Nature-Derived Flame Retardant for Cotton Fabrics and Bio Composite with Banana Peel

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ABSTRACT

Purpose: This study uses bio-coatings generated from banana peels and bio-composites manufactured from waste fabric to explore creating and assessing new flame-retardant materials.

Design/Methodology/Approach: Polyvinyl acetate (PVAc) was used as a binder with banana peels, a readily available organic waste, to create bio-composite materials and flame-retardant fabric (FRF) coating. The 45° Burning Test, BS 4790 Fire Test (Hot Nut Test), Direct Metal Heat (DMH) Test, Welding Spark Test, Direct Heat Test, and Chemical Resistance Testing (H_2SO_4) were among the tests used to evaluate the samples' fire retardancy.

Findings: During the 45-degree burning test, untreated cloth showed poor resistance, lighting after 23 seconds, whereas FRF required 93 seconds, and flame-retardant composite (FRC) demonstrated the best flame resistance, igniting after 315 seconds, followed by plywood at 245 seconds. Additionally, FRC showed outstanding fire resistance, endured exposure to strong sulfuric acid without suffering any harm, and remained unaffected for 600 seconds.

Conclusion: The overall findings show that, compared to untreated fabric and plywood, the bio-composites and bio-coated textiles demonstrated noticeably improved flame resistance. The bio-composites demonstrated outstanding performance with prolonged resistance to ignition and prolonged exposure to direct heat and chemical conditions, suggesting their potential as cost-effective and ecologically friendly alternatives to synthetic materials in fire safety applications.

Keywords: *Banana peel, Bio-composite, Bio-coating, Fire-retardant, Flame-retardant, Textile waste fiber, Fire safety material.*

1. INTRODUCTION

Fire has the potential to cause substantial property damage and a large number of deaths as well. Textile fire is also renowned for its massive destruction of wealth and life (Cen, Cao, & Wang, 2024). The chances of any fire-related incidents occurring can be reduced by using different fire safety arrangements. This could be done by using fire-retardant building materials, installing sprinkler systems, smoke detectors, fire extinguishers, and wearing fire-retardant clothing or equipment, particularly in the work environment (Rabajczyk, Zielecka, Popielarczyk, & Sowa, 2021).

Recently, there has been a necessity to search for flame retardants that can inhibit the flame from spreading rapidly. This will increase the chance to take necessary action to prevent the flame and minimize the damage to a minimum scale. For example, due to superior flame retardancy, halogenated flame retardants (FRs) were used as flame-retardant options, which, however, lost their appeal and significance due to the associated toxicity and environmental effects (Cen et al., 2024). As a result, halogen-free alternatives are gaining more popularity as the demand for health safety and environmental standards is becoming more desirable among both consumers and producers. For instance, tannins, lignin, polyphenols, etc., are naturally derived materials showing their potential to be an effective alternative to FRs (Lokhande, Bhakare, Bondarde, Dhumal, & Some, 2022). These plant-based

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compounds produce char while burning, which eventually slows down the flame propagation and enables enough time to take necessary prevention to tackle the situation (Basak, Raja, Saxena, & Patil, 2021). Other advantages of plant-based FRs are their widespread accessibility, lack of toxic byproducts, and lack of the need for intricate synthesis processes (Covello, Price, & Wnek, 2024). Because of their effectiveness, efficiency, and cost, fire-retardant coatings are desirable treatment alternatives for enhancing the fire resistance of materials. According to recent studies on its uses, fire retardant coatings enhance the mechanical qualities of underlying substrate materials while shielding them from fire damage (Zheng, Li, & Ek, 2019). Nowadays, the most widely utilized additives in coating preparation for the creation of thin layers on substrate surfaces are oil-based binders, especially epoxy and acrylic resin. As sustainable substitutes for conventional oil-based coatings, other coating materials are trying to develop (Richmond, 2014).

Biodegradability, lowering atmospheric carbon dioxide, and cost savings from using less expensive bio-fibers are some of the benefits that have made bio-composites extremely popular in recent years (Ramesh, Deepa, Kumar, Sanjay, & Siengchin, 2020). Most often, natural fibers or fibrous materials from comparable sources are combined to create composite materials that are either entirely or partially biodegradable. The use of natural fiber composites as a more or less suitable substitute for synthetic materials that are detrimental to the environment can help reduce pollution. These materials also provide the benefits of affordable prices and acceptable mechanical qualities. Above all, these composites have minimal energy requirements for manufacture (Sanjay et al., 2018; Vinod, Sanjay, Suchart, & Jyotishkumar, 2020). Bio-fibers can result in poor composite qualities due to swelling and inappropriate bonding between fibers and matrix molecules, as they are hydrophilic and absorb moisture. Poor mechanical qualities are also caused by the variable size, shape, and density of the fibers (Teklu, Wangatia, & Alemayehu, 2019). Cellulosic fibers in particular are very flammable, which is a serious problem. Their usage of materials with lower exposure levels is constrained by their susceptibility to UV radiation. UV rays have little effect on the strength of bio-composites because they depend on the crystallinity of cellulose (Chang, Mohanty, & Misra, 2020). Thus, selecting the right fiber is essential to creating bio-composites that are stronger and more resilient. Natural materials and bio-fibers are frequently utilized to save costs and make composites lighter and more eco-friendly, instead of emphasizing the improvement of other qualities. According to recent studies, surface modification and the use of filler materials are popular techniques for creating bio-composites (Chang et al., 2020).

Banana peels are generated in vast amounts worldwide, and it has been estimated that the peel or skin of bananas accounts for 10% of output (Ferrante, Santulli, & Summerscales, 2020). The enormous amount of banana peels produced worldwide must be used more effectively than is the case at the moment. The components of banana peels include a high percentage of moisture (57–60%), a significant amount of cellulose fiber (15–25%), carbohydrates (23–35%), a small amount of ash (6–9%), various sugars (1–3%), and more (Khawas & Deka, 2016). However, because banana peels contain relatively little fiber and the fibers have poorer mechanical qualities than other natural fibers, they have not been employed to create composite constructions (Ferrante et al., 2020; Sanjay et al., 2018). To lower the cost of finished goods, banana peels, a waste product, can be included in composites. However, as natural hygroscopic materials cannot form chemical connections with synthetic resin components, adding banana peels to composites may have a detrimental impact on their tensile qualities (Anannya & Mahmud, 2019). This condition can be improved with surface-modifying chemicals, but the cost of the material would go up. The cellulose and carbohydrate components of banana peels are extremely combustible, however, the char they produce can help extinguish fires (Minn, Kim, Lee, & Kim, 2024). Banana peels can also make the structure more pliable and less hard. Because cellulosic materials may form char that can limit flame spread, the high moisture level of banana peels may assist decrease flammability (Sain, Park, Suhara, & Law, 2004). Banana peels are generally a more affordable option than pricey polymers.

The banana peels were used by several researchers to gain flame retardancy. In keeping with this, Kong et al. (2020) and Kong et al. (2022) attempted to create composites using phytic acid and powdered banana peels to add flame retardancy. Banana peel was also used to prepare flame-retardant fabric (Minn et al., 2024) and composite (Anannya et al., 2022; Nguyen & Nguyen, 2021).

The purpose of this study is to design a novel flame-retardant fabric bio-coated with banana peels and a bio-composite made from waste fabric incorporating banana peels and finally evaluate the flame retardancy performance. 45° Burning Test, BS 4790 Fire Test (Hot Nut Test), Direct Metal Heat (DMH) Test, Welding Spark Test

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(Gas Metal Arc Welding), Direct Heat Test, and Chemical Resistance Testing (H_2SO_4) were used to assess the flame retardancy of these samples.

2. MATERIALS AND METHODS

2.1. Materials

2.1.1. Bio-Coating

Scoured and bleached plain woven fabric made of 100% cotton was sourced from a market in Dhaka, Bangladesh. Banana peels were collected from various local tea stalls. A synthetic binder, Polyvinyl acetate (PVAc), known commercially as Fevicol, was purchased from the local market. A blender was used to process the banana peels into a fine paste, and after applying the coating, the samples were dried using a dryer machine.

2.1.2. Bio-Composite

The excess fabric remnants were gathered from "Mirpur Jhut Polli" in Mirpur, Dhaka, Bangladesh. These small fabric pieces underwent processing in a willowing machine to transform them into fibers known as Jhut waste fibers (JWF). Banana peels were sourced from various local tea stalls. A synthetic adhesive, polyvinyl acetate (PVAc), commonly known as Fevicol, was acquired from a local market. A blender was employed to finely blend the banana peels into a paste, which was then mixed with JWF. Subsequently, samples were dried using a dryer machine.

Figure 1. Process flowchart of the preparation of fire retardant (FRF) fabric sample.

2.2. Method

2.2.1. Preparation of Fire-Retardant Coated Fabric

As shown in the Figure 1, collected banana peels were cut into small pieces which later on made into paste using a blender machine followed by the addition of synthetic binder in a ratio of 4:1. Finally, this pre-made coating was applied on the cotton fabric sample by hand layoff process followed by drying by a hand dryer at 100°C for 45 min.

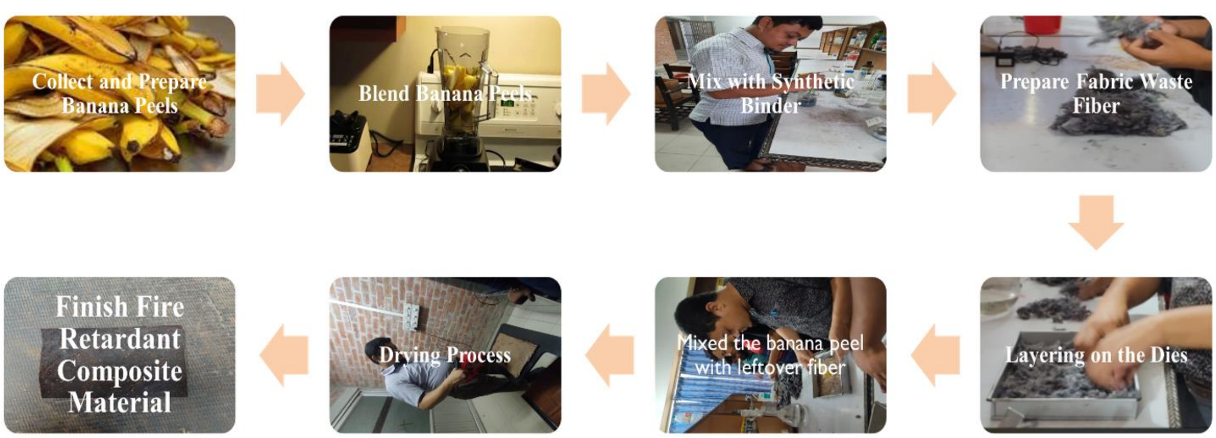

Figure 2. Process flowchart of the preparation of fire-retardant composite (FRC) sample.

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2.2.2. Preparation of Fire-Retardant Bio-Composite

As depicted in Figure 2, the banana peels gathered were sliced into small segments and processed into a paste using a blender. Synthetic binder was then added in a 4:1 ratio to the paste. The remaining fabric waste material was thoroughly cleaned of any yarn or dust particles. A composite material was created by layering banana peels and the cleaned waste material in a rectangular mould followed by drying using a hand dryer at 100°C for 45 minutes.

2.3. Testing

Bio-coated fabric samples and bio-composite samples were compared with uncoated bleached cotton fabric and plywood respectively as a preliminary fire-retardance test. Sample preparation for the fire-retardance testing involved comparing bio-coated fabrics and bio-composite samples with uncoated bleached cotton fabric and plywood to evaluate their fire-retardant capacities. The bio-coated fabrics and control fabrics were cut into a size of 2 inches × 2 inches to conduct the test. Bio-composite samples and plywood were also cut into the same size with a thickness of 0.5 cm to maintain uniformity of tests.

2.3.1. Direct Heat Test

The direct heat test is a technique for assessing the ability of materials to minimize or prevent fire from spreading when exposed to high temperatures or an open flame. It is an important assessment technique to evaluate the fire retardance of various materials, such as textiles, coatings, and building supplies. The ISO 1716 was followed to determine the calorific values during tests. The time taken to spread an open fire was measured for a variety of materials, including plywood, fire-retardant fabric, plain-woven fabric, and fire-retardant bio-composite.

2.3.2. 45° Burning Method

The 45° burning test evaluates the resistance of a material to fire exposure when exposed to radiant heat at a 45° angle. This test aligns with many international standards, including ISO 5658-2, which measures the fire spread characteristics of materials, and ASTM E119 and UL 263 in the US. Samples treated with banana peel and controls were placed at 45 degrees on fire to find how long a material can endure exposure to fire. Figure 3 depicts the experimental setup for the 45° burning test.

Figure 3. Typical 45° burning arrangement.

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2.3.3. Chemical Resistance Testing (H_2SO_4)
The drop test, which uses 100% concentrated sulfuric acid (H_2SO_4), is a method used to assess a material's fire resistance or fireproof qualities. This technique is particularly helpful for determining how well a material withstands exposure to acidic and corrosive conditions, such as those seen in fire scenarios. After the sulfuric acid drops are applied, carefully inspect the sample material for any changes that occur right away. Variations like discoloration, degradation, swelling, or any other signs of damage might be among them.

2.3.4. BS 4790 Fire Test (Hot Nut Test)
The British Standard BS 4790 outlines a fire testing protocol for assessing how well flooring materials behave in the presence of a tiny flame or ignition source. Its main objective is to determine these materials' critical radiant flux (CRF). The CRF is a measure of a material's ability to control flame propagation and resistance to ignite. This test is essential for evaluating flooring materials' fire safety qualities, especially in settings where fire safety is a top priority. The amount of time it takes for the sample to ignite is noted throughout this process.

2.3.5. Direct Metal Heat (DMH) Test
The ASTM E2925-recommended direct metal heat (DMH) test evaluates the fire resistance of composite materials by subjecting them to controlled heating to simulate fire conditions. For materials used in a variety of industries, including construction, aerospace, and automotive, where maintaining fire safety is crucial, fire-resistant properties are important. This technique entails timing each sample's ignition.

2.3.6. The Welding Spark Test
The Welding Spark Test is a method used to assess a material's potential to produce sparks or ignite when subjected to welding or hot work activities. It follows the American Welding Society (AWS) standard. Its primary purpose is to evaluate the fire hazard posed by welding activities near flammable or combustible materials. During this process, sparks produced during welding are directed toward a sample of the composite material to observe its reaction. The focus is primarily on identifying signs of ignition or sustained burning. The key parameter measured in this method is the time taken for the samples to ignite.

3. RESULT AND DISCUSSION
Images of samples are shown in the figure and results obtained from different tests are listed in Table 1.

Figure 4. Banana peel-treated bio-coated fabric and banana peel-associated bio-composite from left to right.

The bio-coated fabric treated with banana peels and the bio-composite based on banana peels are shown in Figure 4 from left to right. It highlights the creative use of banana peels to create eco-friendly textile and composite materials.

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Table 1. Results were obtained from the 45° Burning method, Hot Nut Test, Chemical resistance testing, Direct metal heat test, Welding spark test, and Direct heat test.

Sample	45° burning method	Hot nut test	Chemical resistance testing	Direct metal heat test	Welding spark test	Direct heat test
	Time (sec)					
Untreated fabric (UF)	23	3.20	204.6	1.80	2.19	6
Plywood	243	57.26	300	18.24	15.02	138
Fire-retardant fabric (FRF)	93	25.52	600	5.70	9.88	39
Fire-retardant composite (FRC)	315	141 (Half hole)	600 (No damage)	36.13	30.01	600 (No fire)

3.1. 45° Burning Test

The 45° Burning Test was utilized to evaluate the flame retardancy of various materials by exposing them to an open flame at a 45-degree angle and measuring the time until ignition. Figure 5 illustrates test results for 45° Burning Test where the plyboard sample ignited after 245 seconds, indicating a moderate level of flame resistance, although it was unable to endure the flame for an extended duration. In contrast, the composite material (FRC) sample exhibited a longer ignition time of 315 seconds, suggesting enhanced flame-retardant properties compared to the plyboard. The fabric sample demonstrated significantly lower flame resistance, igniting in just 23 seconds, while the Flame Retardant (FRF) fabric sample ignited after 93 seconds, indicating improved flame retardancy relative to the standard fabric.

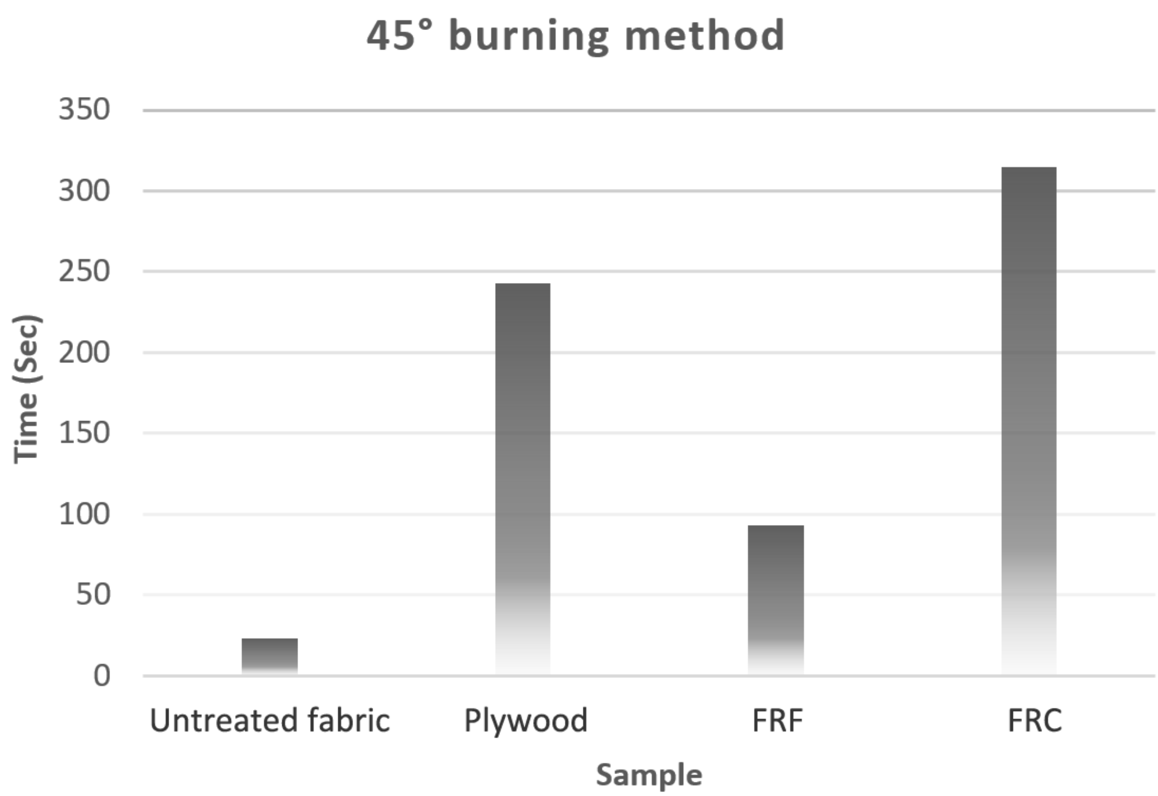

Figure 5. Results obtained for 45° *Burning test.*

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3.2. BS 4790 Fire Test (Hot Nut Test)

Figure 6 illustrates the ignition time for samples obtained from the BS 4790 Fire Test (Hot Nut Test). A low degree of flame resistance was shown by the plyboard sample's total penetration, which happened in just 57 seconds. On the other hand, the composite material sample showed better endurance than the plyboard, requiring 155 seconds to reach a half-holed condition, indicating improved flame retardancy. With complete penetration taking only 3.7 seconds, the cloth sample demonstrated very low flame resistance. On the other hand, the Flame-Retardant fabric (FRF) sample demonstrated better flame retardancy than the conventional fabric, taking 25.52 seconds to reach a half-holed state.

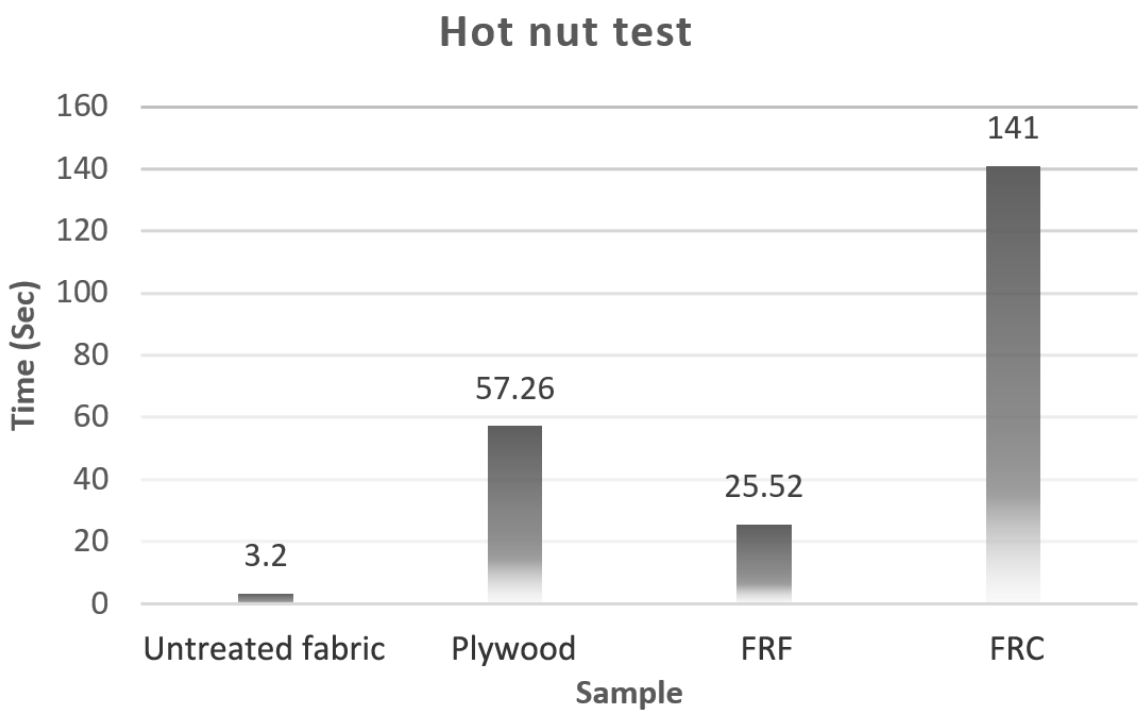

Figure 6. Results obtained from BS 4790 Fire Test (Hot Nut Test).

3.3. Direct Metal Heat (DMH) Test

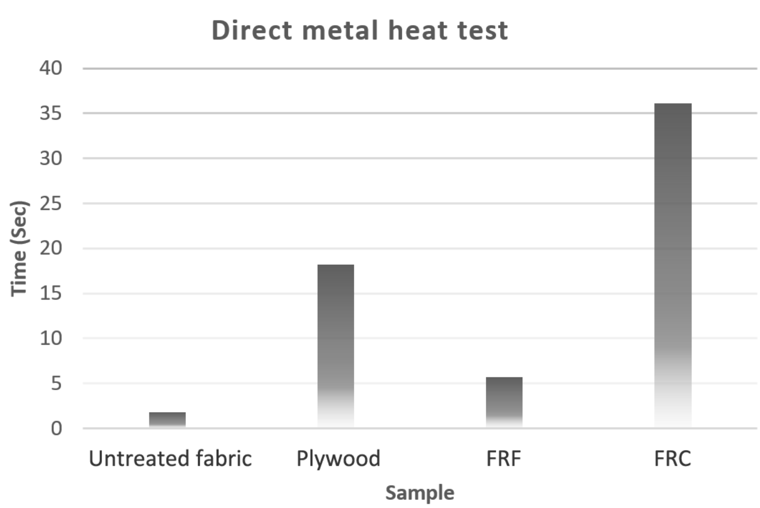

Figure 7. Results obtained from direct metal heat test.

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Figure 7 shows test results for the Direct Metal Heat (DMH) Test. The findings showed that the plyboard had a low level of fire resistance since it completely lit in 18.24 seconds. However, the composite material only partially burnt after 36.13 seconds, demonstrating far higher heat resistance and better flame-retardant qualities than the plyboard. When the cloth sample came into touch with the hot metal, it completely ignited in about 1.8 seconds, demonstrating a very low level of fire resistance. The Flame-Retardant cloth, on the other hand, showed better heat resistance and burned partly after 5.7 seconds. This extended period before igniting demonstrates how much more flame-retardant the FRC is than regular cloth.

3.4. Welding Spark Test

Figure 8 represents the results obtained from the welding spark test where the plyboard sample showed less resistance to fire as it was completely lit in 15.02 seconds after coming into contact with the Gas Metal Arc Welding (GMAW) spark. On the other hand, the bio-composite material revealed exceptional fire-retardant properties, suffering a little damage after 30.01 seconds without igniting. Similarly, the untreated cloth sample showed incredibly low fire resistance than the bio-coated samples, burning completely in just 2.19 seconds. However, the flame-retardant fabric prevented ignition for up to 9.88 seconds indicating better performance, suffering just a little damage after that period.

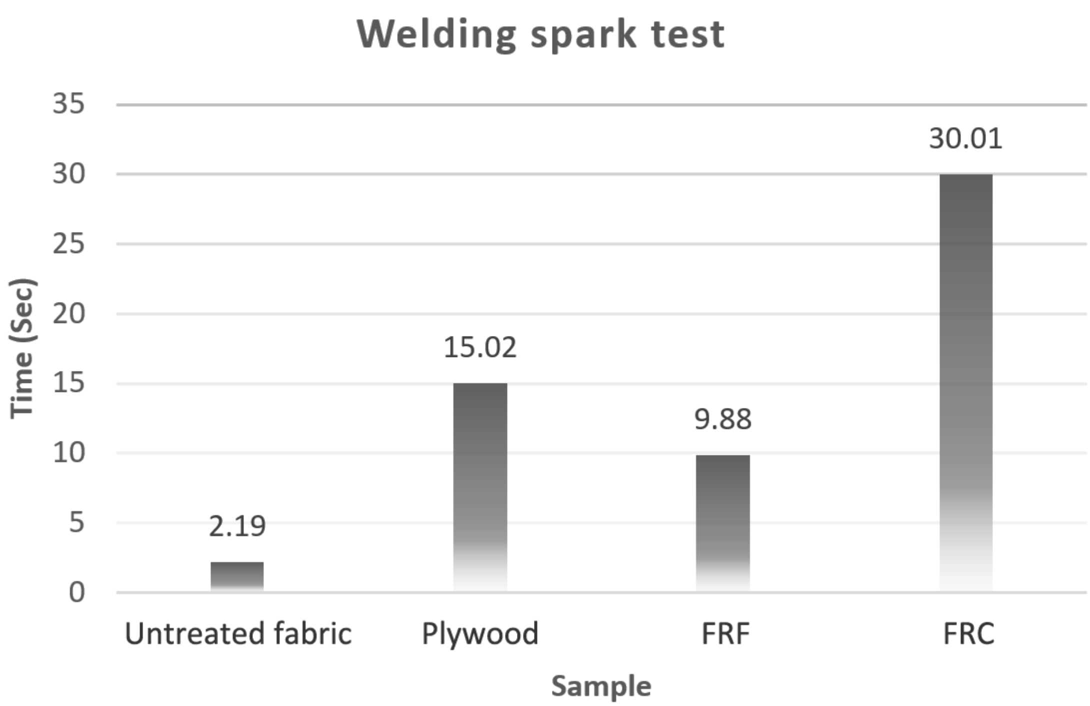

Figure 8. Results obtained from welding spark test.

3.5. Direct Heat Test

In Figure 9, results obtained from the direct heat test are represented. Results show that the plyboard ignited after only 138 seconds of exposure to direct fire, indicating relatively poor fire resistance. In contrast, the composite material demonstrated significantly better performance, showing no noticeable effects from fire even after 600 seconds of direct contact. This extended resistance underscores the superior flame-retardant properties of the composite material. The fabric sample exhibited extremely low fire resistance, igniting after just 0.10 minutes (6 seconds) of exposure to direct fire. Conversely, the Flame-Retardant fabric ignited after 0.65 minutes (39 seconds), indicating a substantially better performance compared to the standard fabric.

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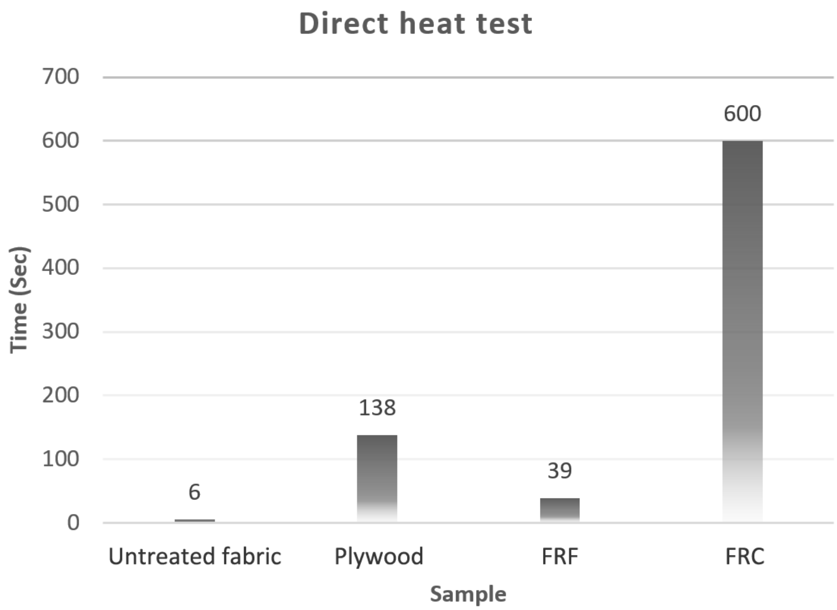

Figure 9. Results obtained by direct heat test.

3.6. Chemical Resistance Testing (H_2SO_4)

Figure 10 illustrates the results obtained from chemical resistance testing. The chemical resistance test with 100% concentrated sulfuric acid effectively evaluates material performance against corrosive chemicals. The plyboard sample showed damage after 300 seconds of exposure, resulting in a partial hole, indicating its lack of resistance. In contrast, the composite material remained unaffected after 10 minutes (600 seconds), demonstrating high chemical resistance. The fabric sample sustained damage after just 204.6 seconds, highlighting its vulnerability. Conversely, the Flame-retardant fabric showed no adverse effects after 10 minutes (600 seconds), indicating comparable chemical resistance to the composite material.

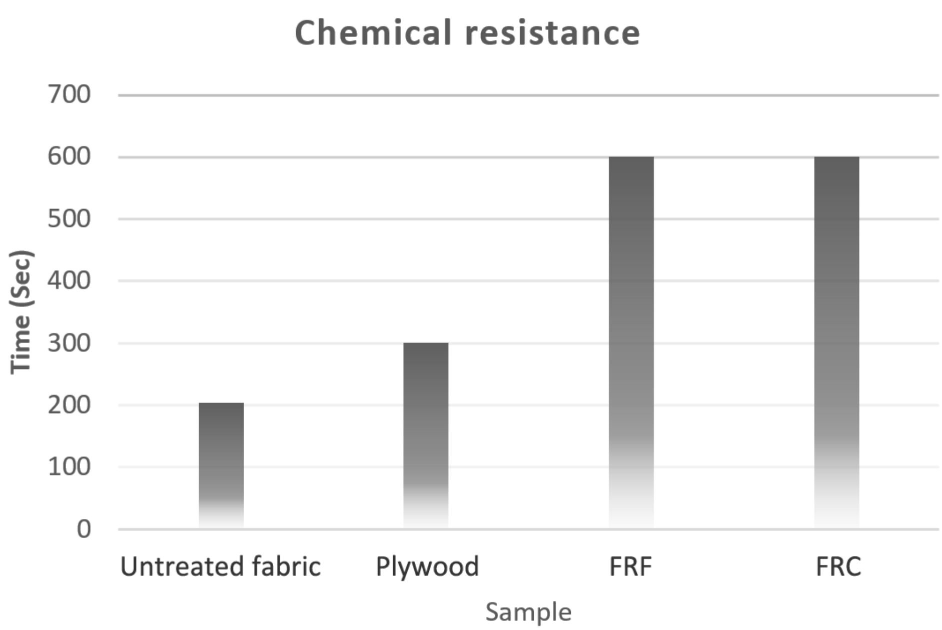

Figure 10. Results obtained by chemical resistance test.

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In the initial fire-retardant tests, the fire-retardant composite (FRC) samples outperformed in all evaluations. In contrast, the fire-retardant film (FRF) samples did not meet expectations, whereas the FRC samples excelled across the board. It can be inferred that the improved thermal and flammability properties of the composite may be attributed to higher moisture levels and the char-forming ability of the cellulosic components found in banana peel (Anannya et al., 2022).

4. CONCLUSION

This study explores the innovative use of banana peels as a bio-coating material for FRF and as a component of bio-composite materials made from fabric waste fibers in an attempt to increase sustainability and fire safety. It might be an affordable, environmentally beneficial substitute for traditional fire-retardant materials. The FRF showed exceptional fire-retardant qualities in a variety of tests after being painstakingly processed and applied banana peel bio-coating over simple woven cotton fabric. These include resistance to concentrated sulfuric acid, the 45° Burning Test, the Hot Nut Test, the DMH Test, the Gas Metal Arc Welding Spark Test, and the Direct Heat Test. The findings of the 45° Burning Test indicated that FRC had the maximum flame resistance, lasting 315 seconds, followed by plywood, which lasted 245 seconds. The treated material also revealed remarkable resilience, managing to form a half-hole in just 155 seconds. It outperformed plywood, and FRF outshone untreated fabric in the Hot Nut test. Furthermore, the welding spark test demonstrates the same superior fire retardancy, lasting 30.01 seconds without igniting. FRC and FRF samples are promising for fire safety applications since they also resisted exposure to strong sulfuric acid for 600 seconds without suffering any harm. Comparing the composite material manufactured from fabric waste fibers and banana peels to commercially available plywood, the former demonstrated better fire-retardant qualities. It demonstrated extended ignition periods and withstood prolonged exposure to direct fire, underscoring its promise as an efficient and sustainable fire-resistant substitute. Even though these first results are encouraging, more investigation is necessary to maximize these materials' performance and examine how different fire-retardant additives interact with natural fibers in composite applications. This ongoing work will improve the creation of workable and feasible fire-resistant materials that combine improved safety characteristics with sustainability. Future studies should concentrate on refining the recipe and increasing manufacturing volume for wider use in environmentally friendly fire safety measures.

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TRANSPARENCY
The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

DATA AVAILABILITY STATEMENT
Not applicable.

COMPETING INTERESTS
The authors declare that they have no competing interests.

AUTHORS' CONTRIBUTIONS
GM Faysal: Methodology, Conceptualization, Investigation, Validation, Supervision. Abdullah Al Fariz: Writing – original draft, Formal analysis, Visualization. Badhon Chandra Mazumder: Writing – original draft, Visualization. Mohammad Mosharof Hossain: Investigation, Validation. Md. Himel Mahmud: Writing –review & editing, Formal analysis, Supervision.

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