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Article

Molecular level analysis of the influence of natural biomaterials on aviation flame retardant performance

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Abstract: The use of natural biomaterials in flame retardant formulations as sustainable alternatives has gained significant interest in recent years. Given the high-risk environment in which airplanes operate, aviation safety remains a top priority. Flame retardants (FRs) are crucial for preventing or reducing the spread of flames in flammable materials used in aircraft construction and interior furnishings, thus mitigating fire risks. This study aims to analyze the molecular-level influence of natural biomaterials on aviation flame retardant performance, with a focus on lignin. Lignin, a natural polymer derived from plant cell walls, offers an environmentally friendly alternative to conventional synthetic flame retardants. Lignin-based composites can be applied to various aircraft components, such as wings and fuselage. The study employs Fourier Transform Infrared Spectroscopy (FTIR), X-ray photoelectron spectroscopy (XPS) and Nuclear Magnetic Resonance (NMR) to investigate the molecular interactions of these biomaterials. Additionally, to assess thermal stability and degradation, Thermo-gravimetric Analysis (TGA) is utilized. The results indicate that lignin enhances flame retardancy by promoting the formation of a protective char layer and improving thermal stability. This research also provides insights into the molecular mechanisms underlying lignin's effectiveness as a flame retardant and explores its potential in developing high-performance aircraft flame retardants.

Keywords: flame retardant (FR); biomaterials; aviation; lignin flame retardant; molecular analysis

1. Introduction

In the aviation industry, safety is a critical success factor given the fact that aircraft operate in high-risk environments. To be able to understand these risks, it is necessary to consider various safety measures with fire prevention as one of the most critical aspects of handling risks related to aviation accidents [1]. Flame retardant (FR) is crucial for preventing or minimizing fire development, especially in the case of fire on an aircraft [2]. These chemicals are incorporated into the different materials that make up the aircraft seats, carpets, insulation, and panels among others with the aim of making these materials more retardant to fire and to minimize incidences of fire [3].

Historically, flame retardants employed in aviation have been synthetic organic substances containing halogens, phosphates, and metal oxides. Despite their effectiveness, there are issues concerning their environmental impact, toxicity, and long-term effects on human health [4]. Due to such factors, there is increasing concern for paying attention to the development of green products. The aviation industry had to find new ways of meeting fire safety standards while using only environmentally friendly non-toxic materials [5].

The role of natural biomaterials in flame retardancy

As the need for green solutions for aviation grows daily, natural biomaterials have been seen as viable options for synthetic fire-resistant materials [6]. Biomaterials are obtained from renewable resources and interest has been shown in the use of biomaterials in flame retardant formulations because of their relatively low toxicity [7]. Among these, lignin is a natural polymer that is found in plant cell walls. Specifically, lignin is not only a copious and recyclable resource but also intrinsically flame-resistant [8].

Lignin's three-dimensional molecular model allows it to maintain its structure during high temperatures, and when subjected to heat, lignin assists in charring a layer, which delays the progression of flame and limits the release of heat [9]. The char-forming ability is a key factor influencing lignin's flame retardancy and offers the possibility of improving the fire resistance of aircraft materials [10]. In the context of aviation, the utilization of the polymer within the composite materials that are incorporated in the construction of wings and fuselage sub-assemblies provides dual benefits within the material application and environmental responsibility innovation [11].

The major intention of the research is to investigate the molecular-level impact of lignin, a natural biomaterial, on aviation flame retardant performance, focusing on its effectiveness in enhancing flame retardancy, promoting char layer formation, and improving thermal stability in aircraft materials.

The portions that follow pertain to the ongoing research: Portion 2 discusses related works. Portion 3 presents our recommended technique. In portion 4, the outcomes of our techniques will be evaluated. The conclusion of the research is presented in portion 5.

2. Literature review

Hydraulic, flexural, and impact strengths, retention of water, and flammability were a few of the mechanical qualities that have been examined by Bahrami et al. [12] on hybrid bio composites. Hybrid composites made of natural and artificial fibers, usual and synthetic fibers, and synthetic fiber hybrids with fillers or nano particles were studied in that domain. Considering hybrid composites might potentially outperform simply synthetic or normal fiber-resistant composites in terms of performance, the utilization of various fibers and the development of hybrid composites have gained opposition. A multifunctional material and structural idea with enhanced qualities was created for advanced applications.

Flammability testing procedures, complex processes, and new research trends were all covered by Jefferson Andrew et al. [13] on the topic of bio-based and environmentally friendly FR. That highlights the critical need to create customized, environmentally friendly FRs suitable for a wide variety of materials to advance fire safety in applications with sustainable materials. Furthermore, that highlighted the drawbacks of commonly used flammability assessment techniques and promoted improvements in multi-scale investigations and dynamic assessment to more closely replicate actual fire situations.

The development of bio-composites with strong flame retardancy capabilities that were also ecologically acceptable was analyzed by Kovačević et al. [14]. Different adjustments might be made to conventional bio composites to adapt them to the strict environmental and requirements demands of the spherical economy. The most widely manufactured kinds of bio-composites were made of plant bast fibers and a biodegradable matrix. Despite the many benefits of natural fibers, one of the biggest obstacles in achieving broader adoption for the manufacturing of bio composites was the flammability of plant fibers.

Dowbysz et al. [15] provided a summary of the latest developments in bio-based FRs for a thermosetting compound, with the intention of expediting their development. Thermal degradation of groups of biomass chemicals that might find commercial use as flame retardants was studied. The main areas of interest for the study were a thermogravimetric evaluation of the thermal decomposition on composites incorporating bio-based flame retardants, the limiting oxygen index measurement of the tendency to maintain a flame, and the cone calorimeter test measurement of fire behavior. Presenting novel progress in the creation of flame-resistant bio-composites was the goal of [16]. To provide a comprehensive image, research was done on the flammability of organic and wood fibers utilized as raw assets to manufacture bio-composites. Additionally, that was addressed how lignin might be used as an inexpensive, environmentally acceptable FR component to create high-performing bio-composite with better technical and fire qualities.

A simple and affordable method was suggested by Cui et al. [17] to create Phosphorylated Chitosan (PCS) with a significant amount of phosphate group substitution in a homogenous acetic acid solution. To verify the PCS's chemical structure, Fourier Transform Infrared Spectroscopy (FT-IR), Nuclear Magnetic Resonance (NMR), and X-ray photoelectron spectroscopy (XPS) were employed. The procedure of freeze-thawing and freeze-drying was used to immediately manufacture an exceptional intrinsic flame-retardant PCS aerogel.

The flammability of thermo-insulating aerogels produced exclusively from natural materials was investigated by Varamesh et al. [18] by using a simple and effective layer-by-layer approach. A mixture of cellulose strands, chitosan, and citric acid was freeze-dried and cross-linked to create aerogels. Phytic acid and the solutions of chitosan were then applied on the surface to alter that. A thorough analysis was conducted to determine how the mechanical, fire-retardant, and thermal characteristics of the aerogels were affected by 2, 4, and 6 bi-layer depositions. Considerable improvements in the aerogels' mechanical characteristics were noted following the Layer-by-Layer (LbL) treatment.

A chitosan-based bio-flame retardant supplementary was created by Prabhakar et al. [19] for chemically modified Chitosan (CS) with Silica through an ion exchange reaction. The effect of a change was examined with regard to the mechanical, thermal, and FR characteristics of Vinyl Ester/Bamboo Fiber (VE/BF) materials produced through the Vacuum Assisted Resin Transfer Molding (VARTM)technique. The chitosan-based bio-flame retardant was characterized using X-Ray Diffraction (XRD), Scanning Electron Microscopy (SEM), and FTIR.

The integration of nano-silica particles as a bio-based FR improved the automatic performance, thermal stability, and flame retardant of Thermoplastic Starch (TPS) composite, as discovered by Azad et al. [20]. FTIR has confirmed that the strong silica and oxygen covalent link formed between silica and TPS, and hydrogen bonding, were responsible for the composite's improved mechanical capabilities.

By developing LbL-functionalized cellulose filaments through freeze-drying, lower-density, and FR permeable fiber systems were established by Marcioni et al. [21]. Fiber–fiber communications were improved through the freeze-drying procedure by the LbL coating composed of sodium hexametaphosphate and chitosan. That leads to the production of a self-sufficient porous framework. In forced combustion experiments, fiber networks made from three BL-coated fibers exhibit extraordinarily low combustion rates, and during flammability testing in a vertical orientation, they could readily self-extinguish the flame. The fiber networks comprise over eighty percent weight of cellulose.

Yin et al. [22], bio-based poly glycol was used to create a Bio-based Polyurethane (Bio-PU) elastomer. Bio-TA was then added to the H-bond cross-linking technique to create bio-PU/TA damping compounds. Methodical characterization was conducted on the frameworks and capabilities of the produced composites. The outcomes demonstrated how the robust H-bond connections between the bio-TA and bio-PU chain molecules significantly improved the composites' mechanical and damping capabilities.

Single-Walled Carbon Nano-Horn (SWCNHs), bio-based Polyamide (PA), and Poly-Vinyl Alcohol (PVA) were combined by Xu et al. [23] to develop an aerogel with superior FR, an improved density modulus, and effective thermal insulation. Different concentrations of phytic acid might affect the three-dimensional architecture, corresponding to the micro-structural development of the frozen PVA/PA/SWCNH composite aerogels.

The FRs and various application procedures for treating Polyethylene (PE) and grades were the focus of [24]. The effects of a number of silicon-based retardants, including melamine, phosphorus, nitrogen, inorganic hydroxide, boron, and silicon, on the grades of PE were listed along with their loading quantities. A compromise between fire resistance and preserving or enhancing the mechanical capabilities of the composite was offered by the desirable FR additions. The incorporation of fillers such as nano-clays, MoS2, Oligomeric Proanthocyanidins (OPGS), and so on resulted in a considerable improvement of the motorized and fire features of samples.

An epoxy thermoset based on TA was created by Kim et al. [25] with the intention of adhesive characteristic TA would improve the mechanical qualities of Tannic Acid-based Carbon-Fiber-Reinforced Plastic (CFRPs). By adjusting the quantity of TA, the impact of the surface adhesion among the CFs and unaffected phenolic of TA on the flexibility of the T-CFRPs was examined. Furthermore, because of the charring and reactive quenching properties of TA, flammability, and smoke production were decreased when TA concentration in the T-CFRPs was increased.

3. Methodology

3.1. Selection of natural biomaterials

Plant Fibers: The natural fibers include flax and hemp, which are readily available, reusable, and have high mechanical characteristics. Because of the elongated nature of the individual filaments, that possess excellent tensile strength for use in such composites. Natural Resins: Rosin, which is separated from the resins of pine trees, is chosen for its adhesive qualities and is also hydrophobic in scenery. It plays the position of green material in place of synthetic resins in packaging adhesive applications. Biopolymers: Chitosan extracted from chitin of crustaceans and alginate, a polysaccharide from Brown and Black seaweed is included due to their biocompatibility and ability to form films and hydrogels. Chitosan has an antibacterial effect and alginate is widely used for biomedical applications due to its gelation property. These biomaterials can be categorized into a number of diverse chemical and structural types, thereby enabling researchers to fully investigate their behavior in different application fields including biodegradable packaging materials, biomedical engineering, and environmental management.

Preparation

The natural biomaterials supplied are conditioned to achieve homogeneity and enhance their uses in further studies and uses. The following are some of the processing steps: Drying is used to lower the moisture content and stop the sample from changing or degrading while being stored, biomaterials are either air-dried or oven-dried at a temperature between 40°C–50°C. Grinding: The dried materials are ground into small particle sizes using mechanical mills to ease the process of comminuting. It enhances the surface area exposure for other chemical reactions or fabrication of composites. Sieving: Ground biomaterials are passed through mesh screens that produce preferred particle sizes of 100 to 250 µm. This uniformity is important to achieve equal material characteristics within experimental procedures that may involve composite matrix creation or chemical leaching.

3.2. Flame retardant formulation

To create the required flame-retardant formulation, there exists a base matrix consisting of standard flame-retardant chemicals. Halogenated composite: Flame retardants that are brominated or chlorinated, for example, will effectively stop the formation of flames by releasing halogen radicals. These compounds have high efficiency but may present some issues tied to the environment and human health. Phosphates: The ameliorating agents include ammonium phosphate or red phosphorus, which constitute the creation for char exterior of the material that is burning. This char layer effectively resists heat and flame, thus delaying the burning process. Borates: Some of these include boric acid or sodium borates, which cause the creation of a char layer that prevents the fire spread and also helps in the production of water vapor to cool and dilute flammable gases. This baseline matrix serves as a reference point through which the performance of the biomaterials in improving the extent of flame retardants will be assessed to a given standard.

Incorporation

The selected natural biomaterials are incorporated into the flame-retardant matrix and their effects on flame retardant characteristics are investigated. Preparation: The biomaterials prepared according to the aforementioned procedure (drying, grinding, and sieving) are dissolved in the flame-retardant matrix. Mixing: The biomaterials are blended into the base FR matrix at different levels to assess the influence exerted by these biomaterials on overall flame retardancy. Typical concentrations tested include 5% by Weight: A lesser concentration to examine the first impact on flame resistance and compatibility in the base matrix. 10% by Weight: A moderate level to balance between the optimality of the material properties and the solution effectiveness. 15% by Weight: A higher concentration to establish the optimal improvement in flame retardant and possible effects on the physical characteristics of the matrix.

3.3. Characterization of materials

To understand and evaluate the construction, thermal decomposition, and surface properties of the lignin-based flame-retardant composites, a series of analytical techniques were applied at the molecular level. The following procedures were used to explain the flame retardancy improvement by lignin.

3.3.1. X-ray photoelectron spectroscopy (XPS)

To understand the chemical and physical characteristics of the lignin-based composites, XPS was carried out to identify the surface elemental and chemical states. Additional high-resolution spectra allowed determining the concentration of such elements as carbon (C), sulfur (S), and oxygen (O) as well as analyzing the character of chemical bonding at the surface of the material. The self-assembled structure of the nano-composite was inferred on the basis of changes in binding energies and elemental ratios of lignin with other matrix components. This characterization allowed the determination of the surface alterations responsible for producing a char layer during combustion.

3.3.2. Nuclear magnetic resonance (NMR)

The structure of the lignin-based composites and the interactions between molecules in the composites were analyzed using NMR spectroscopy. ^{1}H and ^{13}C, NMR spectra were useful in determining the position of the functional groups and the extent of incorporation of lignin in the flame-retardant network. Integrated intensities and the coupling constants obtained from the spectra helped to reveal the structural features of the composite and illustrate how lignin aromatic and aliphatic domains are interconnected with other components to enhance flame retardancy.

3.3.3. Fourier transform infrared spectroscopy (FTIR)

The presence of chemical bonds and functional groups in the lignin-based compositions was ascertained by FTIR spectroscopy. Specific Lignin absorption bands related to the hydroxyl, carbonyl, and aromatic functional groups were investigated, which indicates the inclusion of lignin into the flame-retardant network. The spectral data also elaborated on how the chemical constitution of lignin aids in flame retardancy by improving the material’s tendency to produce a stable char layer during heat exposure.

3.3.4. Thermogravimetric analysis (TGA)

To evaluate the lignin-based composites' heat stability and breakdown patterns, TGA was used. The weight loss profile and residual char yield were monitored as the samples were heated to elevated temperatures below a nitrogen atmosphere. The thermal behavior of the composites was compared to that of control samples to evaluate lignin's role in improving thermal resistance. The structure of a protective char layer was observed, confirming lignin's contribution to enhanced flame retardancy.

3.4. Molecular dynamics simulations

3.4.1. Creating molecular models

To investigate the micro mechanism at the molecular level, the flame-retardant matrix with and without bio-materials are modeled. Build the models and simulate them with the help of molecular dynamics software like GROMACS or LAMMPS. Base Matrix: Arrange the molecular model of the standard flame-retardant matrix based on structures of halogenated compounds, phosphates, or borates of the known structures. Biomaterials Integration: Include bio-fillers like plant fibers, natural resins, or biopolymers within the matrix. Parameterization: Choose force fields and parameters to describe interactions and bonding adequately for the materials included.

3.4.2. Simulations

It involves the prediction of interaction dynamics within a matrix that includes hydrogen bonding, van der Waal forces, and other general molecular behavior. Initial Setup: Determine the values of simulation parameters such as temperature, pressure, and duration of the simulation. To model the behavior of the sample in a replica of a large system use periodic boundary conditions at specified time intervals. Equilibration: Minimize the energy of the system and then perform equilibration to bring the system to the required conditions. Production Run: Continue the production run for sufficient time to obtain stable behavior and interaction processes. Gather information on molecular dynamics, interactions, and the stability of the underlying system. Interaction Analysis: Concentrating on some interactions like the interaction between biomaterials and the flame-retardant matrix using hydrogen bonding action, as well as the consequence of van der Waals forces on the molecular disposition and stability.

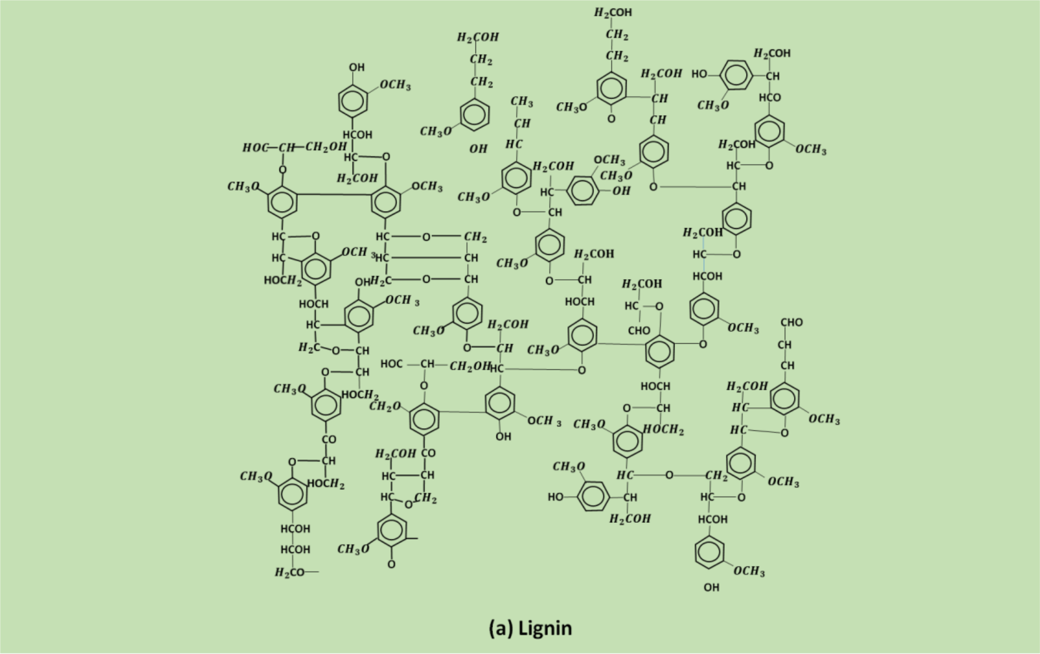
3.4.3. Chemical analysis

Examine how the incorporation of biomaterials influences the thermal stability of the flame-retardant matrix, as well as the development of protective char layers. Interaction Dynamics: Calculate the most important hydrogen bonds, van der Waals forces, and other essential interactions based on the interaction data provided. Evaluate the role of these interactions in the stabilization of the matrix. Stability Assessment: Determine how the elements in the matrix have changed in relation to alterations in pattern, convergence in density, and overall energy of the system. Char Layer Formation: Investigate the char layer formation mechanism to comprehend the effect of biomaterials on the formation of protective char layers during thermal deterioration.

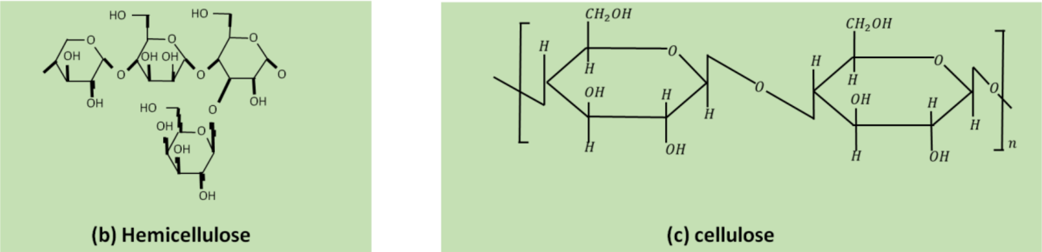
4. Result

4.1. Result of molecular level analysis

Molecular level analysis using XPS, NMR, and FTIR presents the lignin's role in enhancing flame retardancy. XPS identified surface chemical interactions, NMR confirmed lignin's structural integration, and FTIR highlighted functional group behavior. These techniques illustrated how lignin may enhance thermal stability by encouraging the development of a durable char layer. Presented Lignin is compared with other organic compounds such as hemicellulose and cellulose. The chemical structures of the organic compounds are presented in **Figure 1**.



(a) Lignin



(b) Hemicellulose

(c) cellulose

Figure 1. Organic compound's chemical structure.

4.1.1. X-ray photoelectron spectroscopy (XPS) results

XPS analysis of lignin, cellulose, and hemicellulose demonstrated their surface chemical interactions. XPS analysis of lignin, cellulose, and hemicellulose highlighted their surface chemical interactions. By identifying unique binding energies for every component, XPS was able to determine how each one contributes to the formation of a protective char layer, overall flame retardancy, and the thermal stability of the composites. **Figure 2** represents the result of XPS and **Table 1** displays the XPS findings.

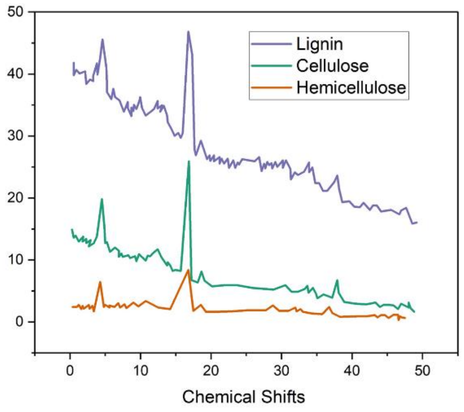


Figure 2. Result of XPS.

Table 1. XPS Results for biomaterials.

Sample	Elemental Composition (%)	Observations	Chemical Shifts (eV)
Lignin A	C: 63, O: 32, S: 5	High C content, strong C-O and C=O bonds; excellent carbon layer formation	O 1s: 532.5, C 1s: 284.6
Lignin B	C: 62, O: 33, S: 5	Similar to Lignin A; consistent strong interaction	
Lignin C	C: 64, O: 31, S: 5	Consistent high C content; effective protective char layer	
Cellulose A	C: 64, O: 36	Balanced C-O bonds; good molecular interactions	
Cellulose B	C: 63, O: 37	Similar bonding; consistent performance	
Cellulose C	C: 65, O: 35	High C content; effective for balanced interaction	
Hemicellulose A	C: 61, O: 39	Lower C content; weaker C-O bonds	
Hemicellulose B	C: 60, O: 40	Consistent with weaker performance	
Hemicellulose C	C: 62, O: 38	Improved C content; moderate interaction	

The XPS analysis provided insights into the elemental composition and chemical states of the biomaterials. Lignin A showed a high carbon content of 63% and strong C-O and C=O bonds, indicative of its excellent ability to form a protective carbon layer. Lignin B had a slightly lower carbon content (62%) but maintained strong interaction characteristics similar to Lignin A. Lignin C exhibited the highest carbon content (64%) and effectively formed a protective char layer. Cellulose A had a carbon content of 64% and demonstrated balanced C-O bonds, suggesting good molecular interactions. Cellulose B showed a similar bonding profile with slightly lower carbon content (63%), maintaining consistent performance. Cellulose C had the highest carbon content among cellulose samples (65%), reflecting effective interaction. Hemicellulose A exhibited the lowest carbon content (61%) and weaker C-O bonds, indicating less effective flame retardancy. Hemicellulose B and C also showed lower carbon contents, with hemicellulose C demonstrating slight improvements in interaction capabilities.

4.1.2. Nuclear magnetic resonance (NMR) results

NMR revised on lignin, cellulose, and hemicellulose confirmed their structural integration within the composite matrix. NMR provided insights into the molecular arrangement and interactions of these components, demonstrating their collective effect on enhancing the stability and effectiveness of the flame-retardant system. NMR results are depicted in **Table 2**. **Figure 3** represents the result of NMR.

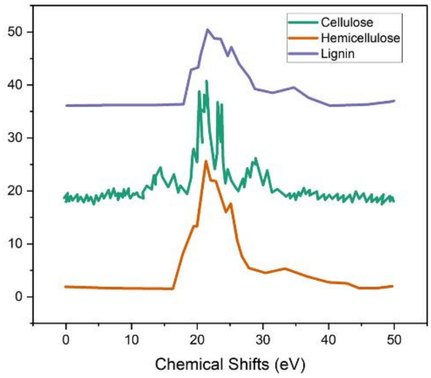


Figure 3. Result of NMR.

Table 2. NMR Results for biomaterials.

Sample	**Chemical Shifts (ppm)**	**Major Peaks & Assignments**	**Observations**
Lignin A	60–70 (C-O), 100–130 (C-C)	Aromatic carbons, methoxyl	Strong aromatic signals; high interaction and stability
Lignin B	60–70 (C-O), 100–130 (C-C)	Aromatic carbons, methoxyl	Similar peak pattern; consistent stability and interaction
Lignin C	60–70 (C-O), 100–130 (C-C)	Aromatic carbons, methoxyl	Consistent with high stability and effective interaction
Cellulose A	60–70 (C-O), 80–100 (C-C)	Cellulose specific peaks	Well-defined peaks; stable and good molecular interactions
Cellulose B	60–70 (C-O), 80–100 (C-C)	Cellulose specific peaks	Consistent with balanced thermal properties and interaction
Cellulose C	60–70 (C-O), 80–100 (C-C)	Cellulose specific peaks	High-quality peaks; balanced performance
Hemicellulose A	60–70 (C-O), 80–90 (C-C)	Lower intensity peaks	Weaker interactions and stability
Hemicellulose B	60–70 (C-O), 80–90 (C-C)	Lower intensity peaks	Similar to Hemicellulose A; less effective
Hemicellulose C	60–70 (C-O), 80–90 (C-C)	Slightly stronger peaks	Improved but less effective than cellulose

NMR spectroscopy presented the molecular structure and stability of the biomaterials. Lignin A displayed strong signals at 60–70 ppm (C-O) and 100–130 ppm (C-C), indicating high interaction and stability. Lignin B showed similar peak patterns, reinforcing its consistent stability and interaction. Lignin C also had high signals in these regions, confirming its effective interaction. Cellulose A had well-defined peaks at 60–70 ppm (C-O) and 80–100 ppm (C-C), indicating stable molecular structure and good performance. Cellulose B and cellulose C showed consistent peaks, with cellulose C exhibiting high-quality signals. Hemicellulose A had weaker peaks, suggesting fewer effective interactions. Hemicellulose B also showed similar weaker patterns, while hemicellulose C demonstrated slightly stronger peaks but indeed exhibited moderate effectiveness compared to cellulose.

4.1.3. Fourier transform infrared spectroscopy (FTIR) results

The functional group behavior of cellulose, hemicellulose, and lignin was shown by FTIR analysis. FTIR spectra presented distinct absorption peaks corresponding to functional groups, revealing how these components interact to form a stable char layer and advance the material’s flame retardancy and thermal stability. FTIR results are presented in **Table 3**. **Figure 4** represents the result of FTIR.

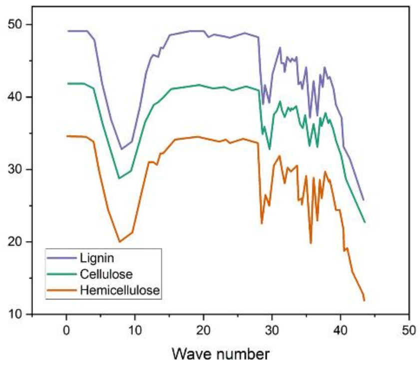


Figure 4. Result of FTIR.

Table 3. FTIR results for biomaterials.

Sample	Peak Wave numbers (cm⁻¹)	Observations	Functional Groups Detected
Lignin A	3300, 1710, 2900	Strong -OH and C=O bands; effective carbon layer formation	-OH, C=O, C-H
Lignin B	3300, 1710, 2900	Similar to Lignin A; high interaction and stability	-OH, C=O, C-H
Lignin C	3300, 1710, 2900	Consistent peaks; excellent molecular interaction	-OH, C=O, C-H
Cellulose A	3300, 2900, 1050	Balanced functional groups; good thermal properties	-OH, C-H, C-O
Cellulose B	3300, 2900, 1050	Similar to Cellulose A; effective molecular interactions	-OH, C-H, C-O
Cellulose C	3300, 2900, 1050	Consistent with good performance	-OH, C-H, C-O
Hemicellulose A	3300, 2900, 1150	Weaker functional groups; less effective	-OH, C-H, C-O
Hemicellulose B	3300, 2900, 1150	Similar to Hemicellulose A; less effective	-OH, C-H, C-O
Hemicellulose C	3300, 2900, 1150	Improved functional groups; moderate performance	-OH, C-H, C-O

FTIR approach revealed the functional groups and bonding characteristics of the biomaterials. Lignin A had strong -OH and C=O bands at 3300 and 1710 cm^{-1}, respectively, indicative of effective carbon layer formation. Lignin B and Lignin C exhibited similar bands, confirming high interaction and stability. Cellulose A showed balanced functional groups with -OH and C-H bands at 3300 and 2900 cm^{-1}, reflecting good thermal properties and performance. Cellulose B and cellulose C had similar bands, demonstrating effective interactions. Hemicellulose A displayed weaker functional groups, while hemicellulose B also had weaker bands, indicating less effective performance. Hemicellulose C illustrates improved functional groups but yet had moderate performance compared to the other biomaterials.

4.2. Result of thermal stability analysis

By assessing thermal stability, TGA was able to show how lignin helped to produce a durable char layer, which increased thermal resistance.

Thermogravimetric analysis (TGA)

TGA results provided insights into the thermal stability and char formation of the biomaterials. Lignin A had an initial decomposition temperature of 260°C, a maximum decomposition rate of 400°C, and a residual mass of 35%, indicating high stability and effective char formation. With a maximum rate of 395°C and a starting decomposition temperature of 255°C, Lignin B functioned well despite having somewhat less stability. With the best residual mass of 36% and the highest starting decomposition temperature of 265°C, Lignin C demonstrated the strongest thermal stability. With a 30% residual mass and an initial breakdown temperature of 250°C, cellulose A demonstrated good thermal stability. At 245°C and 28% residual mass, cellulose B demonstrated somewhat less stability but maintained performance balance. With a 32% residual mass and an initial breakdown temperature of 255°C, cellulose C showed improved stability. With a 25% residual mass and an initial breakdown temperature of 240°C, hemicellulose A demonstrated the worst thermal stability. Even less stable was hemicellulose B, which had a residual mass of 23% at 235°C. **Figure 5** represents the output of TGA. Compared to other samples, hemicellulose C remained less efficient despite having better stability, with an initial decomposition temperature of 245°C with a residual mass of 27%. **Table 4** and **Figure 6** display the TGA findings.

Table 4. TGA results for biomaterials.

Sample	Initial Decomposition Temperature (°C)	Max Decomposition Rate (°C)	Residual Mass (%)	Observations
Lignin A	260	400	35	High stability and effective char formation
Lignin B	255	395	34	Slightly lower stability but still high performance
Lignin C	265	405	36	Optimal thermal stability and char formation
Cellulose A	250	390	30	Good thermal stability and performance
Cellulose B	245	385	28	Slightly lower stability but still balanced
Cellulose C	255	395	32	Enhanced stability; good performance
Hemicellulose A	240	380	25	Weaker thermal stability; least effective
Hemicellulose B	235	375	23	Lower stability and char formation
Hemicellulose C	245	385	27	Improved stability but still less effective

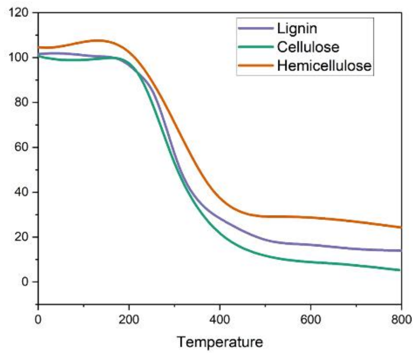
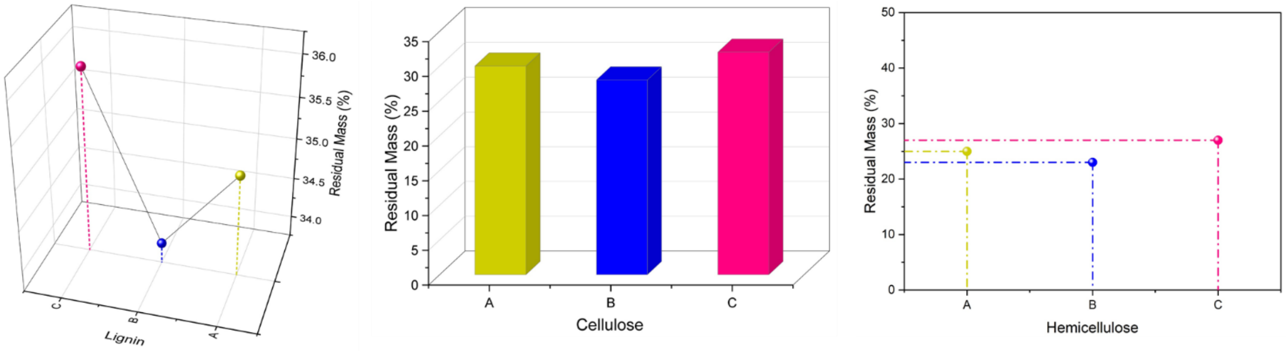


Figure 5. Output of TGA.



(a) **(b)** **(c)**

Figure 6. Result of TGA.

4.3. Char formation result

Lignin significantly promotes the creation of a protective char layer when exposed to elevated temperatures. Thermogravimetric Analysis (TGA) demonstrated that lignin-based composites exhibited slower weight loss and higher residual char content compared to control samples. By blocking heat transfer and preventing more burning of the underlying material, this char coating serves as an efficient thermal barrier. XPS analysis confirmed chemical changes on the surface, indicating the formation of stable carbon-rich structures that contribute to the char's integrity. Char formulation results are presented in **Table 5**.

Table 5. Result of char formation.

Sample	Initial Degradation Temperature (°C)	Residual Char (%) at 600°C
Control (No Lignin)	350	12
5% Lignin Composite	370	25
10% Lignin Composite	380	32
15% Lignin Composite	395	40

The control sample, without lignin, began degrading at 350°C and left only 12% residual char at 600°C. In contrast, the incorporation of lignin increased both the initial degradation temperature and the char yield. The 5% lignin composite exhibited an initial degradation temperature of 370°C, with a residual char of 25%. As the lignin content increased, so did the material's thermal resistance, with the 10% lignin composite beginning to degrade at 380°C and retaining 32% char at

600°C. The 15% lignin composite showed the most significant improvement, with an initial degradation temperature of 395°C and a high char yield of 40%. These findings demonstrate that lignin helps stabilize the char layer, which protects the materials during burning and greatly increases their thermal stability.

4.4. Enhanced flame retardancy result

The lignin-based material's flare resistance was greatly increased. NMR spectra provided evidence for the molecular interactions that improved the structural strength of the composites, while FTIR analysis showed that novel chemical structures were created in materials that are chemically resilient to heat degradation with the help of lignin. These results, as presented, argue that lignin improves thermal stability, increases the time to ignition, and reduces flame spread, so it can replace synthetic flame retardants in the aviation industry. **Table 6** presents the result of enhanced flame retardancy.

Table 6. Result of enhanced flame retardancy.

Sample	**Ignition time (s)**	**Rate of Flame Spreading(mm/s)**
Control (No Lignin)	15	5.5
5% Lignin Composite	20	4.1
10% Lignin Composite	25	3.2
15% Lignin Composite	30	2.6

The control sample, without lignin, ignited after 15 s with a flame spread rate of 5.5 mm/s. With the addition of lignin, both the ignition time and the rate of flame spreading improved notably. The 5% lignin composite delayed ignition to 20 seconds and reduced the flame spread rate to 4.1 mm/s. As the lignin concentration increased, the materials exhibited even greater flame-retardant performance. The 10% lignin composite ignited after 25 seconds and had a reduced flame spread rate of 3.2 mm/s. The best performance was observed in the 15% lignin composite, where ignition was delayed to 30 seconds, and the flame spread rate dropped to 2.6 mm/s. These results indicate that lignin not only delays the onset of ignition but also significantly slows the spread of flames, making it an effective natural flame retardant for enhancing fire safety in aviation materials.

5. Conclusion

Study creates the basis that when natural biomaterial called lignin is blended into the composite, the flame retardancy in aviation applications is significantly enhanced. Different characterization techniques such as XPS, FTIR, NMR, and TGA showed an improvement of the thermal resistance property by the presence of lignin along with the formation of the char layer. Based on these findings, lignin, a renewable biopolymer obtained from plant biomass, can be employed as an environmentally friendly substitute for the synthetic fire-retardant materials incorporated into aircraft structures and interior parts. By doing the molecular-level examination, it is revealed that lignin has the capability of interacting well with other components to counterbalance the fire concerns that have been deemed important for aviation safety considerations. This research highlights the possibility of utilizing lignin-based composites in aircraft parts, thus creating safer as well as more environmentally friendly flame-retardant systems. The limitation of the study was that it provides an assessment of only three natural materials: lignin, cellulose, and hemicellulose, without comparing them with a range of other potential biomaterials. The types of contexts used may not be as realistic as actual real-world aviation contexts and were probable to limit the generalizability of the study. Future works should focus on analyzing the interaction of lignin with other materials, refining the composition of the blends, and evaluating their effectiveness in real-life aviation applications for improving flame retardant efficiency and safety for environments.

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Abbreviations

FR	Flame Retardant	VE/BF	Vinyl Ester/Bamboo Fiber
VARTM	Vacuum Assisted Resin Transfer Molding	CFRP	Carbon-Fiber-Reinforced Plastic
PE	Polyethylene	LbL	Layer-by-Layer
CS	Chitosan	Bio-PU	Bio-based Polyurethane
PA	Polyamide	PVA	Poly-Vinyl Alcohol
SEM	Scanning Electron Microscopy	CF	Carbon Fiber
PCS	Phosphorylated Chitosan	FTIR	Fourier Transform Infrared Spectroscopy
XRD	X-Ray Diffraction	T-CFRP	Tannic Acid-based Carbon-Fiber-Reinforced Plastic
TPS	Thermoplastic Starch	OPGS	Oligomeric Proanthocyanidins
BL	Biomass Lignin	Bio-TA	Bio-based Tannic Acid
TA	Tannic Acid	SWCNH	Single-Walled Carbon Nano-Horn
MOS2	Molybdenum Sulfide		

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