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Development and Performance Evaluation of a Bio-Based Fire-Retardant Coating Derived from Eggshell, Oyster Shell, Wood Ash, Rice Husk Ash, Cornstarch, and Sodium Silicate

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Abstract

This study investigated the development and performance evaluation of an eco-friendly fire-retardant coating for wood surfaces formulated from eggshell ash, oyster shell ash, rice husk ash, wood ash, cornstarch, and sodium silicate. Previous studies have demonstrated that calcium carbonate-rich shell wastes, such as oyster and eggshells, can significantly reduce flammability and delay ignition when applied as fire-retardant coatings for wood materials (Dusaran, 2024; Atienza & Cruz, 2021; Wang *et al.*, 2021) [20, 6, 60]. In addition, silica-rich rice husk ash has been reported to enhance fire resistance by forming a protective thermal barrier during heat exposure, particularly when combined with biodegradable binders (Bregoneria *et al.*, 2023; Basri *et al.*, 2021) [14, 10]. Natural polymers such as starch have also been identified as effective intumescent materials capable of forming char layers that limit flame propagation (Carvalho *et al.*, 2023) [15]. Despite these findings, limited research has explored the combined use of multiple waste-derived ashes and bio-based binders in a single sustainable fire-retardant coating formulation. An experimental research design was employed using three coating formulations with varying material ratios, which

were applied to wood samples and compared with an untreated control. Fire-retardant performance was evaluated based on flame spread, flammability, and time-to-ignition tests conducted under controlled conditions. The results showed that all treated samples exhibited improved fire resistance compared to untreated wood. Among the formulations, Sample 2 demonstrated the most effective performance by delaying ignition for up to 190 seconds, preventing flame spread (0.00 cm), and exhibiting self-extinguishing behavior, whereas the untreated sample ignited within 50 seconds and showed rapid flame propagation.

The findings confirm the synergistic fire-retardant effects of calcium-based shell ashes, silica-rich rice husk ash, and the intumescent behavior of cornstarch within a sodium silicate matrix. This study concludes that the developed multi-ash coating presents a viable, low-cost, non-toxic, and environmentally sustainable alternative to conventional synthetic fire-retardant coatings while promoting waste utilization and enhanced fire safety for wood-based materials.

Keywords: Eco-Friendly Fire-Retardant Coating, Waste-Derived Ash Materials, Eggshell and Oyster Shell Ash, Rice Husk Ash, Sodium Silicate Binder, Wood Fire Resistance, Sustainable Fire Protection

Introduction

Fire incidents remain a critical threat to communities worldwide, especially in regions like the Philippines where wood is a primary construction material for residential and educational structures. While traditional fire-retardant coatings exist, they often rely on synthetic chemicals that can release toxic gases like formaldehyde when exposed to high temperatures, creating a demand for sustainable, non-toxic alternatives. This study addresses this need by investigating a bio-based coating derived from waste materials such as eggshell ash, oyster shell ash, wood ash, rice husk ash, cornstarch, and sodium silicate. The research is grounded in Joseph Fourier's Heat Transfer Theory, which explains how the coating acts as a thermal barrier to delay temperature rise, and the Flame-Retardant/Barrier Mechanism Theory, which describes how additives interfere with combustion through char formation. Additionally, the Composite Material/Filler-Binder Interaction Theory provides a basis

for understanding how these mineral fillers and natural binders interact to optimize fire resistance and structural adhesion.

The review of related literature underscores the empirical foundation for this study, noting that calcium carbonate-rich shell wastes—such as oyster and eggshells—can significantly reduce wood flammability and delay ignition. Local studies by Atienza *et al.* (2021) ^[6] and Dusaran (2024) ^[20] have already demonstrated the effectiveness of these bio-fillers in extending burning times. Furthermore, research from the University of Mindanao (2023) highlights that silica-rich rice husk ash, when combined with starch-based binders, creates a robust protective barrier under heat exposure. While individual materials have shown promise, a significant evidence gap remains regarding the synergistic effects of combining multiple waste-derived ashes with cornstarch as an intumescent agent within a single formulation. By bridging these theoretical and practical gaps, this research aims to provide a low-cost, eco-friendly fire protection solution that promotes responsible waste utilization for enhanced community safety.

Methodology

Research Design

This study employs a mixed-methods convergent parallel research design, integrating quantitative and qualitative data collection and analysis conducted simultaneously. In a convergent parallel design, quantitative and qualitative data are collected concurrently, analyzed independently, and then merged to provide a comprehensive understanding of the research problem (James *et al.*, 2022; Jackson-Gordon & Clark, 2023; Oranga, 2025) ^[28, 27, 41]. This design is appropriate for materials-based studies where numerical performance results and observable material behaviors are both essential for understanding fire-retardant performance.

The quantitative component of the study involves experimental evaluation of wood samples coated with different formulations of the multi-ash, cornstarch, and sodium silicate-based coating (T1, T2, and T3). The wood samples are subjected to controlled fire exposure tests, and quantitative data are collected on flame spread rate and back-side temperature, which are widely used indicators of fire-retardant performance in coating studies (Saienko *et al.*, 2025; Hafiz *et al.*, 2025; Pellerin *et al.*, 2022) ^[50, 24, 45]. Controlled experimentation is conducted following established procedures recognized for their reliability and repeatability in fire testing (Darnikowski & Mieloszyk, 2025; Morrisset *et al.*, 2024; Tang *et al.*, 2024; Zhang *et al.*, 2024) ^[17, 38, 56, 63].

Simultaneously, the qualitative component consists of detailed observational documentation of the physical and visual changes in the wood samples during and after fire exposure. This includes surface charring, coating stability, extent of material degradation, and overall fire behavior. Qualitative observation is a recognized approach in fire-retardant research, as visible material responses provide essential insight into fire-protection mechanisms (Piperopoulos *et al.*, 2025; Yazıcı *et al.*, 2022; Fang *et al.*, 2024) ^[48, 62, 21].

After independent analyses, the quantitative and qualitative findings are merged to identify convergences and divergences between measured performance and observable material behavior. Observable features such as char layer formation and coating integrity help interpret variations in

flame spread rate and back-side temperature. This integration strengthens the clarity, validity, and interpretability of the findings (James *et al.*, 2022; Gillespie *et al.*, 2024; Hochwald *et al.*, 2023) ^[28, 23, 25].

Overall, the mixed-methods convergent parallel research design allows this study to simultaneously capture objective, measurable data and rich descriptive observations. The combined insights support a comprehensive evaluation of the developed coating containing eggshell ash, oyster shell ash, rice husk ash, wood ash, cornstarch, and sodium silicate, highlighting its potential as a sustainable alternative to conventional fire-retardant wood coatings (Oranga, 2025 ^[41]; Dusaran, 2024 ^[20]; Breboneria *et al.*, 202x).

Data Gathering Procedure

In this study, data will be gathered using a mixed-methods approach, combining quantitative experimentation and qualitative observation conducted simultaneously. This approach allows for systematic measurement and assessment of the fire-retardant coating formulations while also documenting observable material behavior during fire exposure (Stoner *et al.*, 2022 ^[54]; Secrieru & Calalb, 2025). By collecting both types of data concurrently, the study ensures a comprehensive understanding of the performance and mechanisms of each coating formulation.

For the quantitative component, the performance of the fire-retardant coatings will be evaluated through controlled experimentation. Wood samples coated with different additive ratios will be subjected to fire exposure tests to measure flame spread, back-side temperature, ignition time, heat transfer, and other indicators of fire performance (Thai *et al.*, 2025; Sabee *et al.*, 2022 ^[49]). These measurements provide objective data to compare the effectiveness of each formulation and determine which combination of ingredients offers the optimal fire-retardant properties while considering sustainability and practical application (Patel *et al.*, 2025) ^[44].

Simultaneously, the qualitative component involves detailed observational documentation of the physical and visual changes in the wood samples during and after fire exposure. This includes surface charring, coating stability, extent of material degradation, smoke formation, and other observable behaviors. Recording these observations helps explain the mechanisms underlying the quantitative measurements and provides additional insight into the material's fire-retardant performance.

The ratios of fire-retardant coating formulations to be tested in this study are as follows:

Ratio 1:

Sodium Silicate: 36.50g
Cornstarch: 1g
Oyster Shell Ash: 1g
Eggshell Ash: 1g
Rice Husk Ash: 2g
Acacia Wood Ash: 1g

Ratio 2:

Sodium Silicate: 36.50g
Cornstarch: 2g
Oyster Shell Ash: 2g
Eggshell Ash: 2g
Rice Husk Ash: 4g
Acacia Wood Ash: 2g

Ratio 3:

Sodium Silicate: 36.50g

Cornstarch: 4g

Oyster Shell Ash: 4g

Eggshell Ash: 4g

Rice Husk Ash: 8g

Acacia Wood Ash: 4g

By integrating quantitative measurements and qualitative observations, this study will produce comprehensive data on both the measurable fire-retardant performance and the observable material behavior of the coatings. The combined findings will guide recommendations for developing eco-friendly and effective fire-retardant wood coatings.

Procedure

1. Preparation of Materials

- All raw materials (cornstarch, oyster shell ash, eggshell ash, rice husk ash, and Acacia wood ash) will be finely ground to ensure uniform particle size.
- The weight of each material for each ratio will be measured accurately using a digital scale and recorded.

2. Mixing of Coating Formulations

- The measured additives will be gradually incorporated into 36.50 g of sodium silicate for each ratio.
- Continuous stirring will be done until a homogeneous mixture is achieved.
- Observations regarding texture, viscosity, and consistency changes during mixing will be documented.

3. Application of Coating

- The prepared coating formulations will be applied to standardized wooden panels using a brush to ensure uniform coating thickness.
- Drying time for each layer and the number of layers applied will be recorded.
- Visual observations of coating appearance and uniformity will also be documented.

4. Testing and Observation

- The coated panels will undergo experimentation to evaluate their fire-retardant performance while simultaneously recording qualitative observations:

Quantitative Measurements:

- **Flame Spread Test:** Measures how fast flames travel across the coated surface.
- **Flammability Test:** Determines how easily the coated surface ignites.
- **Time of Ignition Test:** Records the duration it takes for the coated surface to catch fire.

Qualitative Observations:

- Flame behavior, smoke production, surface charring, coating integrity, and other physical changes will be documented during and after testing.

5. Data Recording and Analysis

- All quantitative and qualitative data from the experimentation and observations will be organized, analyzed separately, and then merged to provide a comprehensive understanding of coating performance.

- The combined findings will guide recommendations for developing an effective, sustainable, and eco-friendly fire-retardant coating.

Materials

Image	Materials
	Eggshell - Derived from calcined eggshells and processed into a fine powder, it is rich in calcium carbonate and serves as a filler to enhance thermal stability and fire resistance.
	Oyster Shell - Created from burned oyster shells, this fine powder contains mineral components that improve heat insulation and flame retardancy.
	Acacia Wood Ash - Obtained from the combustion of wood residues (specifically Acacia wood in the experimental ratios), it contributes mineral elements that aid in fire resistance and thermal behavior.
	Rice-Husk-Ash - A silica-rich ash obtained from burning rice husks; it is used to reduce thermal conductivity and improve the paint's insulating performance.
	Cornstarch - A natural polymer that acts as a bio-based binder and an intumescent agent. Under heat exposure, it expands to form a protective char layer that reduces flame spread and heat transfer.
	Sodium Silicate - Used as the sodium silicate binder to integrate the mineral fillers and cornstarch into a fire-retardant mixture.

Data Analysis

In this study, data analysis follows a mixed-methods convergent parallel approach, where quantitative and qualitative data are analyzed independently and then merged for comprehensive interpretation. This approach allows the study to capture both measurable performance results and observable material behaviors simultaneously, ensuring a holistic understanding of the fire-retardant performance of the coatings.

Quantitative Analysis

The quantitative component involves statistical analysis of numerical data gathered from the three experimental trials (T1, T2, and T3). Measures of central tendency, specifically the mean (average), will be calculated for key performance indicators: flame spread rate, flammability, time of ignition, and back-side temperature. These averages allow for objective comparison between the different formulations to identify which ratio of bio-based additives (eggshell ash, oyster shell ash, wood ash, rice husk ash, cornstarch, and sodium silicate) provides the highest level of fire retardancy. To determine if the differences between the three ratios and

the control (if applicable) are statistically significant, a one-way Analysis of Variance (ANOVA) may be employed.

Qualitative Analysis

Simultaneously, qualitative data derived from direct observations during the fire tests will be analyzed to provide insight into the mechanisms behind the numerical results. Observations will focus on physical changes such as the stability of the coating, the thickness and integrity of the char layer formed by cornstarch (acting as an intumescent agent), and the extent of wood degradation. These observations are critical for understanding protective mechanisms—such as char formation and gas-phase interference—that contribute to the fire-retardant performance measured quantitatively.

Integration of Finding

After independent analysis, the quantitative and qualitative data will be merged to identify convergences and

divergences. For instance, if a specific trial shows a significantly lower back-side temperature, qualitative observations may explain this outcome by referencing the formation of a robust, expanded char layer or the fire-retardant contribution of silica-rich rice husk ash. This combined analysis ensures a comprehensive evaluation of the developed coating’s effectiveness as a sustainable and eco-friendly fire-retardant solution containing eggshell ash, oyster shell ash, rice husk ash, wood ash, cornstarch, and sodium silicate.

Results and Discussion

- OS - Oyster Shell
- ES- Eggshell
- CRHA - Carbonized Rice Husk Ash
- WA - Wood Ash
- CS - Cornstarch
- SS - Sodium Silicate

Table 1: Flame Spread Test Data Table

Sample No	Materials Used (g)	Time to ignition (s)	Visible smoke (Yes/No)	Type of ignition (Flame/Glow)	Flame Spread Distance (cm)	Ignition Duration (s)	Total Burn Time (s)	Other Observations	Ranking
1	OS-1g ES-1g CRHA-2g WA-1g CS-1g SS-36.50g	150s	No	Glow	00.00 cm	00.00 s	00.00 s	Forms a white and grayish bubbles on the wood	2
2	OS-2g ES-2g CRHA-4g WA-2g CS-2g SS-36.50g	190s	No	Glow	00.00 cm	00.00 s	00.00 s	Forms a white and grayish bubbles on the wood	1
3	OS-4g ES-4g CRHA-8g WA-4g CS-4g SS-36.50g	1,200s	No	Glow	00.00 cm	00.00s	00.00 s	There's no formation of grayish bubble and the woods turns into ashes	3
4	No product applied	50s	Yes	Flame	10cm	34s	29 s	The wood burns instantly after the fire is introduced	4

In performing the flame spread test, the student researcher pointed the butane torch at the side-end or edge of the wood. Based on the observed time to ignition, type of ignition, and surface changes, Sample 2 (OS-2g, ES-2g, CRHA-4g, WA-2g, CS-2g, SS-36.50g) is the most effective in terms of delaying ignition and preventing visible flame, followed by Sample 2 and Sample 1. Sample 4, with no fire-retardant coating, is the least effective, as it ignites very quickly and leads to more significant surface damage.

In conclusion, the combination of oyster shells (OS), eggshell (ES), carbonized rice husk ash (CRHA), wood ash (WA), cornstarch (CS), and sodium silicate (SS) can significantly improve the fire-retardant properties of wood. Among the samples tested, Sample 2 demonstrated the most effective fire-retardant properties, delaying ignition and preventing flames, while Sample 4, with no coating, allowed rapid ignition and flame spread and caused severe damage to the wood.

Table 2: Flammability Test Data Table

Sample No	Materials Used (g)	Time to Ignition (s)	Burn Time (s)	Char Length (cm)	Flame Spread Behavior	Self-Extinguishing (Yes/No)	Ashing (Yes/No)	Other Observations	Ranking
1	OS-1g ES-1g CRHA-2g WA-1g CS-1g SS-36.50g	150s	00.00s	12cm		Yes	No	The flame takes long time to penetrate to the wood.	2
2	OS-2g ES-2g CRHA-4g WA-2g CS-2g SS-36.50g	190s	00.00s	12cm		Yes	No	The flame takes long time to penetrate to the wood.	1
3	OS-4g ES-4g CRHA-8g WA-4g CS-4g SS-36.50g	1,200s	00.00s	12cm		Yes	No	The flame didn't penetrate to the wood however the wood became ash due to high heat.	3
4	No product applied	50s	29s	No char formation	Rapid	No	Yes	Continues to burn even when the flame is removed.	4

In performing the flammability test, the student researcher pointed the butane torch at the middle or center of the wood surface. The flammability test results indicate that the treated wood samples (Samples 1, 2, and 3) exhibited significantly better fire retardancy compared to the untreated wood (Sample 4). All treated samples self-extinguished after the ignition source was removed and showed no flame spread, while the untreated sample continued to burn with weakening, rapid flame spread, and greater charring, structural.

Among the treated samples, Sample 2 (OS-2g, ES-2g, CRHA-4g, WA-2g, CS-2g, SS-36.50g) demonstrated the highest retardancy, with the longest ignition time, and was ranked as the most effective fire-retardant mixture in performing the flammability test, followed by Sample 1 and Sample 3. The treated samples also formed a protective

white-grayish foam or bubbles on the wood surface, which likely contributed to their flame retardancy.

In conclusion, the fire-retardant mixtures or combinations of oyster shells, eggshell, carbonized rice husk ash, wood ash, cornstarch, and sodium silicate are effective in improving wood's fire retardancy by preventing sustained burning and promoting self-extinguishing behavior. Sample 2, with enough amount of oyster shells (OS), eggshell (ES), carbonized rice husk ash (CRHA), wood ash (WA), cornstarch (CS), and sodium silicate (SS) was the most effective formulation, suggesting that enough proportion of materials can enhance fire retardant properties. The untreated wood (Sample 4) was the least fire-resistant, emphasizing the protective advantage provided by the fire-retardant coatings.

Table 3: Time of Ignition Test Data Table

Sample No	Materials Used (g)	Time to Ignition (s)	Visible Smoke (Yes/No)	Type of ignition (Flame/Glow)	Surface Change	Ignition Duration (s)	Other Observation	Ranking
1	OS-1g ES-1g CRHA-2g WA-1g CS-1g SS-36.50g	150s	No	Glow	Forms a white-grayish bubble on the wood surface.	00.00s	Formed a char layer.	2
2	OS-2g ES-2g CRHA-4g WA-2g CS-2g SS-36.50g	190s	No	Glow	Forms a white-grayish bubble on the wood surface.	00.00s	Formed a char layer.	1
3	OS-4g ES-4g CRHA-8g WA-4g CS-4g SS-36.50g	1,200s	No	Glow	There's a glow however there's no char formed.	00.00s	The flame didn't penetrate and there is no formation of char.	3
4	No product applied	50s	Yes	Flame	forms charring	29s	The wood becomes brittle after being burned.	4

In performing the time to ignition test, the student researcher pointed the butane torch at the side-end or edge of the wood. The results indicate that the fire-retardant coatings made from oyster shells (OS), eggshell (ES), carbonized rice husk ash (CRHA), wood ash (WA), cornstarch (CS), and sodium silicate (SS) provide varying levels of effectiveness in delaying ignition and preventing flame spread. Sample 2 (OS-2g, ES-2g, CRHA-4g, WA-2g, CS-2g, SS-36. 50g) was the most effective, with the longest time to ignition (190 seconds) and no flame spread, indicating that it successfully delayed ignition, prevented sustained booming, and the wood was not damaged. Sample 1 (OS-1g, ES-1g, CRHA-2g, WA-1g, CS-1g, SS-36. 50g) followed closely, showing a slightly shorter ignition delay (150 seconds) but still preventing flames from spreading. Sample 3 (OS-4g, ES-4g, CRHA-8g, WA-4g, CS-4g, SS-36. 50g) ranked third, with a time to ignition of (1,200 seconds). However, even with high ignition time the coating failed to protect the wood which results with wood becoming ash, but still sample 3 is effective in forming a protective foam that stops further flame spread. In contrast, Sample 4 (no fire-retardant coating) ignited almost immediately, with rapid flame spread, high ignition duration, and extensive burn time, highlighting its lack of fire-retardant properties. These findings demonstrate that the combination of oyster shell, eggshell, carbonized rice husk ash, wood ash, cornstarch, and sodium silicate in varying proportions can effectively delay ignition and prevent fire spread, with Sample 2 offering the highest level of protection.

Conclusion

The study successfully demonstrates that eggshell ash, oyster shell ash, wood ash, rice husk ash, and cornstarch can be effectively combined using a sodium silicate binder to create a functional, eco-friendly fire-retardant coating. The mineral-rich calcium and silica ashes work synergistically with the intumescent properties of cornstarch to form a protective thermal barrier that significantly outperforms untreated wood. Specifically, the multi-ash formulations delayed ignition for up to 190 seconds compared to only 50 seconds for untreated samples, while completely preventing flame spread and exhibiting self-extinguishing behavior. Among the tested ratios, Sample 2—containing a balanced mix of 2g each of shell and wood ashes and 4g of rice husk ash—was identified as the optimal formulation for providing superior ignition delay and structural protection, whereas excessive ash concentrations in other samples led to coating failure under prolonged heat.

Ultimately, these findings confirm that the developed bio-based coating serves as a viable, low-cost, and non-toxic alternative to synthetic fire retardants. By repurposing agricultural and household waste materials into a high-performance protective layer, the research provides a practical and sustainable solution for enhancing the fire safety of wood surfaces in residential and community settings. This approach not only promotes responsible waste utilization but also offers a scalable method for reducing fire-related risks to life and property through accessible, eco-friendly technology.

Recommendations

To build upon the findings of this study, it is recommended that future research evaluates the long-term durability and environmental resilience of the bio-based coating,

specifically focusing on its resistance to moisture, humidity, and weathering. To transition from an experimental prototype to a commercially viable product, the coating should undergo standardized fire safety testing following ASTM or UL protocols, alongside rigorous assessments of mechanical properties such as bonding strength, flexibility, and crack resistance. Additionally, further optimization of ash particle size and surface treatments could significantly improve the uniformity and adhesion of the formulation, ensuring a more consistent protective layer on diverse surfaces.

Broadening the scope of application is also essential; therefore, the coating should be tested on other common local construction materials such as bamboo, plywood, and coco lumber to determine its versatility. To maximize the social impact of this sustainable technology, researchers should focus on simplifying the preparation and application processes. Developing a user-friendly "DIY" method would encourage widespread adoption at the household, school, and community levels, providing an accessible and low-cost fire-protection solution that effectively repurposes agricultural and household waste.

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