4323.78 to 6462.24 J/g. This suggests that a higher energy input is required to overcome the protective barrier formed by PFR.

The incorporation of PFR improved the fire retardancy of the wood panels. However, TGA data revealed that the total residual mass for the 4 g PFR sample (22.98%) was lower than that of the 2 g PFR sample (31.48%). This discrepancy warrants further investigation on the critical mass of PFR, which should involve smaller intervals of PFR loading.

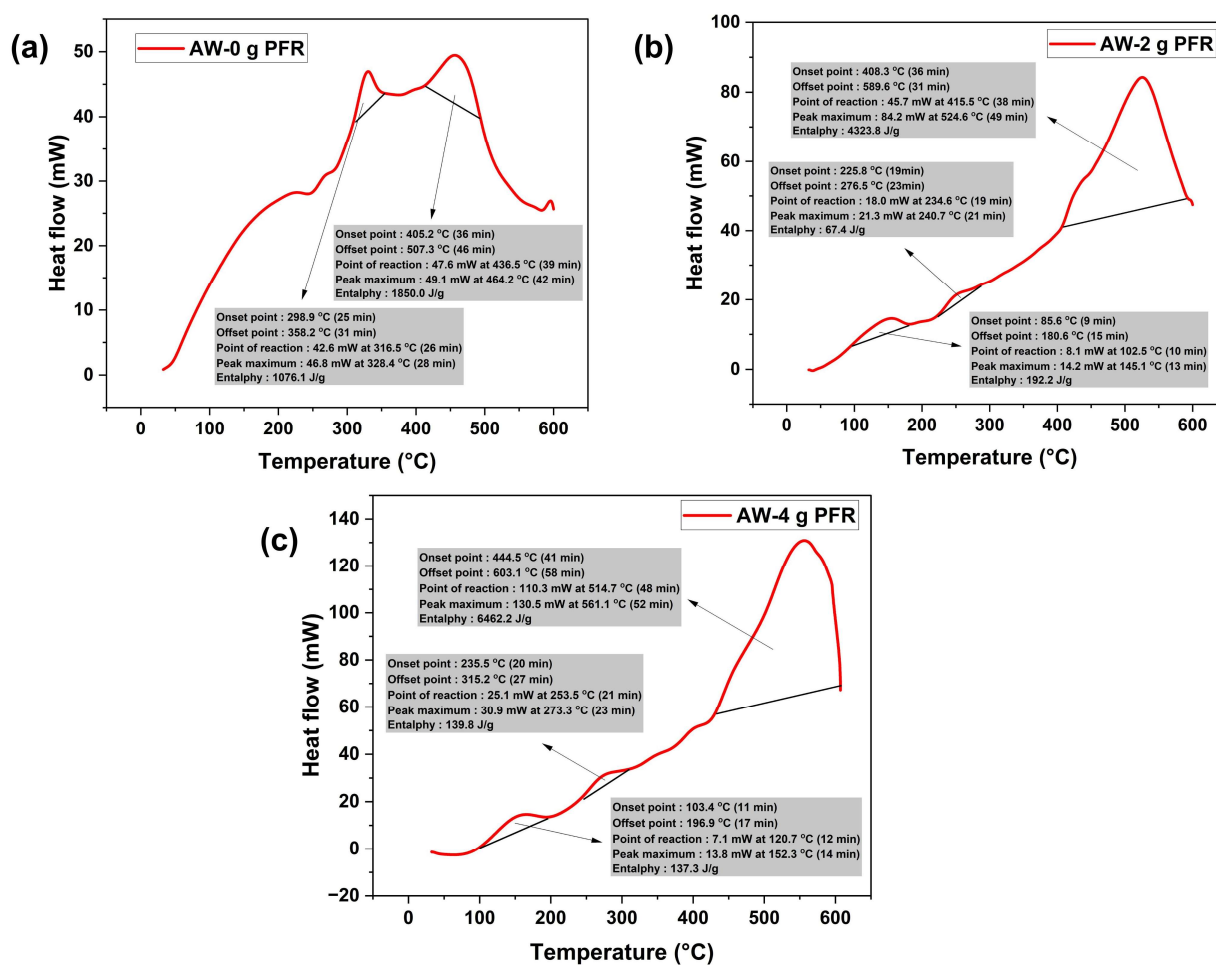


Figure 3. DSC curves of AW with PFR content of: (a) 0 g; (b) 2 g; and (c) 4 g.

Table 5. DSC and TGA result of AW boards coated with 0, 2, and 4 g of PFR using PVA as the adhesive.

Sample	DSC					TGA				
	Peak	t range	T range(°C)	Heat flow	Enthalpy	Peak	t range	T range	Δm	Residual
		(min)		(mW)	(J/g)		(min)	(°C)	(%)	mass (%)
AW-0 g	1	25–31	299–358	46.82	1076.09	1	21–30	220–350	72.32	19.24
PFR	2	36–46	405–507	49.06	1850.00	2	38–51	420–530	8.44	
AW-2 g	1	9–15	86–181	14.17	192.15	1	14–27	170–320	36.47	31.48
PFR	2	19–23	226–277	21.28	67.39	2	43–52	470–558	32.05	
	3	37–55	408–590	84.23	4323.78					
AW-4 g	1	11–17	103–197	13.83	137.27	1	15	50–180	15.00	22.98
PFR	2	20–27	236–315	30.92	139.81	2	16–31	180–350	37.60	
	3	41–58	444–603	130.46	6462.24	3	36–57	400–600	24.42	

Note: t range is the time interval, T range is temperature range, and Δm is mass loss.

TGA of WCB coated with 2 g of PFR using EP and UF as the adhesive, and compared with WCB without PFR, are presented in Table 6 and Figure 4 with increase in temperature in the range of 40–400 °C, at a rate of 10 °C /min.

Table 6. TGA results of WCB without and with 2 g of coating.

Coating	Δm_1 (%)	T ₁ range (°C)	t ₁ range (min)	Δm_2 (%)	T ₂ range (°C)	t ₂ range (min)	Δm_3 (%)	T ₃ range (°C)	t ₃ range (min)	Residual mass (%)
None	52.21	229–345	15–31	7.69	350–408	31–37	0.00	409–500	38–50	40.10
PFR/EP	7.37	175–228	15–19	30.59	240–344	20–30	0.00	345–400	31–40	62.04
PFR/UF	6.47	54–101	6–10	14.90	177–216	15–18	38.90	221–293	18–25	39.73

Note: Δm is mass loss, T range is temperature range at which mass loss occurs, t range is the time interval over which mass loss occurs, and the numbering 1, 2, 3 indicates the stages of mass loss in the sample.

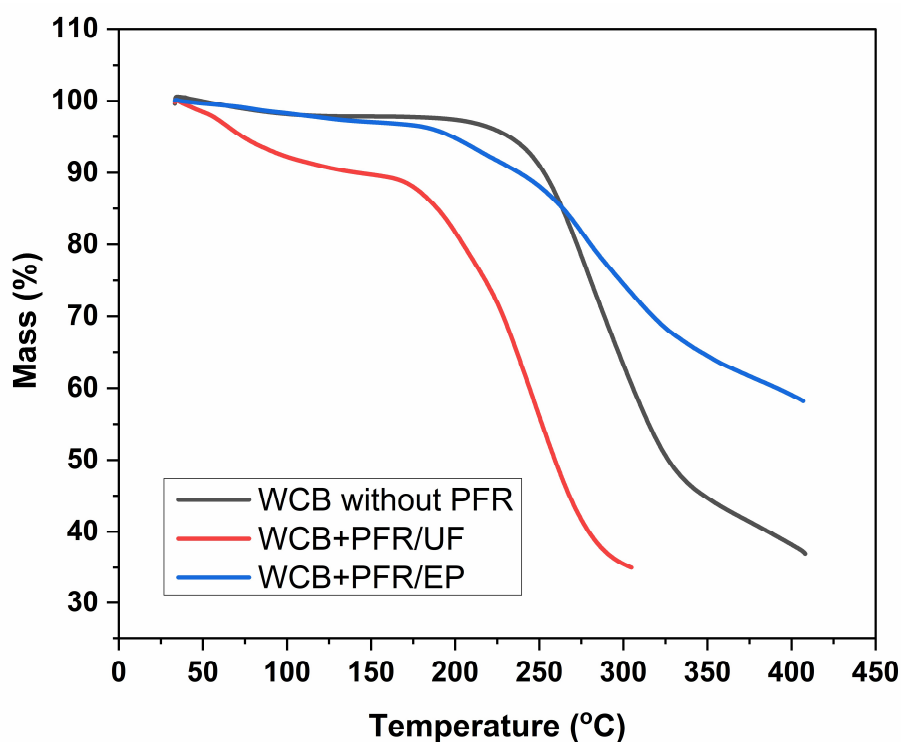


Figure 4. Effect of fire retardancy on the degradation of WCB without and with PFR coating using EP or UF adhesive.

For the WCB without PFR coating, TG data indicate two distinct mass degradation events, as represented by the black curve in Figure 4. The first degradation accounted for a mass loss of 52.21%, occurring in the temperature range of 229 to 345 °C and within a time span of 15 to 31 min. This degradation was attributed to the decomposition of composite components, which included PVAc adhesive and various fiber fillers. The second degradation resulted in a mass loss of 7.69%, observed between 350 and 408 °C over 31 to 37 min. This stage corresponded to the further decomposition of filler components with higher melting points [4]. The total residual mass after combustion up to 408 °C for 37 min was 40.10%.

For the WCB coated with PFR using EP as the adhesive (WCB-PFR/EP), TGA data also showed two distinct mass degradation stages, as depicted by the blue curve in Figure 4. The first degradation corresponded to a mass loss of 7.37%, occurring between 175 and 228 °C during the period of 15 to 19 min. The second degradation accounted for a 30.59% mass loss, occurring between 240 and 344 °C over 20 to 30 min. The total residual mass after combustion up to 409 °C for 37 min was 62.04%.

For the WCB coated with PFR using UF as the adhesive (WCB-PFR/UF), TGA data revealed three stages of mass degradation, as indicated by the red curve in Figure 4. The first degradation accounted for a mass loss of 6.47%, occurring within the temperature range of 53.5 to 101 °C and during 6 to 10 min, likely due to the evaporation of the coating material. The second degradation resulted in a 14.90% mass loss, occurring between 177 and 216 °C from 15 to 18 min, and was attributed to the initial decomposition of the UF polymer in the coating material. The third degradation, with a mass loss of 38.90%, occurred between 221 and 293 °C over 18 to 25 min. The total residual mass after combustion up to 293 °C for 25 min was 39.73%.

DSC characterization of WCB coated with 2 g of PFR/EP and PFR/UF, and uncoated WCB are shown in Figure 5 and Table 7. DSC analysis of the WCB without PFR (Figure 5a) revealed three thermal peaks: an initial exotherm (−501 J/g, 158–267 °C) followed by two endotherms (263 J/g, 286–335 °C; 72 J/g, 338–355 °C), whereas TGA data confirmed significant mass loss (52.21%) occurring solely between 229–345 °C, with no decomposition below 229 °C. This initial exothermic peak, absent of any mass loss, was attributed to the structural reorganization of the hot-pressed PVAc-bound fiber mixture (biomass, paper, plastic, and fabric) into more thermally stable configurations during initial heating [25]. For the uncoated waste composite, the second DSC endotherm (262.79 J/g) exhibited a near-doubling of heat flow (from 30.58 to 59.19 mW), while the third peak showed a sharp enthalpy drop to 72.00 J/g, reflecting weakened intermolecular bonding. Corresponding TGA data recorded a minor subsequent mass loss of 7.69% (350–408 °C, 31–37 min). Overall, the board retained 40.10% residual mass with only 59.90% total mass loss up to 408 °C, confirming its excellent inherent fire retardancy.

DSC of the PFR/EP-coated composite (Figure 5b) revealed an initial endotherm (184.81 J/g, 84–196 °C, 20.39 mW) from coating evaporation, which TG data subsequently correlated with two degradation stages (7.37% at 175–228 °C; 30.59% at 240–344 °C). A second DSC exotherm (−99.47 J/g, 369–409 °C, 45.51 mW) occurred without corresponding mass loss, indicating formation of a thermally stable structure via reaction between the EP (a thermosetting polymer degrading at 250–400 °C) and PFR, whose phosphorus reacts effectively with EP hydroxyl groups [12]. This synergy yielded a high residual mass of 62.04% after 37 min at 409 °C. For the PFR/UF-coated composite (Figure 5c), DSC exhibited two endotherms. TGA confirmed 6.47% mass loss (53–101 °C, 6–10 min) from coating evaporation, while the first DSC peak (268.93 J/g, 86–206 °C, 17.87 mW) corresponded to this evaporation followed by initial decomposition (TG: 14.90% loss at 177–216 °C). The second DSC peak showed a sharp enthalpy drop to 38.35 J/g (220–261 °C, 17.70 mW), concurrent with a major TGA loss of 38.90% (221–293 °C). Because UF degrades at 200–300 °C, well below the PFR activation temperature (~340 °C) [26,27], this thermal mismatch prevents synergistic char formation. Consequently, the coating provided minimal protection, leaving only 39.73% residual mass after 25 min at 293 °C.

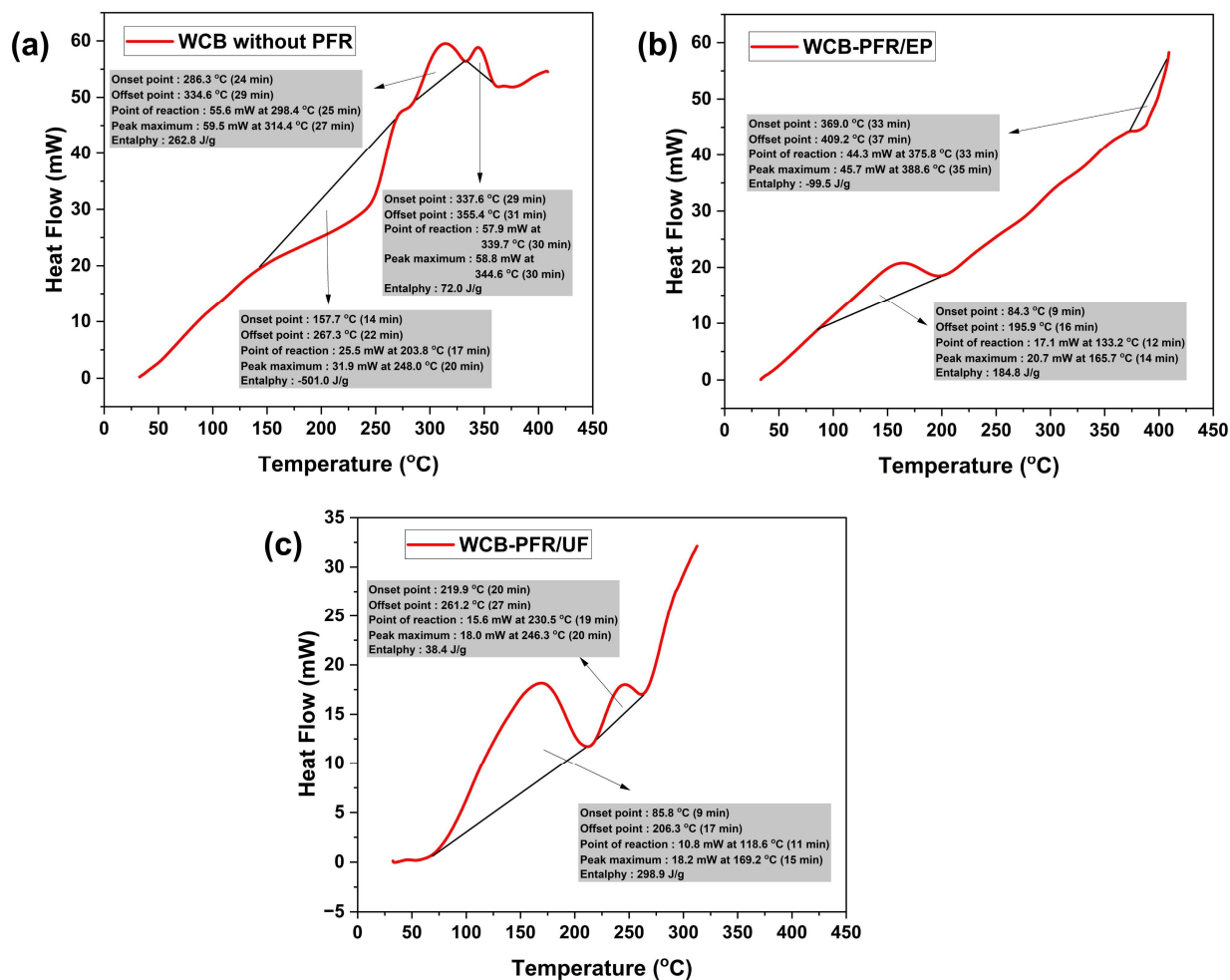


Figure 5. DSC curves of WCB: (a) without PFR coating; (b) with PFR/EP coating; and (c) with PFR/UF coating.

Table 7. DSC and TGA results for coated and uncoated WCB.

Coating	DSC					TGA				
	Peak	t range	T range	Heat flow	Enthalpy	Peak	Δm (%)	T range	t range	Residual
		(min)	(°C)	(mW)	(J/g)			(°C)	(min)	mass (%)
None	1	14–22	158–267	30.59	−501.04	1	52.21	229–345	15–31	40.10
	2	24–29	286–335	59.19	262.79	2	7.69	350–408	31–37	
	3	29–31	338–355	60.10	72.00					
PFR/EP	1	9–16	84–196	20.39	184.81	1	7.37	175—228	15–19	62.04
	2	33–37	369–409	45.51	−99.47	2	30.59	240–344	20–30	
PFR/UF	1	9–17	86–206	17.86	268.93	1	6.47	54–101	6–10	39.73
	2	18–22	220–261	17.70	38.35	2	14.90	177–216	15–18	
						3	38.90	221–293	18–25	

Note: t range is the time interval, T range is temperature range, and Δm is mass loss.

In comparison, the residual mass of the WCB coated with PFR and EP adhesive was 62.04%, whereas the WCB coated with PFR and UF retained only 40%. These results demonstrated the superior fire retardancy of WCB using PFR combined with EP. This result also confirmed the significant role of the synthetic polymer components of WCB matrix in enhancing the fire retardancy properties of natural fiber components. An unexpected result was observed in the combustion behavior of the uncoated WCB. The residual mass was 40%, nearly equivalent to that of the composite coated with PFR and UF adhesive. When compared with the combustion of untreated AW board (Table 3), it was evident that the WCB exhibited better inherent fire retardancy than AW. In Table 3, the TGA data indicate that a 4 g PFR loading yielded a lower total residual mass than a 2 g loading. This unexpected result suggested that the influence of PFR dosage on the combustion rate requires further investigation.

Using an EP adhesive, we optimized the FR dosage to achieve maximal combustion delay. The amount of FR applied to the composite ranged from 0.5 to 3.0 g. The temperature profiles recorded during combustion are presented in Figure 6. Overall, increasing the FR mass appeared to slow the combustion rate; however, an anomaly was observed, with the slowest combustion rate occurring at a 1.5 g FR loading. One would expect that higher FR loadings would provide even greater inhibition of combustion. A rather similar phenomenon was noted for AW samples coated with 0 to 4 g of PFR, as shown in Figure 2 and Table 3.

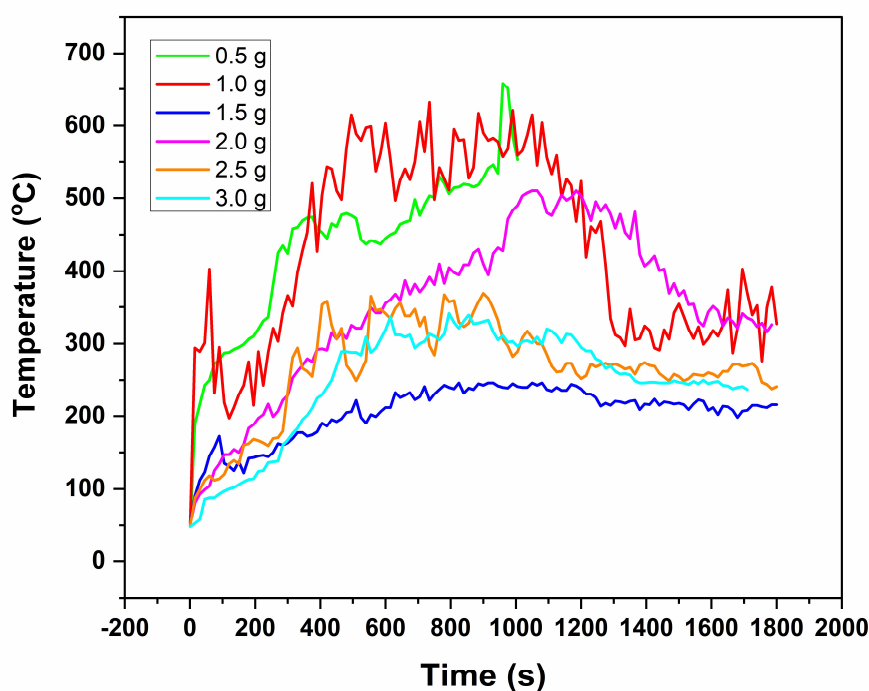


Figure 6. Effect of PFR/EP coating mass on the combustion rate of WCB.

To optimize combustion delay with UF adhesive, PFR loading was varied from 0.5 to 3.0 g against an untreated control (Figure 7). All PFR loadings slowed combustion, yet temperature increases showed minimal differences during the first 900 s but diverged noticeably between 900–1900 s. The slowest rate occurred at 2.0 g PFR, while 3.0 g PFR unexpectedly accelerated combustion. UF-based composites burned only up to ~250 °C, compared to ~600 °C for EP-based systems, underscoring that the binder's thermal degradation behavior critically governed performance, consistent with TGA/DSC data (Figures 4 and 5, and Table 7).

The addition of FR powder to a certain mass succeeded in slowing the combustion rate, and after that, the addition of FR mass increased the combustion rate. As happened to the AW-0 g PFR, AW-2 g PFR, AW-4 g PFR, the largest residual mass was observed when using 2 g PFR (Figure 2 and Table 3). On the WCB coated with PFR/EP, the slowest burning rate of WCB occurred at 1.5 g coating mass (Figure 6). When coated using PFR/UF, the slowest burning rate of WCB occurred at 2 g coating mass (Figure 7). The additional PFR coating beyond a certain mass (hereafter referred to as the critical mass) accelerated the combustion rate.

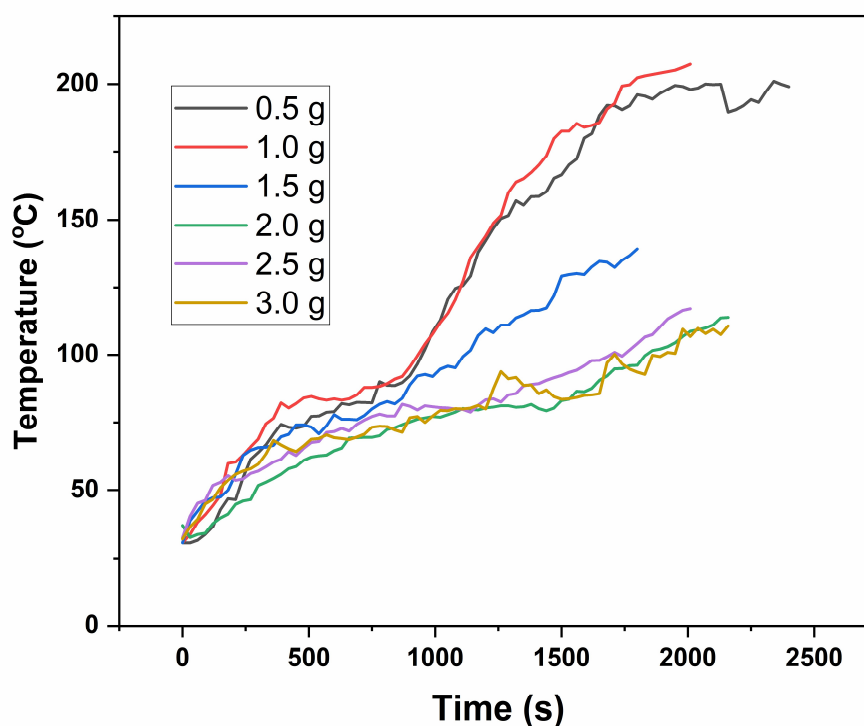


Figure 7. Effect of PFR coating mass with UF adhesive on combustion rate of WCB.

The fire-retardant coating forms of insulation were designed to reduce heat transfer from the fire to the protected substrate. When the surface temperature of the coating reaches a critical temperature under the fire heat, the surface begins to melt. This turns into a viscous liquid, simultaneously starting a reaction that results in the release of gas. These gases are trapped in the viscous liquid, forming bubbles and leading to the formation of a barrier layer. This layer forms protective carbon charcoal, which acts as an insulating barrier between the fire and the substrate. The amount of phosphorus determines the amount of char layer formed. Excessive PFR can cause violent and rapid exothermic decomposition. The pressure of trapped combustion flue gases within the molten char exceeds its tensile strength. The barrier layer breaks due to this, enabling heat to transfer from the fire to the substrate, thereby increasing the combustion rate. A certain minimum amount of PFR (i.e., critical mass) is required to form a charcoal layer. However, after the layer is formed, additional FR is no longer needed [28].

The combustion rate measurements of composite boards made from waste materials (WCB), natural wood (AW), and mixed wood particles (PB) coated with 2 g of PFR using an EP adhesive are presented in Figure 8. The green line represents the combustion rate of AW, the red line corresponds to the PB, and the blue line represents the WCB. Fire resistance testing was conducted using a Bunsen

burner. It is evident that the WCB exhibits superior fire resistance compared to AW and PB. This improved performance is attributed to the heterogeneous composition of the WCB, which includes leaves, plastics, paper, fabric, and PVAc. PVAc is a thermoplastic polymer known for its low flammability [29]. In contrast, AW is primarily composed of cellulose, hemicellulose, and lignin, all of which are rich in carbon, hydrogen, and oxygen, elements that contribute to its high combustibility. PB, which typically consist of wood particles (C, H, O) and polymer-based adhesives, are more fire retardant than natural wood but more flammable than the waste-derived composite developed in this study.

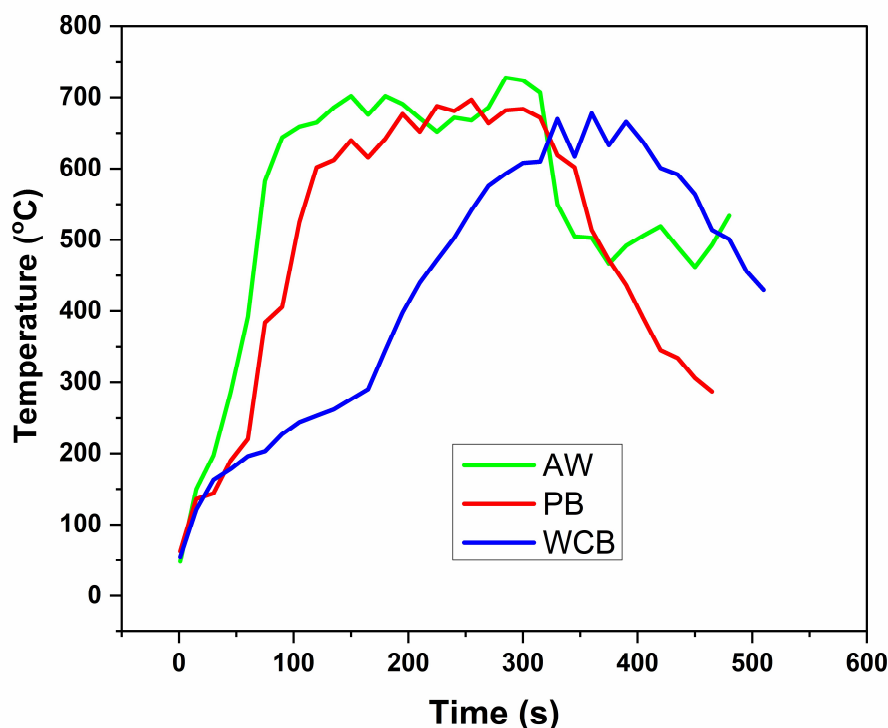


Figure 8. Comparison of combustion rate in terms of the temperature increase of AW, PB, and WCB. All samples are coated with 2 g of PFR/EP and burned in the same way.

The fire resistance test using a Bunsen burner revealed that the WCB exhibited superior fire resistance compared to the AW board. These results are consistent with the TGA result, as presented in Tables 3 and 5 shows that the residual mass of the AW board after combustion up to 600 °C without PFR was 19.24%. In comparison, Table 7 indicates that the residual mass of the WCB after combustion up to 400 °C without PFR was 40.10%. The fire-retardancy test using a Bunsen burner can serve as a low-cost and straightforward alternative method for evaluating the fire retardancy performance of composite materials.

4. Conclusions

We report the fabrication of fire-retardant WCBs by incorporating a PFR through a simple physical process. The fire retardancy of the composites was enhanced via three approaches: (i) mixing PFR as a filler within the composite matrix, (ii) coating the composite surface with PFR using a thermoset polymer adhesive with a high decomposition temperature, and (iii) varying the amount of

PFR to achieve optimal combustion resistance. Mixing 2 g of PFR into WCB delayed the reaching of peak temperature 400 °C into 5 min, and coating it onto the surface of WCB increased peak temperature into 650 °C. The use of WCB coated with 2 g of PFR/EP delayed the ignition time by 4.3 and 2.7 times longer compared to AW and PB with similar coating, respectively. Coating the WCB with 2g of PFR using EP adhesive resulted in a residual mass of 62.04%, with a burning duration of 37 min and a maximum temperature of 409 °C. In contrast, using a UF adhesive yielded a residual mass of 39.73%, with a burning duration of 25 min and a peak temperature of 293 °C. Even without the addition of PFR, the WCB demonstrated inherent fire retardancy, producing a residual mass of 40.01%, with a burning time and peak temperature of 37 min and 408 °C, respectively. For WCB using an EP adhesive, the optimal PFR content for achieving the slowest burning rate was 1.5 g. Further research is required to investigate this critical mass phenomenon, where higher FR loading may increase the burning rate. Methods employed in this study enabled the production of sustainable wood-substitute composite boards suitable for applications such as insulation in low-cost housing and packaging, thereby contributing to sustainable waste management initiatives.

5. Limitations

This study is an initial exploratory investigation into the incorporation of PFRs into natural fiber composite boards by blending or coating methods. Several parameters, such as standardized combustion environment control, precise layer thickness measurements, and detailed thermo-kinetic analysis, are beyond the scope of this study. The combustion tests were conducted under ambient laboratory conditions, where ambient temperature and relative humidity were not instrumentally monitored. The TGA/DSC characterization was intended for comparative evaluation between samples. Some instrumental parameters, such as test atmosphere and heating rate, were not fully documented during the initial measurements. Therefore, the results should be interpreted qualitatively rather than as absolute thermo-kinetic data. Moreover, all samples were tested under the same experimental setup and environmental conditions to ensure consistency in the comparative evaluation. In future studies, we will focus on optimization under a standardized fire test protocol, complete dryness of resin coating prior to fire tests, monitoring TGA/DSC characterization parameters for more comprehensive characterization results, more controlled environmental parameter monitoring, using similar range and interval of PFR loading throughout composite types, and standardizing the number of samples tested for statistical analysis, thus enhancing the reproducibility of the results.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Acknowledgments

We would like to express our sincere gratitude to Prof. Dr. Andrivo Rusydi, M.Si. for his support and advice. We also extend my thanks to Zahra Muthia Fadhillah, S.Si. for her contribution in helping to create some of the graphs in this study.

Author contributions

N.S.: prepared samples, data processing and analysis. E.L.: contributed to data visualization. N.S. and E.L.: contributed to writing the initial manuscript. N.S., E.L., and N.H.F.: contributed to writing the revised manuscript.

Conflict of interest

The authors declare no conflict of interest.

References

1. Indonesian Ministry of Environment (2025) National Waste Management Performance Information System. Available from: <https://sipsn.kemenvh.go.id/sipsn/>.
2. Surtiyeni N, Rahmadani R, Kurniasih N, et al. (2016) A fire-retardant composite made from domestic waste and PVA. *Adv Mater Sci Eng* 2016: 7516278. <https://doi.org/10.1155/2016/7516278>
3. Marney DCO, Russell LJ (2008) Combined fire retardant and wood preservative treatments for outdoor wood applications—A review of the literature. *Fire Technol* 44: 1–14. <https://doi.org/10.1007/s10694-007-0016-6>
4. Horrocks AR, Price D (2001) *Fire Retardant Materials*, 1 Ed., Cambridge: Woodhead Publishing Limited. Available from: <https://www.sciencedirect.com/book/edited-volume/9781855734197/fire-retardant-materials>.
5. Dunky M (2017) Adhesives in the wood industry, In: Pizzi A, Mittal KL, *Handbook of Adhesive Technology*, 3 Eds., Boca Raton: CRC Press, 509–572.
6. Mantanis GI, Athanassiadou ET, Barbu MC, et al. (2018) Adhesive systems used in the European particleboard, MDF and OSB industries. *Wood Mater Sci Eng* 13: 104–116. <https://doi.org/10.1080/17480272.2017.1396622>
7. Lazar ST, Kolibaba TJ, Grunlan JC (2020) Flame-retardant surface treatments. *Nat Rev Mater* 5: 259–275. <https://doi.org/10.1038/s41578-019-0164-6>
8. Kim NK, Dutta S, Bhattacharyya D (2018) A review of fire properties of natural fibre reinforced polymeric composites. *Compos Sci Technol* 162: 64–78. <https://doi.org/10.1016/j.compscitech.2018.04.016>
9. Schartel B (2010) Phosphorus-based flame retardancy mechanisms—Old hat or a starting point for future development? *Materials* 3: 4710–4745. <https://doi.org/10.3390/ma3104710>
10. Özer MS, Gaan S (2022) Recent developments in phosphorus based flame retardant coatings for textiles: Synthesis, applications and performance. *Prog Org Coat* 171: 107027. <https://doi.org/10.1016/j.porgcoat.2022.107027>
11. Liang Y, Jian H, Deng C, et al. (2023) Research and application of biomass-based wood flame retardants: A review. *Polymers* 15: 950. <https://doi.org/10.3390/polym15040950>
12. Rakotomalala M, Wagner S, Döring M (2010) Recent developments in halogen free flame retardants for epoxy resins for electrical and electronic applications. *Materials* 3: 4300–4327. <https://doi.org/10.3390/ma3084300>

13. Liu T, Shao Y, Huang T, et al. (2025) Chitosan-based adhesive for fabrication of organic-inorganic hybrid wood composites with robust interfacial bonding and flame retardancy. *ACS Sustainable Chem Eng* 13: 20863–20882. <https://doi.org/10.1021/acssuschemeng.5c09842>
14. Liu T, Shao Y, Huang T, et al. (2025) A chitosan-based adhesive with high flame retardancy and superior bonding strength fabricated by interface engineering. *Int J Biol Macromol* 305: 140984. <https://doi.org/10.1016/j.ijbiomac.2025.140984>
15. Levchik GF, Selevich AF, Levchik SV, et al. (1994) Thermal behaviour of ammonium polyphosphate—Inorganic compound mixtures. Part 1. Talc. *Thermochim Acta* 239: 41–49. [https://doi.org/10.1016/0040-6031\(94\)87054-3](https://doi.org/10.1016/0040-6031(94)87054-3)
16. Glassman I, Yetter RA, Glumac NG (2015) *Combustion*, 5 Eds., Oxford: Academic Press. Available from: <https://www.sciencedirect.com/book/monograph/9780124079137/combustion>.
17. Li X, Gao Q, Xia C, et al. (2019) Urea formaldehyde resin resultant plywood with rapid formaldehyde release modified by tunnel-structured sepiolite. *Polymers* 11: 1286. <https://doi.org/10.3390/polym11081286>
18. van der Veen I, de Boer J (2012) Phosphorus flame retardants: Properties, production, environmental occurrence, toxicity and analysis. *Chemosphere* 88: 1119–1153. <https://doi.org/10.1016/j.chemosphere.2012.03.067>
19. Kuang K, Huang X, Liao G (2008) A comparison between superfine magnesium hydroxide powders and commercial dry powders on fire suppression effectiveness. *Process Saf Environ Prot* 86: 182–188. <https://doi.org/10.1016/j.psep.2007.11.002>
20. Jimenez M, Duquesne S, Bourbigot S (2006) Intumescent fire protective coating: Toward a better understanding of their mechanism of action. *Thermochim Acta* 449: 16–26. <https://doi.org/10.1016/j.tca.2006.07.008>
21. Rimez B, Rahier H, Van Assche G, et al. (2008) The thermal degradation of poly(vinyl acetate) and poly(ethylene-co-vinyl acetate), part I: Experimental study of the degradation mechanism. *Polym Degrad Stab* 93: 800–810. <https://doi.org/10.1016/j.polymdegradstab.2008.01.010>
22. Bliem P, van Herwijnen HWG, Meissl R, et al. (2022) Engineering of open assembly time of water-based polyvinyl acetate (PVAc) wood adhesives by post-addition of additives. *Int J Adhes Adhes* 117: 103011. <https://doi.org/10.1016/j.ijadhadh.2021.103011>
23. Lowden LA, Hull TR (2013) Flammability behaviour of wood and a review of the methods for its reduction. *Fire Sci Rev* 2: 4. <https://doi.org/10.1186/2193-0414-2-4>
24. Junior MDV, Guerrero F, da Silva FMA, et al. (2024) Thermal decomposition and kinetic analysis of Amazonian woods: A comparative study of *Goupia glabra* and *Manilka huberi*. *Fire* 7: 390. <https://doi.org/10.3390/fire7110390>
25. Hamciuc C, Vlad-Bubulac T, Serbezeanu D, et al. (2022) Effects of phosphorus and boron compounds on thermal stability and flame retardancy properties of epoxy composites. *Polymers* 14: 4005. <https://doi.org/10.3390/polym14194005>
26. Wan Z, Zhang D, Gao C, et al. (2024) Experimental study on the thermal decomposition of epoxy/anhydride thermoset matrix in composite insulator core rods. *Polym Degrad Stab* 222: 110697. <https://doi.org/10.1016/j.polymdegradstab.2024.110697>
27. Tsiptsias C (2022) On the specific heat and mass loss of thermochemical transition. *Chem Thermodyn Therm Anal* 8: 100082. <https://doi.org/10.1016/j.ctta.2022.100082>

28. Liidakis SE, Statheropoulos MK, Tzamtzis NE, et al (1996) The effect of salt and oxide-hydroxide additives on the pyrolysis of cellulose and *Pinus halepensis* pine needles. *Thermochim Acta* 278: 99–108. [https://doi.org/10.1016/0040-6031\(95\)02790-4](https://doi.org/10.1016/0040-6031(95)02790-4)
29. Kim S, Kim HJ (2005) Effect of addition of polyvinyl acetate to melamine-formaldehyde resin on the adhesion and formaldehyde emission in engineered flooring. *Int J Adhes Adhes* 25: 456–461. <https://doi.org/10.1016/j.ijadhadh.2005.01.001>



AIMS Press

© 2026 the Author(s), licensee AIMS Press. This is an open access article distributed under the terms of the Creative Commons Attribution License (<https://creativecommons.org/licenses/by/4.0>)