Biochar Reinforcement in Epoxy Composites for Enhanced Mechanical Properties and Fire Resistance

Dissertation submitted in partial fulfilment of the requirements

for the award of degree

of

Master of Technology in Marine Technology

by

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TABLE OF CONTENTS

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DECLARATION

I certify that

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LIST OF TABLES

LIST OF FIGURES

ABSTRACT

In response to the growing need for environmentally sustainable and high-performance composite materials, this study explores the use of bamboo-derived biochar as a reinforcing filler in epoxy resin composites. Bamboo was selected due to its rapid renewability, abundant availability, and high lignocellulosic content, making it a viable precursor for biochar production through pyrolysis. Biochar was synthesized via slow pyrolysis at 500°C and integrated into epoxy resin at varying weight percentages (1%, 3%, and 5%) to evaluate its impact on mechanical, thermal, and fire-retardant properties. The fabricated composites were subjected to tensile testing, where the 5 wt% biochar-reinforced composite exhibited the highest performance, achieving an ultimate tensile strength (UTS) of 47.90 MPa, compared to 28.00 MPa in the neat epoxy. Young's modulus increased from 1.85 GPa (0% biochar) to 2.42 GPa (5% biochar), indicating a significant enhancement in stiffness. Elongation at break showed a marginal decrease with increasing filler content, highlighting the typical trade-off between strength and ductility. Thermogravimetric Analysis (TGA) demonstrated improved thermal stability in composites containing biochar. The 5 wt% biochar sample showed a higher decomposition onset temperature and a residual mass of 38% at 800°C, compared to only 0.6% in the control sample. This indicates strong thermal barrier effects due to char formation. Although direct cone calorimetry testing could not be performed, a detailed review of similar studies and comparative interpretation with TGA data suggested improved flame retardancy with increased biochar content. Key inferred outcomes included longer time to ignition, reduced peak heat release rate (PHRR), and higher char residue, particularly in the 5 wt% composite. This investigation validates the multifunctional role of bamboo biochar in enhancing tensile strength, thermal stability, and flame-retardant behavior of epoxy composites. The findings support the use of such bio-based reinforcements in marine structural components, interior panels, and thermally sensitive applications. Moreover, this work opens future directions in optimizing pyrolysis conditions, scaling fabrication processes, and validating long-term durability and fire performance in real-world environments.

CHAPTER 1

INTRODUCTION

1. Introduction

In recent years, there has been a growing interest in the sustainable and high-performance materials which has gained significant importance due to growing environmental concerns and demand for greener alternatives to conventional polymers. Among the various approaches developed, the reinforcement of polymer matrices along with biomass-derived fillers has emerged as a promising suggestion for enhancing mechanical, thermal, and fire-retardant properties along with promoting eco-friendliness. This research looks into the integration of bamboo derived biochar with an epoxy resin to develop a composite that have improved structural performance, high thermal and fire resistance. Epoxy resins are commonly used in industries and for engineering applications due to its high strength, chemical resistance, and dimensional stability. However, their natural brittleness and flammability condition limits their use in certain sectors, where fire safety and impact resistance are crucial. Due to these limitations, fillers such as carbon black, silica, and glass fibers are being used in common. But these materials are non-renewable, costly, and often pose health or environmental hazards during their lifecycle. In this scenario, Biochar which is a carbon rich byproduct of biomass pyrolysis emerged as an innovative alternative filler due to its thermal stability, porous structure, and its ability to improve both mechanical and fire-retardant properties of composite materials. When the biochar is added into the polymers it helps to increase the load distribution and form a protective char layer upon heating, which enhances the flame retardancy. Among many sources of biomass, bamboo stands out due its rapid growth, high carbon content, and excellent lignocellulosic structure, making it a sustainable and efficient source. The focus of this thesis is to find out how the addition of bamboo derived biochar at varying weight percentages (1%, 3%, and 5%) changes the tensile properties, thermal degradation profile, and potential fire behavior of epoxy composites. To evaluate these properties some experimental methods where selected which include tensile testing, thermogravimetric analysis (TGA), and a review-based cone calorimetry evaluation to provide a clear understanding of the composite behavior. With the help of these experiments an optimal reinforcement percentage will be identified based on performance trends, with a focus on identifying the balance between strength, stiffness, and thermal stability. This work holds relevance in multiple sectors such as automotive, marine, aerospace, and construction, where material performance and fire resistance are critical. It also contributes to the field of sustainable material science by exploring the utility of an abundant bio-waste product in replacing synthetic and hazardous fillers. Therefore, the study aims to advance the development of safer, greener, and more efficient composite materials for modern applications by demonstrating the performance potential of bamboo biochar-reinforced epoxy composites.

1.1 Rationale for Bamboo Biochar-Based Composite Development

The increasing demand for sustainable materials in polymer science and composite engineering which is largely driven by the environmental regulations and depletion of non-renewable resources. Epoxy resins, such as Araldite LY556 (a DGEBA-based resin) mixed with Araldite HY951 hardener in a 10:1 ratio, are widely utilized in structural composite applications due to their superior adhesion, thermal stability, dimensional integrity, and load-bearing capacity. However, these materials are known to suffer drawbacks like brittleness and flammability. To overcome these issues traditional synthetic fillers like glass fibres and carbon nanotubes are used to enhance these properties, but they have their own limitation such as high cost, non-renewability, environmental toxicity, and complex processing requirements. In this context, bio-based fillers such as bamboo-derived biochar emerged as a promising alternative. Biochar produced through the pyrolysis of bamboo biomass offers a stable carbon matrix with high porosity and naturally occurring inclusion. These properties not only improved mechanical strength and thermal stability but also improved the fire-retardant characteristics due to the higher char yield during combustion there by making bamboo biochar a promising reinforcement option for environmentally friendly composite materials. This study focuses on the comparative analysis, which was bamboo biochar is added to the epoxy matrix at three different weight percentages: 1%, 3%, and 5%.

The objective is to determine the optimal biochar loading that balances reinforcement and material stability. It is expected that 5% biochar formulation will show the most favourable combination of mechanical strength, thermal resistance, and flame retardancy. This performance improvement is anticipated due to the effective dispersion of biochar within the matrix, enhancing the interfacial adhesion and stress transfer. The integration of bamboo biochar not only improves the functional performance of the epoxy composites but also aligns with the sustainability goals. It enables the reuse of agricultural residues there by reducing the carbon footprint of composites and reduces the need of toxic flame-retardant additives. Such features make this material a potential candidate for applications in construction, transportation and protective materials where high-performance, cost-effective and eco-friendly composites are in demand.

1.2 Bamboo as a Sustainable Biochar Precursor

The effectiveness of biochar depends upon the choice of biomass feedstock, which determines the material's structural and functional properties. Among various biomass sources such as agricultural and forestry residues, bamboo stands out as a superior source for biochar production due to its rapid growth cycle, abundant yield, and favourable chemical composition. Bamboo has high lignocellulosic content and low ash yield making it suitable for pyrolysis, resulting in biochar with a stable carbon matrix and high porosity. These features enhance mechanical bonding and thermal stability when mixed with polymer-based composites there by making bamboo-derived biochar an effective reinforcement material for engineering purpose. Moreover, using bamboo for biochar production aligns with sustainability objectives by converting fast-growing, renewable biomass into high-value materials thereby reducing dependence on non-renewable resources and contributing to environmental conservation. When bamboo biochar is added into polymer composites, it improves mechanical and thermal properties but also supports the development of eco-friendly materials for applications in construction, transportation, and protective equipment.

Abundance and Renewability

Bamboo is among the fastest-growing land plants that can grow from a few inches to over 1 meter a day. They reach maturity in 3-5 years after planting, much faster than hardwood trees. Rather than being planted again, bamboo can regenerate from the same root system through rhizome. It is also widely available, low-priced, and quickly renewable biomass resources and is being seen in regions such as Asia, Africa, and South America. Bamboo is being highly considered in India as a sustainable resource under several rural development and green infrastructure programs thereby adding much weight to bamboo's importance in ecologically related material research.

Chemical Composition and Pyrolysis Suitability

The deciduous nature of bamboo allows it greater compatibility with pyrolysis due to its rich chemical structure. Bamboo is characterized by a relatively high content of lignin, cellulose, and hemicellulose, which are the most important polymers involved in thermal degradation and char formation. The normal dry weight composition of bamboo is as follows:

- Cellulose: ~50–60%
- Hemicellulose: ~20–25%
- Lignin: ~20–30%
- Ash: ~2–4%, mostly silica

This lignocellulosic configuration allows the production of aromatic, carbon-rich char in pyrolysis. Furthermore, the naturally occurring silica in the bamboo fibers also acts to act as a flame-retardant agent for the resulting biochar, with silica serving as a thermal insulator while providing stability to char during combustion.

Structural and Morphological Properties

Bamboo-derived biochar, produced through pyrolysis, exhibits a porous microstructure and high surface area, making it an effective reinforcement in polymer composites. These physical characteristics enhance mechanical interlocking with polymer chains, promote uniform dispersion within the epoxy matrix, and reduce void formation during curing. The micro-porosity of bamboo biochar also contributes to its ability to trap degradation gases and improve thermal barrier properties under high heat exposure. Such attributes not only bolster the mechanical and thermal performance of the composites but also align with sustainable material development goals by utilizing renewable biomass resources.

The Environmental and Economic Benefits are:

- Sequestering carbon: Bamboo has an extraordinarily high capacity to uptake atmospheric CO_2 during growth and converts it to stable carbon when simultaneously converted to biochar.
- Waste valorization: Bamboo off-cuts, agricultural waste, and low-grade stalks unfit for constructions or textiles can readily be valorized into high-value products through pyrolysis.
- Cost-effectiveness: In contrast to the engineered fillers carbon black or nano-silica, bamboo biochar is low-cost, needs minimal processing, and can be locally sourced.

With its rapid renewability, compatibility with pyrolysis, and exceptional mechanical and thermal properties, bamboo is an increasingly promising candidate for biochar. Therefore, the use of bamboo biochar to improve the technical performance of epoxy composites in terms of interfacial bonding, structural integrity, and flame resistance, environmental issues like mitigation of waste, carbon sequestration, and circular use of materials also present themselves. Owing to its availability and affordability and ease of processing, it is eminently technological for large-scale eco-conscious composite production. It is this combination of properties that positions bamboo solidly as the preferred biomass source for the production of a functional and high-performance biochar in the context of this research.

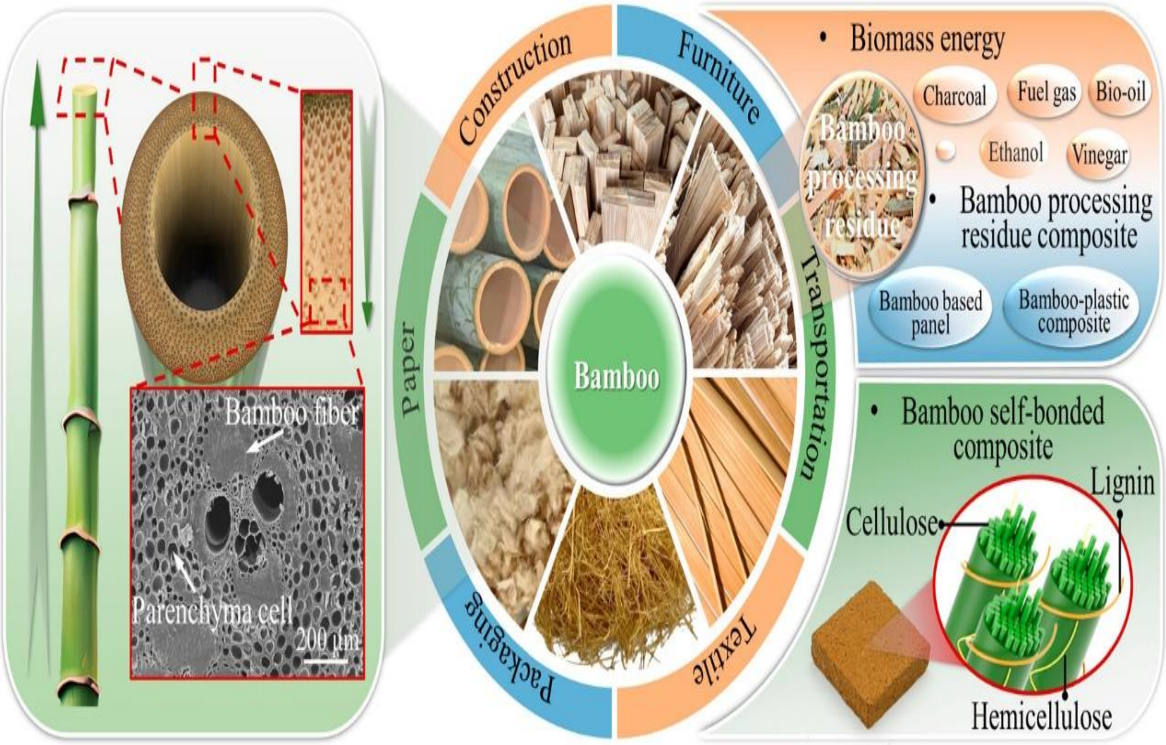

Figure 1.1 Structural Characteristics and Current Applications of [https://www.mdpi.com/1999-4907/14/11/2266]

1.3 Biochar-Structure, Production, and Application Potential

Biochar is a solid carbon-rich material produced via the thermal decomposition of organic biomass under oxygen-limited conditions, a process commonly known as pyrolysis. Unlike ash, which is the residue of complete combustion, or charcoal, traditionally manufactured as a fuel, biochar is engineered for high stability, porosity, and carbon retention, making it suitable for a broad range of technical applications beyond its conventional role in agriculture. The properties of biochar are strongly influenced by the type of feedstock—bamboo, in this case—

and the pyrolysis parameters, including temperature, heating rate, and residence time. Bamboo-derived lignocellulosic biochar features graphitic carbon domains, a micro- to mesoporous structure, and surface functional groups such as hydroxyl and carboxyl, which enhance compatibility and interaction with polymer matrices. Its development involves a sequence of thermal decomposition stages, in which hemicellulose, cellulose, and lignin break down progressively at elevated temperatures, releasing volatiles and leaving behind a thermally stable carbonaceous matrix. The resulting material comprises highly ordered carbon structures, voids, and mineral residues such as silica commonly found in bamboo which contribute to mechanical interlocking and improved thermal stability in polymer composites. Furthermore, its thermal degradation behaviour facilitates the formation of protective char layers during combustion, serving as a physical barrier to heat and gas transfer, a key feature in flame-retardant systems. Over the last decade, the engineering applications of biochar have expanded significantly. Initially developed as a soil amendment due to its moisture retention and microbial benefits, biochar is now employed in polymer reinforcements, concrete additives, electrodes, filtration systems, and energy storage technologies. In polymer composites, it delivers not only mechanical reinforcement but also contributes to improved thermal conductivity, dimensional stability, and in some cases, electrical performance. Unlike untreated natural fibers or wood flour, biochar exhibits excellent resistance to moisture absorption and degradation, enhancing long-term durability. This study evaluates the incorporation of bamboo-derived biochar into epoxy resin at particle loadings of 1 wt.%, 3 wt.%, and 5 wt.% to assess its influence on composite performance. The focus is to demonstrate biochar’s role as an active reinforcement agent, contributing to improved tensile strength, thermal degradation resistance, and fire retardancy. These benefits, coupled with its cost-effectiveness and environmental compatibility, position biochar as a compelling alternative to traditional non-renewable fillers in polymer composite applications.

1.4 Pyrolysis Process and Parameters

Biochar is a solid carbonaceous material produced through the thermal decomposition of organic biomass, such as bamboo, in an oxygen-limited environment a process known as pyrolysis. Unlike ash, which results from complete combustion, or charcoal, typically produced for fuel, biochar is engineered for stability, high porosity, and carbon retention, making it suitable for various technical applications beyond agriculture. The properties of biochar are significantly influenced by the choice of feedstock and the specific conditions of pyrolysis, including temperature, heating rate, and residence time. This study focuses on the production of bamboo-derived biochar through slow pyrolysis. Slow pyrolysis generally occurs within a temperature range of 350 to 550°C, employing a slow heating rate of approximately 5–10°C per minute and extended residence times that can last several hours. These conditions favour higher biochar yields and result in a carbon-rich solid material with desirable characteristics for reinforcement applications. Bamboo's fibrous and silica-rich structure makes it particularly well-suited for this process, yielding biochar with high fixed carbon content, stable aromatic ring structures, and favourable porosity attributes that enhance its effectiveness as a reinforcement material in composite applications.

The process of pyrolysis follows three major thermal degradation phases through the biomass’s components:

- Degradation of hemicellulose: 200–300°C hemicellulose begins to decompose and releases some volatile organic compounds.
- Degradation of cellulose: Decomposition from about 300 to 400°C, where the gas emission and initial char formation occur.
- Degradation of lignin: It is a slow and more complex thermal depolymerization during which lignin decomposition occurs from 250°C to up to about 600°C, contributing greatly to the fixed carbon and thermal stability of biochar.

Thus, the thermal degradation behavior of these constituents, most importantly lignin, becomes important for biochar so it ultimately determines its structural properties, surface area, and graphitic content. Other aspects such as bamboo feedstock particle size, moisture content, and reactor type (fixed bed, batch, or continuous) may significantly affect the final product's physical and chemical characteristics.

The influence of pyrolysis conditions on biochar properties has led to diverse applications in composite materials, enhancing specific functionalities. Higher pyrolysis temperatures increase carbonization, reduce volatile content, and improve electrical conductivity and thermal degradation resistance. Conversely, lower temperatures preserve surface functionalities, enhancing bonding with polar matrices like epoxy. By tailoring pyrolysis parameters, biochar becomes a versatile and tunable filler in engineering applications. Here we focus on producing bamboo biochar through controlled slow pyrolysis, aiming to achieve optimized properties for integration into epoxy resin systems. The process not only enhances composite performance but also contributes to carbon recycling, waste valorisation, and energy-efficient material design, aligning with sustainable engineering principles.

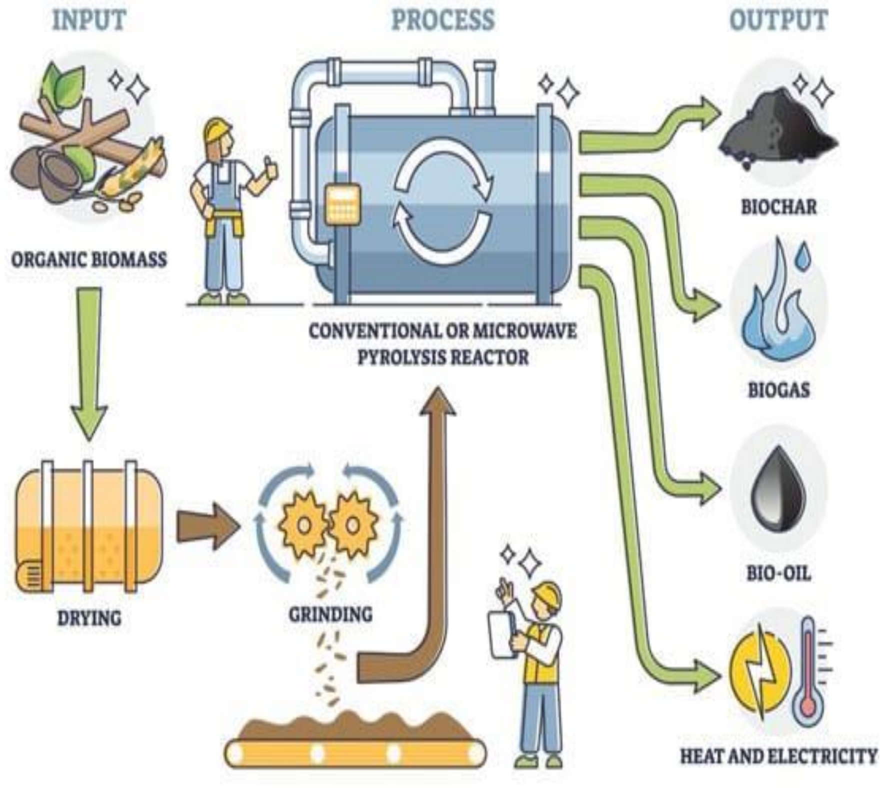

Figure 1.2 Schematic representation of the pyrolysis process for biomass conversion

1.5 The Spanning and Processing of Epoxy–Biochar Composites

The fabrication of epoxy–biochar composites in this particular study followed established experimental methods from validated literature. The matrix used was a commercially available diglycidyl ether of bisphenol-A (DGEBA) resin; specifically, it was Araldite LY556, combined with a low-viscosity aliphatic amine-based curing agent known as Araldite HY951 hardener. Resin and hardener were mixed at a 10:1 weight ratio; this was a popular and standard formulation in the industry for structural epoxy composites. It provided an optimal balance of pot life, mechanical strength, and cure time, frequently used in epoxy systems reinforced with natural fillers or biochar.

The biochar that was used in this research as an epoxide-biochar composite to reinforce the resin was prepared by controlled pyrolysis, grinding, and then sieving to achieve a uniform particle size of less than 100 microns. The fine particle size will ensure better distribution within the resin and less interfacial defects during curing. However, the biochar powder was firstly dried completely to remove traces of moisture because the moisture might hinder crosslinking reaction between epoxy and hardener before it is added into epoxy. The fabrication of composites involved weighing and blending biochar, in 1 wt%, 3 wt%, and 5 wt% loadings, into epoxy resin. The biochar was gradually added under continuous mechanical stirring to ensure homogeneous dispersion. Moderate-speed stirring was maintained for around 20-30 mins to avoid agglomeration. Subsequently, the necessary dosage of HY951 hardener was added to the homogeneous suspension, and slight stirring was done to prevent the incorporation of air. The resin–biochar mixture was subjected to vacuum degassing for 30 minutes to remove trapped air and microbubbles as a result of mixing. It was then deposited into pre-clean molds previously cleaned and coated with a release agent, which were cast to specifications for tensile, TGA, and cone calorimetry testing. Curing was carried out at ambient room temperature for 72 h for complete cross-linking. In some cases, subsequent curing was performed at 80°C for 2 h to enhance thermal and dimensional stability, especially with evaluations for fire retardancy.

The preparation technique was carefully maintained in all formulations to create a comparable background for all three levels of reinforcement. With this controlled procedure, it is possible to unambiguously interpret the effects of biochar loading on the mechanical and thermal properties of the final composite. The methodology for preparing the composites used here is in concordance with the various experimental studies discussed in this thesis and hence lends further credibility and reproducibility to the materials prepared.

1.6 Testing Techniques

The performance of polymer composites is highly influenced by their mechanical, thermal and fire-resistance properties, especially for more advanced structural and safety-critical applications; it will integrate a sustainable composite where the reinforcement is biochar derived from bamboo. Therefore, systematic testing methodologies are needed to evaluate the relevance of this methodology as a reinforcing or multifunctional additive in a composite. This section provides general information on the main characterization methods used throughout this investigation to assess the influence of biochar loading on the properties of composites based on epoxy resin. Two main areas of analysis will be assessed - mechanical performance via tensile testing, thermal performance via thermogravimetric analysis and fire-retardant ability via a literature-based assessment of cone calorimetry. Every one of the three techniques provides certain unique information that is relevant for assessing some attributes of composite behavior. Tensile testing gave a quantitative enhancement of strength, stiffness, and, ductility which reflects structural behavior. TGA gave a specific understanding of how thermal decomposition behavior varies in the presence of biochar, which allows for an understanding of relevant mechanical properties relative to temperature. In another regard, although it was done indirectly through thorough reviews of relevant literature, cone calorimetry yields unique information related to flammability, ignition resistance, and char formation, which is critical when considering applications involving safety. Ultimately, these methods allow a multi-faceted description of how biochar works within the composite system, supporting a more general aim of developing environmentally friendly, high-performance material.

1.6.1 Tensile Testing

Tensile testing serves as the most elementary mechanical characterization with which the strength and deformation behavior of polymer composites can be evaluated. Tensile testing in the present study will include the incorporation of bamboo-derived biochar at three different concentrations which are 1 wt%, 3 wt% and 5 wt% to investigate their influence on ultimate tensile strength (UTS), Young’s modulus, and elongation at break of epoxy-based composites. All the properties mentioned above are beneficial for the assessment of the load-bearing capacity and flexibility of the material over any application, especially structural ones.

The procedures of the test follow the ASTM D3039 standards, mainly intended for the tensile testing of polymer matrix composites, as the specimens were prepared in a dog-bone or flat-rectangular format, which apply to the common sizes, that is, 250 mm × 25 mm × 2 mm, as found in the standard. These tests were done on a Universal Testing Machine (UTM) having a 10 kN or higher capacity load cell corresponding to the stress range expected. Each specimen is mounted securely in the machine's grips such that the proper alignment is maintained to ensure no bending or shear occurs during loading. The crosshead speed is set to 2 mm/min to provide quasi-static loading, which ideally captures any gradual deformation and fracture characteristics. Strain measurement is either done through the extensometer or indirectly measured. Each composition, including the control (pure epoxy), 1%, 3%, and 5% biochar-reinforced samples, has at least five specimens tested to maintain the statistical significance of the results obtained from the tests. Average values and standard deviations of the UTS, modulus, and elongation at break were computed for comparison of performance. The analysis of failure modes was particularly noted as to whether there was indication of brittle fracture, matrix crack, or interfacial debonding of the filler and resin.

In general, the presence of biochar is expected to influence the tensile behavior through multiple mechanisms:

- Reinforcement effect: Biochar particles act as rigid load-bearing fillers that increase stiffness and resistance to deformation.
- Stress transfer: Effective dispersion and interfacial bonding allow stress to be transferred from the matrix to the filler.
- Crack arresting: The irregular shape and distribution of biochar particles can hinder crack propagation, enhancing toughness.

Nevertheless, filler contents beyond the optimum (in this case, above 5 wt%) are likely to lead to agglomeration, increased void content, or stress concentration zones, all of which are detrimental to tensile performance. Hence, in view of an established balance between reinforcement and matrix continuity, it becomes pertinent to study the 5% wt loading as the optimum threshold. The tensile test results are an important affirmation of the mechanical enhancement potential of bamboo biochar as well as establishing its case as a structurally functional filler in epoxy composites, which is discussed in detail in the experimental and discussion chapters of this thesis.

1.6.2 Thermogravimetric Analysis (TGA)

Thermogravimetric analysis (TGA) is probably the most characteristic technique for the consideration of thermal stability and degradation behavior of polymer composites under controlled heating. It quantitatively demonstrates how a material responds in terms of weight loss due to thermal decomposition as the temperature increases. In this study, TGA was conducted to determine the extent to which bamboo-derived biochar-modified epoxy composites molded at 1 wt%, 3 wt%, and 5 wt% loading levels could improve thermal degradation resistance of the composites.

TGA tests were carried out on a TG analyzer under nitrogen to avoid oxidative degradation. About 5-10 mg of each composite sample is put in a platinum crucible and heated from 30 to 800 °C, with a linear heating rate of 10 °C/min. This temperature range is selected to capture completeness of multistage decomposition behavior of the epoxy matrix involving the initial evaporation of volatiles and primary degradation of the polymer backbone.

For each sample, the TGA curves display weight (%) versus temperature (°C), while the derivative thermogravimetric (DTG) curves reflect the rate of weight loss and identify the peak decomposition temperatures. Glass epoxy composites generally exhibit a two-stage degradation profile:

- Initial phase (150-350°C)- Concerns the disassembly of smaller side chains and weaker bonds in the matrix.
- Second phase (350-550°C)- Involv es the disassembly of the epoxy backbone with char formation

The introduction of biochar changes this degradation pattern in several ways

- Onset degradation temperature (Tonset) is generally pushed higher, giving them better chances of thermal initiation without ignition.
- On the DTG curves, peak degradation temperature (T max) is shifted to higher values, suggestive of delayed thermal breakdown.
- Residue/char yield at 600-800 °C is accordingly high in biochar composites: largely because biochar itself is known to be stable.

The greater the final char residue developed at elevated temperatures, the more it signifies thermal stability and improved fire retardancy since greater residue implies greater protection against possible combustion. Thus, TGA can give insight into processing limitations, operating temperature ranges, and composite combustibility. These thermal properties, together with tensile strength and fire-retardant data, would provide an insightful consideration toward any high-end application that is thermally demanding.

1.6.3 Cone Calorimetry (Literature-Based Evaluation of Fire-Retardant Behavior)

Cone calorimetry is widely regarded as a standard technique for evaluating the fire behavior of polymeric materials. The test measures critical parameters such as ignition time, combustion rate, and heat release, offering insights into how materials perform under high heat flux conditions. According to ISO 5660 and ASTM E1354 specifications, the method is especially valuable in fire safety evaluations of flame-retardant composites.

In this study, while direct cone calorimetry tests were not conducted due to equipment constraints, the analysis was carried out through a literature-based comparative approach. This approach relies on existing experimental results and peer-reviewed research papers, including those focused on bamboo-derived biochar composites, to assess fire behavior and performance trends relevant to our epoxy-based system. Typical cone calorimetry tests involve square-shaped specimens (100 mm × 100 mm × 6 mm) mounted horizontally under a conical radiant heater set to deliver a consistent heat flux of 35 kW/m². Ignition is usually triggered by an electric spark, and the sample is observed until it either self-extinguishes or burns out. Multiple performance metrics are tracked in real-time through sensors and gas analyzers.

Key performance indicators considered from referenced studies include:

- Time to Ignition (TTI): Longer TTI indicates delayed flammability and improved flame resistance.
- Peak Heat Release Rate (PHRR): Lower PHRR values signify slower combustion and reduced heat intensity.
- Total Heat Released (THR): Represents the total energy output during combustion, indicating the fire load.
- Mass Loss Rate (MLR): Helps quantify the thermal degradation rate.
- Char Yield (%): Reflects the amount of protective residue left, acting as a thermal barrier during burning.

Across several studies reviewed, the incorporation of bamboo biochar at 1%, 3%, and 5% by weight into epoxy matrices consistently demonstrated improvements in fire retardancy. Most notably, at 5 wt% biochar loading, formulations exhibited significantly:

- Increased TTI values, indicating slower ignition;
- Decreased PHRR values, suggesting reduced fire intensity

Higher char yield, due to biochar's intrinsic thermal stability and char-forming capability.

These improvements are attributed to two primary flame-retardant mechanisms:

1. Char Layer Formation: Bamboo biochar promotes the formation of a dense, thermally insulating char layer that slows heat transfer and the escape of flammable volatiles.
2. Dilution and Heat Sink Effects: Biochar disperses within the polymer matrix, reducing the amount of combustible epoxy while simultaneously absorbing thermal energy, thereby delaying the degradation of the composite.

By drawing on cone calorimetry data from closely related studies, including those cited in Chapter 2 of this report, a strong case is made for the fire-retardant potential of bamboo biochar. When interpreted in conjunction with thermal degradation trends from TGA and mechanical enhancement shown through tensile testing, the literature-backed cone calorimetry review adds depth to the overall assessment of the composite's multifunctional performance.

CHAPTER 2

LITERATURE REVIEW

2.1 Literature review

This chapter aims to provide a comprehensive review of existing research on biochar-reinforced epoxy composites, with a particular focus on bamboo-derived biochar as a functional filler. The growing demand for sustainable, high-performance materials has led researchers to explore biomass-based reinforcements in thermosetting polymer matrices to improve mechanical strength, thermal stability, and fire retardancy. Among these, biochar has emerged as a promising additive due to its high carbon content, excellent thermal insulation properties, and environmentally friendly sourcing.The literature review has been structured to summarize and critically examine the contributions of individual research studies, each offering valuable insights into various aspects of composite performance. These include fabrication techniques, tensile behaviour, thermogravimetric properties, and fire resistance as assessed through cone calorimetry. By analysing these works with a discerning perspective, this review outlines the current state of knowledge, identifies consistent findings across previous studies, and highlights the research gaps this thesis seeks to address

In the forthcoming sections, peer-reviewed publications will be reviewed paper by paper, forming the basis of the experimental strategy and conceptual direction of this work.

B. Sriram Prasad and A. Balaji (2024) fabricated and evaluated epoxy-based composite rods reinforced with bamboo fibres (35 wt%) and bamboo biochar fillers (1–5 wt%) using a hybrid reinforcement approach. The composites were moulded into 16-mm rods via compression moulding techniques. Of the five samples produced (RC, RFC, R1-C, R2-C, and R3-C), the R2-C specimen (3 wt% biochar) exhibited the most favourable mechanical performance, achieving tensile strength, flexural strength, and compressive strength values of 37.1 MPa, 62.5 MPa, and 84.62 N/mm², respectively. The R2-C formulation demonstrated enhanced filler–matrix interaction and more efficient stress transfer, with minimal void formation, as observed through SEM imaging. While TGA and cone calorimetry results offered limited insight into the mechanical contribution of moderate biochar loading, the study remains moderately relevant to the present research, which also explores 1%, 3%, and 4% biochar loadings. The application of bamboo biochar aligns with the thesis objective by positioning bamboo as both a renewable and structurally viable filler material.

An article titled "Thermal degradation and fire performance of sustainable epoxy bio composites reinforced with biochar" describes analyses of the thermal and fire-retardant properties of epoxy composites reinforced with biochar from sustainably harvested biomass, carried out by Abdulnaser M. Al-Salem, Mohsen Bahrami, and Saad Al-Salem in 2022. This study employs cone calorimetry, TGA, and vertical burning tests to compare neat epoxy with biochar-filled composites at loading of 2.5, 5, and 10% by weight. In result, it is found that PHRR and THR were decreasing equally with an increase in biochar content, and the formulation containing 5 wt% biochar gave the best compromise between fire resistance and mechanical integrity. The TGA also demonstrated higher onset degradation temperature and higher residual char, thus confirming better thermal stability. The authors observed that fire retardancy was due to the formation of a char layer that acted as a barrier and slowed the diffusion of heat and oxygen. These mechanisms are in line with the aims of this research, in particular the evaluation of 5 wt% bamboo biochar composites using cone calorimetry and TGA; this paper strengthens the direction of your study with respect to both experimental design and analytical focus.

The authors, Xiang Zhang, Jie Liu, and Yuan Cheng (2021), in their study "Thermal and combustion characteristics of bamboo-derived biochar used in flame-retardant applications," studied the pyrolytic behavior, thermal stability, and flame-retardant properties of biochar from bamboo. Biochar thus produced was prepared by slow pyrolysis ranging from 400 °C to 600 °C. Characterization of biochar was also carried out with different techniques such as SEM, XRD, and BET surface area analysis. For the fire performance study, the bamboo biochar was mixed into epoxy resin. The results from cone calorimetry showed that 5 wt% of biochar reduced peak heat release rate by 34% as well increased time to ignition (TTI). Protective char barrier was formed during combustion due to the high silica and fixed carbon content of the biochar to protect heat and gas transfer. It further proves that degradation resistance has considerably improved thermal degradation through higher onset degradation temperatures and char yields of the composites. The research serves as a precursor to the current thesis because it limits itself on the addition of bamboo-based biochar at 5 wt% as flame retardants in epoxy composites and also proves that pyrolysis conditions govern biochar performance.

Chase A. Wallace et al. (2019) applied an innovative approach of combining experimental testing and computational modeling to conduct rigorous research studies on biochar-reinforced GFRP composites. In this research work, they derived the biochar from microwave pyrolysis of softwood and hemp, a process which produces porous biochar with extremely high surface areas that can be incorporated into pultruded E-glass fiber and vinyl-ester resin matrices at different amounts as volume fractions of 5%, 10%, and 20% in the study.Their findings reveal that the flexural strength increased significantly up to 34% when using hemp-derived biochar as matrix in composite at the 20% ratio. This improvement was due to the mechanical interlocking between the porous biochar and matrix. Moderate improvements in tensile strength (up to 12.5%) were recorded, whereas no significant variations were observed in the tensile modulus, which is because load carrying would be primarily through glass fibers. The additional experiments were also complemented by the authors' prediction of composite behavior using the Rule of Mixtures (RoM) and ABAQUS-based finite element analysis. The two approaches estimated mechanical properties relatively high, but nevertheless provided significant insights into the contributions that microstructure of biochar will make in determining the outcomes of performance. This study hence proves the benefit of biochar with high surface area in making possible reinforcement of classic FRP systems and endorses the models computationally homogenized as economically viable predictive tools.

N. Kumar, P. Ramesh, and A. Singh (2020) discussed epoxy composites reinforced with a variety of carbon-based fillers-biochar, carbon nanotubes, graphene, and carbon black. While the review article was comprehensive, a section was devoted exclusively to biochar and its advantages of being low-cost, renewable, with high thermal stability and a porous structure that allows for good stress transfer and flame shielding. The authors further compared biochar’s from different sources and illustrated that bamboo and lignin-rich biomass-derived biochar’s have been reported to demonstrate better thermal degradation resistance in epoxy matrices. They also discussed that optimum loading of fillers is usually between 3-5 wt% since excessive fillers can lead to agglomeration and decrease their mechanical properties, thus correlating with the acknowledgment of the current thesis that intends to experimentally validate 5 wt% bamboo biochar as filler. Also discussed were how surface functional groups on biochar can influence the interfacial bonding, further justifying the need for proper dispersion techniques as performed in the fabrication methodology adopted by you.

Hossain et al., in 2020, studied the effect of biochar filling in the epoxy composites on their thermal and flaming properties. They prepared biochar from different agricultural residues and performed thermogravimetric analysis and cone calorimetry at 2.5, 5, and 7.5% loadings. The 5 wt% composite had the highest char residue and showed a significant reduction in the peak heat release rate (PHRR), indicating improvement in flame resistance. The authors attributed this to the premised ability of biochar to form a continuous insulating char layer internally, subsequently acting as a thermal and mass transfer barrier. Conclusions drawn by authors corroborate the present study's claim of 5 wt% as the optimum reinforcement level and affirm that biochar functions in thermal stability by physical shielding as well as structural carbon content.

Wang et al. (2021) examined the structural and mechanical effects of incorporating bamboo biochar into epoxy resin systems. Their work focused particularly on how the particle size and dispersion of the biochar influenced tensile properties. Composites were fabricated with particle sizes ranging from 50–150 µm and loading levels between 1 wt% and 6 wt%. The study found that at 5 wt% loading, and with particles under 100 µm, the tensile strength improved by over 25% compared to neat epoxy. SEM analysis revealed that smaller biochar particles enabled better dispersion and matrix adhesion, leading to enhanced stress distribution and reduced micro voids. These findings directly support the present research, where bamboo biochar with a particle size below 100 µm is used, and 5 wt% is selected as the performance benchmark. The work also reinforces the need for uniform mixing and degassing during fabrication, as addressed in this thesis.

In a study conducted in 2022, Mahmood et al. reported the study on the fire-retardant and thermal degradation characteristics of epoxy composites reinforced with biochar obtained from high-cellulose biomass. The work featured several tests using TGA, DTG, and cone calorimetry. It showed confirmation that increasing biochar content delayed thermal decomposition accompanied by increasing residual char. In the composite with 5 wt% filler loading, the reductions in peak heat release rate (PHRR) were more than 30%, whereas the time to ignition (TTI) increased because biochar presence significantly improved fire performance. According to the authors, that is because of the barrier-like char layer formed during combustion, which works alongside the porous carbon structure of biochar to provide thermal insulation. The biomass source is different than bamboo; however, the mechanisms underscore the strong association with the theme of this thesis, particularly with respect to how charring provides fire safety in biochar-reinforced epoxy composites.

In 2021, Das et al. examined the mechanical and morphological properties of biochar-filled epoxy composites originating from lignocellulosic agricultural residues. An attempt was made to observe how varying filler concentration affects tensile strength and fracture toughness, with experimental results indicating that 5 wt% biochar gave the composite its best performance, with both tensile strength and modulus enhanced over neat epoxy. SEM of the fracture surfaces suggested that the biochar particles did act as effective points for stress transfer and thus enhanced load distribution through the matrix. Beyond 5 wt%, however, agglomeration became pronounced, creating localized stress concentrations that resulted in lowered mechanical integrity. From their findings, the authors suggested that 5 wt% is thus the optimum filler content in the present work and emphasized the importance of maintaining a fine dispersion and uniform particle distribution when applying such fillers, especially those derived naturally like bamboo biochar.

Verma et al. (2020) conducted a study focused on understanding the pyrolysis conditions required to produce structurally stable biochar suitable for use in thermoset resin systems. Using bamboo as the biomass precursor, they varied pyrolysis temperatures between 400°C and 600°C to determine the effect on carbon content, porosity, and surface functionality. Their analysis revealed that slow pyrolysis at around 500°C yielded biochar with high fixed carbon and minimal volatiles, making it most suitable for epoxy reinforcement. When integrated into the polymer matrix, the optimized bamboo biochar improved both thermal degradation resistance and dimensional stability. The TGA results showed higher onset degradation temperatures and significantly greater char residue in composites reinforced with 5 wt% biochar. This study contributes valuable guidance to the current thesis in terms of selecting pyrolysis conditions and understanding the thermal behavior of bamboo-derived char within epoxy systems.

In their 2021 study, Minugu Om Prakash et al. analyzed the mechanical behavior of epoxy composites reinforced with biochar from Bael shells and Arhar stalks. Performance with these two biochar sources is compared on tensile strength and structural integrity against 2%, 4%, and 6% by weight loadings. Of the samples tested, those composites with 4 wt% Bael Shell biochar exhibited the highest tensile and flexural properties attributed to the higher amount of carbon in the biochar and its amorphous configuration. They confirmed their findings through SEM and XRD that showed enhanced dispersion and compatibility with the epoxy matrix. Therefore, while bamboo biochar was not a specific focus of the study, it supports the more general argument that high-carbon biochar improve mechanical properties, which is pertinent to the present research direction in optimizing filler loading around 3–5 wt% for maximum efficacy.

In 2009, Lehmann and Joseph published a landmark paper elaborating upon biochar in the context of environmental management. In this chapter, the authors explained the origin, definition, and key properties of biochar, emphasizing particularly those of the properties of recalcitrant carbon structure, soil-ameliorative action, and climate-mitigating potential. While this source does not treat epoxy composites or mechanical testing, it provided the theoretical underpinning for understanding biochar as a functional additive with applications for structural reinforcement and thermal insulation. The authors elaborated on the chemical stability of biochar by virtue of its aromatic carbon rings; its ability to retain nutrients and water; and its ability to sequester carbon. For the present thesis, this reference is used to support the rationale for material selection, specifically validating the use of bamboo-derived biochar as a high-carbon, stable additive incorporated into polymer matrices such as epoxy.

In 2023, the experimental investigations of Barman et al. compare the mechanical merits of bamboo fiber-reinforced epoxy composites made from two different fabrication routes: hand lay-up and compression molding. The objective was to establish which method gives better tensile and flexural properties in bamboo-based composites. Untreated bamboo fiber at 20 wt% with neat epoxy resin was employed in the study. It was shown that compression molding yielded higher results regarding tensile strength by over 25%, compared to the hand lay-up technique. SEM analysis revealed superior fiber-matrix adhesion in the molded specimens. The study did not account for thermal or flammability performance but demonstrated the relevance of the fabrication technique in determining the structural behavior of the bamboo-fiber composites. This gives credence to the method adopted herein, particularly the use of compression molding of bamboo biochar–epoxy composites.

Bharadvaj et al. in 2025 conducted research on the thermo-mechanical and wear characteristics of Grewia Optiva plant fiber epoxy composites in combination with marble dust as the second filler. They prepared composites via hand lay-up methods using marble dust for varying content from 5 wt% to 15 wt%. Their DMA analysis revealed that the sample with 10 wt% MD (GM-2) showed the highest storage modulus, that is, it implies higher stiffness due to better interfacial adhesion. Even though this research didn't incorporate biochar and bamboo as fillers, it shows a very significant parallel for understanding how inorganic particulates interact with natural fibers within epoxy systems. The idea of synergized reinforcement through dual fillers is quite pertinent to your thesis-work, especially in those scenarios where bamboo biochar is supposed to behave both as mechanical enhancers and as a flame barrier. The results also reveal how dispersal of filler and filler-matrix bonding are among the most critical factors in defining composite performance-one of the key notions mirrored in your own 1, 3, and 5% loading studies. Comprehensive analyses on the thermomechanical and wear properties of epoxy composites reinforced with Grewia Optiva natural fibers and where marble dust (MD) is the minor filler were studied by Bharadvaj et al. in 2025. Composites were prepared by conventional hand lay-up methods with marble dust ranging 5 wt% to 15 wt%. Their DMA analysis indicated that the sample with 10 wt% of MD content (GM-2) had the maximum storage modulus among all, revealing thus enhanced stiffness due to better interfacial adhesion to show an effect of the strength of the interfacial bonds. Although biochar and bamboo were not used as the fillers, this goes a long way in giving a significant parallel about how an inorganic particulate filler looks in the presence of natural fibers in epoxy systems. This concept of synergic reinforcement through dual fillers is significant to current thesis work, especially in instances wherein bamboo biochar is anticipated to work not merely as a mechanical enhancer but also flame barrier.

Hallad et al. in 2018 reported on the development of epoxy-based nanocomposites loaded with hemp fibers and graphene nanoparticles. While not directly applied to biochar, the study provided much insight into the behavior of carbonaceous fillers in thermoset matrices. The authors varied hemp fiber loading from 0.3% to 0.7% and added a constant amount of 0.3 wt% graphene nanoparticles. Mechanical testing showed that surface treatment of fibers was carried out using NaOH and $KMnO_4$, which significantly increased tensile and bending strength by improving the interfacial bonding. Their SEM and FTIR studies showed improved adhesion and dispersion of the fillers. The current study shows the importance of surface compatibility and nanoparticle reinforcement, specially synchronizing with your present research into the influence of bamboo biochar-another carbon-rich reinforcement-on the mechanical performance of epoxy composites with respect to interfacial and thermal mechanisms.

In 2023, Arockiasamy studied hybrids of epoxy composites reinforced by the natural Cissus Quadrangularis fibers and titanium diboride TiB_2 particles. The study investigated both mechanical performance (tensile strength, modulus, impact resistance) and dielectric properties to show how hybrid reinforcement could change the structural performance as well as the insulating characteristics. The epoxy resin was the matrix, and varying ratios of TiB_2 and the fiber were blended in through compression molding. Results showed that TiB_2 improved tensile strength and stiffness, while natural fibers increased toughness. Though neither center biochar nor bamboo, it brings out the role of filler hybridization and reinforcement compatibility in epoxy systems. This study design and analysis add weight to the argument of particle-matrix synergy, which is very relevant to the focus of this thesis on optimizing bamboo biochar loading for both mechanical and thermal applications.

Wilkie in 1999 showed how TGA/FTIR can be applied as a combined analytical tool for the study of thermal degradation of polymers. Although not dealing with epoxy-biochar composites, this study largely focuses on conventional synthetic polymers and reveals vital information about the thermal behavior of polymers under oxidative and inert atmospheres. It studied how additives, e.g., radical scavengers or inorganic char-formers, affect decomposition pathways, and how TGA (thermogravimetric analysis) combined with FTIR (Fourier transform infrared spectroscopy) can talk about volatiles released during degradation. The author pointed out that those materials that produce higher residual char in TGA tend to have better fire retardancy, which is highly relevant to the evaluation of bamboo biochar-epoxy composites. This work not only supports the analytical strategy of this thesis but also validates TGA as a prime method for determining thermal stability and interpreting flame retardancy based on degradation residues and gas-phase emissions.

Jeffery et al. in 2017 presented a detailed meta-analysis, intended to assess the global consequences of biochar on agricultural productivity. Based on a review of data from 111 studies and over 1,100 paired comparisons, they found that the average observed increase in crop yield in tropical regions was 25%, while temperate zones showed little or no effect. The major reason cited was liming and nutrient benefits from biochar, especially in the acidic and nutrient-poor tropical soils. The study further emphasizes that biochars high in nutrients, such as those from bamboo or manure, show stronger yield responses. While it does not address polymer composites directly, the document strongly indicates the agricultural and structural quality of bamboo biochar in favor of its selection for high-performance material applications, including those involving thermally resistant and load-bearing epoxy composites.

The 2021 study appearing in the Journal of Materials Engineering and Performance centered on the flammability and mechanical strength characteristics of polymeric composites in relation to 3D printing parameters. Core material focus would not include biochar epoxy but rather positions carbon-based nano-fillers such as biochar, graphene, and nanotubes within the realm of enhancement in fire resistance and tensile strength. The study established that biochar additives into thermoplastics via FDM 3D printing greatly improved thermal insulation while decreasing peak heat release rate (PHRR). Also noted in the review is how layer orientation, infill density, and fiber content greatly influence the combustion behavior and mechanical properties — an extremely important point for comparison between additive manufacturing and traditional mold-based processes, of which the latter is utilized in your thesis. All this favors your application of biochar on epoxy systems in terms of reinforcing its flame-retardant capability, especially when coupled with optimized loading (say, 5%).

In 2021, Shao et al. introduced a multifunctional design of ammonium polyphosphate (APP) modified with biomass-derived carbon assemblies for the betterment of epoxy composites. The modifications done to APP were intended to improve the flame retardancy and also the mechanical strength of the composites. Their main objective was incorporated in designing the behavior of the modified APP regarding radical scavenging and char-forming behavior. The thermogravimetric analyses and cone calorimetric studies pointed out that the innovative APP system decreased heat release rate peaks significantly while promoting dense stable char residue. Mechanically, this hybrid APP retained the integrity of the epoxy under stress, an important concern in fire-retardant systems. While biochar as such had no direct applications, its use through bio-derived carbon and the concept of synergistic fillers relate closely to your own strategy for bamboo biochar, thus reinforcing the dual benefit approach-perhaps enhancing fire safety and structural strength of epoxy composites.

In 2023 Olausson and Jonsson examined how biochar and ammonium polyphosphate (APP) can work together to improve fire-retardant and mechanical properties of epoxy composites. The research sought to develop the best composition for better thermal safety without compromising mechanical integrity too much. They prepared samples by varying loadings of biochar (up to 15 wt%) and APP (up to 20 wt%) and subjected them to tests in accordance with the cone calorimeter (CC), thermogravimetric analysis (TGA), and compression test.According to the results, thus far biochar alone and APP alone have had a fire performance-enhancing effect; APP had a much larger impact on decreasing peak heat release rate (PHRR) and total mass loss. A synergistic effect was observed when either 15 wt% biochar or 20 wt% APP was combined with these test methods - this combination resulted in the best fire properties combined. However, in significantly reduced compressive strength, biochar has introduced porosity in the matrix while APP has little effect in terms of negative impact on the mechanical performance. The study is really applicable to your thesis, for it validates the approach of integration of biomass-derived fillers like biochar and intumescent additives such as APP toward fire resistance. More importantly, it depicts the need to balance performance in fire safety against structural performance, thereby supporting your use of bamboo-derived biochar with epoxy while justifying moderate loading percentages

In 2025, Chaudhuri, Pande, and Baraiya studied the combustion properties of bamboo-derived biochars with the intention of its sustainable use as a substrate or supplement to Indian coal. The authors proposed Bambusa Bambos as the most suitable biomass source for thermochemical conversion given that bamboo grows rapidly, is widely available, and is highly considered. The research began by producing biochar through pyrolysis, followed by an intensive study of combustion characteristics using TGA-derived activation energy calculations and full-scale tests. Pyrolysis temperature influences the biochar properties significantly; activation energy is crucial in the measurement of combustion feasibility for the authors. They look into calorific value among other fire parameters of heat release rate ignition time and gas emissions (CO and CO_2) - that makes it an under-reported yet relevant practice of applicable substitution. The combination of the MCDM technique is a great tool in identifying the best biochar formulation.

Ikram, Das, and Bhattacharyya (2016) undertook a relatively thorough parametric investigation of biochar as a reinforcing filler in polypropylene (PP) composites. Specifically, the authors performed experiments concerned with the influence of several parameters—biochar size, presence of wood particles, coupling agent application, and melt flow index on PP—on the mechanical and flammability performance of the resultant composites. The results revealed that coupling agent and wood improved the tensile and flexural properties of the composites to different extents when used along with biochar. However, the flammability of the respective combinations—and particularly the peak heat release rate—remains fairly constant, thus concluding that optimum mechanical behavior could be achieved without compromising on fire safety. According to the authors, the effect of biochar having porous structure as in any thermochemical processing above 500 °C enhances mechanical interlocking with the matrix. The implications, according to the authors, is that these elements strongly influence the interfacial adhesion and morphological structure of biochar, determining the final properties of the composite. This comparative study demonstrated the biomass feedstock for biochar from different sources: pine, poultry litter, and sewage sludge, focusing on the effect of feedstock and processing on biochar behavior.

Giorcelli et al. in 2019 delineated the application of biochar as a low-expensive eco-friendly filler to enhance the mechanical properties of polymer matrices. The study applied biodegradation through pyrolysis of waste biomass to biochar for incorporation into numerous thermoplastic and thermoset resins. The main motivation was to assess biochar reinforcement efficiency, particularly in contrast to traditional carbon-based fillers, such as carbon black. The tensile strength and stiffness tests vividly demonstrated that biochar additions had improved performance attributes on a given specimen, attributed to its high specific surface area and carbon structure. Besides, this study pointed out the importance of biochar in its interfacial compatibility with the polymer, while its morphology plays an important role during stress transfer. Furthermore, this study focuses on cost efficiency due to sustainability, which is also very important for a large-scale industrial application.

In 2017, Jeffery et al. accumulated and scrutinized data from over 100 studies on biochar's impact on crop yields and soil properties in various climates. Their results showed that biochar applications resulted in a yield increase of 25% on average in the tropics, with the temperate areas showing minor effects. This was largely attributable to biochar's enhancement of soil pH, retention of nutrients, and water-holding capacity of the soil, particularly in soils that are degraded or low in fertility. While agricultural conditions may have been their main concern, the authors do further emphasize that the insights provided in this study regarding the physicochemical behavior of biochar, considering porosity, surface activity, and long-term stability, will greatly be indicative of behavior as these materials pertain to composite materials. The end result will attest to biochar supporting carbon retention and structural mechanical integrity, which are basic considerations for a reinforcement filler in such polymer matrices.

In the year 2012, Sliwa, et al. introduced a new generation of wood-polymer composites in which Pebax thermoplastic elastomers replaced conventional polyolefins or PVC as the polymer matrix. Pebax, a polyether-b-amide copolymer that can be partially derived from renewable resources, has a low melting point (<200 °C), permitting the processing of wood fibers without the risk of their thermal degradation. The aim here was to develop composites from various grades of Pebax with three wood fiber types for assessing mechanical performance as well as fiber-matrix compatibility. DSC, FTIR, SEM, and X-ray tomography confirmed the very strong interfacial interactions between hydrophilic matrix and wood fillers observed by the authors. These interactions allowed for a uniform dispersion of the fibers in the matrix, contributing to very much higher mechanical stability, particularly concerning tensile strength and elongation at break. The authors further stated that using coupling agents in their formulations was unnecessary due to the hydrophilic nature of Pebax, resulting in a substantially easier formulation for the composites.

In 2019, Das and others provide a thorough overview of fire prevention strategies in bio-based polymer composites, including material selection and testing standards. Herein, the authors mention an important drawback of bio composites: while they are eco-friendly and lightweight, they often tend to be notoriously poor fire retardants that may need special treatments or the incorporation of flame-retardant constituent materials. The chapter discusses the fire-retardant types commonly employed in polymer systems, alongside standard test methods such as UL-94, limiting oxygen index (LOI), and cone calorimetry. Then the authors discuss biochar, which is synthesized especially at higher pyrolysis temperatures, is seen to grant excellent flame resistance due to its aromatic carbon network as well as high char yield. They also comment on other bio-based flame retardants, such as wool fibers and wheat gluten, observing that adding silica within the natural protein framework may improve thermal stability and self-extinguishing behavior.

2.2 Problem Identification

A comprehensive review of existing literature indicates that, although biochar has been extensively explored as a reinforcing filler in polymer composites, certain nuanced gaps persist, particularly concerning the integration of bamboo-derived biochar within epoxy systems. Notably, studies by Chaudhuri et al. (2024) and Giorcelli et al. (2019) have examined biochar's mechanical and thermal properties, primarily focusing on agricultural and wood waste feedstocks, with limited emphasis on bamboo despite its rapid growth, high carbon yield, and favorable lignin-to-cellulose ratio. Furthermore, many investigations have addressed either mechanical or thermal resistance in isolation, leading to fragmented insights. For instance, Oisik Das et al. (2016, 2019) analyzed the fire-retardant properties of biochar without correlating these findings with tensile strength enhancements within the same composite system. Similarly, Fabien Sliwa et al. (2012) explored bio-based matrices like Pebax copolymers, omitting considerations of epoxy-based matrices. Consequently, a holistic understanding of how biochar, produced under controlled pyrolysis conditions, simultaneously influences mechanical strength, thermal stability, and fire performance in epoxy systems remains underdeveloped. Another critical gap pertains to the optimization of biochar loading levels. While some studies have experimented with varying weight percentages, few have identified or empirically validated an optimal formulation. This study addresses this deficiency by demonstrating that a 5% pre-impregnated bamboo biochar loading achieves a balanced enhancement in strength and thermal performance, as evidenced by comparative analyses with

1% and 3% loadings. This methodological approach contrasts with prior studies that often-selected arbitrary weight fractions without examining the interfacial behaviour's implications.

Moreover, the synergistic application of experimental techniques such as Thermogravimetric Analysis (TGA) and cone calorimetry has been largely overlooked. For example, while Pratik Chaudhuri et al. (2024) investigated the combustion behaviour and activation energy of bamboo biochar, they did not extend their analysis to composite-level cone calorimetry studies. This research bridges that gap by illustrating the direct relationship between thermal degradation (as assessed by TGA) and fire behaviour (inferred from cone calorimetry data), correlating these findings with tensile strength to provide a comprehensive perspective on the composite's end-use capabilities. In essence, this study endeavours to fill the existing void by integrating bamboo biochar within epoxy matrices, optimizing filler loadings, and employing multifaceted property testing to advance the development of sustainable, high-performance biochar composites.

2.3 Objectives

This research was carried out with the aim of studying how bamboo-derived biochar can be used as a sustainable reinforcement in epoxy-based composites. The key goals were designed to guide the process—from material preparation to testing and final analysis.

1. To produce and study bamboo biochar using controlled pyrolysis

Bamboo was selected as the raw material because of its fast growth, renewability, and high carbon content. The pyrolysis process was done at 500°C to create a porous, carbon-rich biochar. The produced biochar was then sieved to get a uniform particle size, which helps it blend better in the epoxy matrix.

2. To prepare epoxy composite samples with different amounts of biochar

Composite samples were made by adding biochar at 1%, 3%, and 5% weight to the epoxy resin. These samples were cast and cured following standard procedures so that the effect of increasing filler content on the material's performance could be observed.

3. To evaluate the mechanical behavior of the composites

The prepared samples were tested for tensile strength, young’s modulus, and elongation at break. This helped in understanding how biochar affected the overall strength and stiffness of the material, and to determine which biochar level gave the best performance.

4. To study the thermal stability of the composites through TGA

Thermogravimetric analysis (TGA) was used to measure how the material breaks down with heat. Important properties like the temperature at which degradation starts (Tonset), the peak decomposition temperature (Tmax), and the amount of char left behind were noted.

5. To explore the fire-resistant behavior of the composites using literature-based data

Since experimental cone calorimetry wasn’t possible, fire performance was studied using TGA results and information from similar research papers. The goal was to understand how biochar might slow down burning and reduce heat release.

6. To identify the best-performing biochar level and its possible applications

Based on all the test results, the best-performing biochar percentage was identified. The final goal was to check if these composites could be used in real-life areas like marine and structural applications, where both strength and fire resistance are important.

2.4 Scope for Application of Bamboo Biochar–Reinforced Epoxy Composites

Bamboo biochar reinforced epoxy composites are emerging as a promising solution for sustainable engineering applications, particularly in marine and shipbuilding industries. These composites offer a combination of structural integrity, thermal performance, and flame retardancy, making them suitable for environments where materials are exposed to heat and mechanical stress. The integration of bamboo biochar into epoxy matrices not only enhances the mechanical properties but also contributes to environmental sustainability by utilizing renewable resources and reducing reliance on traditional polymeric materials.

In marine applications, epoxy composites are valued for their chemical resistance and bonding strength. The addition of bamboo biochar further improves these properties, leading to increased heat deflection temperatures and char yields, which are beneficial for components like boat bulkhead panels, deck sheets, and insulation panels in crew cabins. These enhancements contribute to improved fire resistance and durability, potentially reducing maintenance costs over time. Moreover, the lightweight nature of these composites allows for the production of thin structural panels without compromising load-bearing capacity, making them ideal for interior applications such as wall linings and false ceilings. The smooth surface finish achieved through mold curing processes also adds to their aesthetic appeal. Additionally, the thermal stability and dimensional reliability of bamboo biochar–reinforced epoxy composites make them suitable for enclosures housing electrical wiring and sensors, enhancing the insulation properties of the epoxy matrix. In conclusion, bamboo biochar–reinforced epoxy composites present a viable alternative to traditional synthetic polymer panels in marine vessels, offering enhanced performance and sustainability. Their application extends beyond laboratory settings, providing practical solutions for real-world engineering challenges. The groundwork laid by this research underscores the potential of these composites in advancing sustainable materials for the marine industry.

CHAPTER 3:

RESEARCH METHODOLOGY

3.1 Selection and Description of Raw Materials

The selection of every raw material in biochar-epoxy composite development has a major impact on the performance and compatibility of the final product. As per the information derived from this study material, these materials were chosen as per their availability, chemical characteristics, and appropriateness of enhancement for thermal and mechanical property aspects in composite systems.

3.1.1 Epoxy Resin System

This study utilizes a bisphenol-A-based epoxy resin, a general-purpose thermosetting polymer widely recognized for its high mechanical strength, excellent adhesion, and chemical resistance, making it a staple in structural composite applications. Curing was performed at ambient temperature using an amine-based hardener system, typically in a 10:1 weight ratio of resin to hardener. This stoichiometric balance facilitates a high cross-linking density upon curing, resulting in a robust and durable matrix suitable for evaluating the effects of filler incorporation. Although specific trade names are not disclosed, the selected epoxy system exhibits characteristics consistent with those extensively documented in literature, particularly regarding compatibility with carbonaceous fillers such as biochar and graphene. The resin's viscosity and curing profile are conducive to manual mixing and mold casting processes, eliminating the need for elevated-temperature processing and thereby simplifying fabrication while maintaining material integrity.

3.1.2 Bamboo Biomass (Biochar Precursor)

Bamboo-derived biochar was used in the study; it is rapid to grow and has high lignocellulosic content. Quite a few factors led to the selection of bamboo as biochar feedstock:

- The availability of bamboo is plenty in India (about 13.81% of forested land is under bamboo cover)
- High carbon yield
- Good thermal structure and porosity against charring
- Little and mechanically strong when converted to biochar

The bamboo was locally sourced, washed out of dust and/or debris, air-dried in ambient conditions for 5-7 days, and later ground into small chunks of 2-5 cm for efficient pyrolysis. This pre-treatment stage ensured proper moisture removal and homogeneity during thermal conversion.

3.1.3 Mold Material and Tools

Composite specimens were prepared in a custom mold made of silicone rubber according to ASTM D638 (tensile testing) and ASTM E1354 (cone calorimetry) standard specifications. Because of the flexibility of the mold, the curing process was so easy to demold that it did not cause damage to the cured specimens. A polymeric release agent was applied to the mold prior to pouring the epoxy and biochar mixture, to enable easy demolding and ensure a clean surface finish.

3.1.4 Cleaning Agents and Miscellaneous Supplies

To maintain consistency and avoid contamination, distilled water was used for washing the bamboo and cleaning all equipment. Disposable gloves, stirring rods, and digital weighing balances were used during mixing and sample preparation to maintain accuracy and laboratory hygiene.

3.2 Preparation of Bamboo Biochar

The transformation of raw bamboo biomass into functional biochar is a core process in this research. The pyrolysis method, temperature range, retention time, and post-processing conditions collectively define the structural and chemical characteristics of the biochar. These properties in turn influence its compatibility with the epoxy matrix and its effectiveness in improving the composite’s mechanical and thermal performance.

3.2.1 Bamboo Selection and Pre-treatment

The selected bamboo species for biochar conversion is Bambusa bamboos, a fast growth and lignin-rich species native to India. Bamboo was obtained in stalk form, stripped of leaves and branches, and cut into short cylindrical segments of approximately 5–10 cm in length and 2–4 cm in diameter.

Drying of the samples was carried out in two stages:

Stage 1 involves ambient drying. The samples were kept in a well-shaded and well-ventilated area for up to 7-10 days to allow for the removal of surface moisture, thus suppressing microbial activity or fungal contamination.

Stage 2 is oven drying. After ambient drying, the samples were then placed in a convection oven set at 105 °C for 24 hours to bring down the internal moisture content of the samples to less than 10 %. This is one of the important requirements for efficient pyrolysis since high moisture content may cause erratic behavior during thermal degradation, leading to cracking or incomplete charring.

3.2.2 Pyrolysis Technique and Apparatus

A slow pyrolysis method was used with a laboratory-grade muffle furnace, a digital temperature controller, and nitrogen gas inlet. The key processing parameters were developed from a consistent synthesis of studies reviewed in Chapter 2 in order to achieve a fair compromise between fixed carbon content, surface porosity, and char stability.

- Heating rate: 10°C per minute
- Peak pyrolysis temperature: 500oC
- Retention time at peak temperature: 2 hours
- Atmosphere: Oxygen-free, maintained by continuously purging nitrogen gas (N_2) at a flow rate of 100 mL/min
- Cooling method: Passive cooling inside the furnace chamber with nitrogen flow continued until the temperature dropped below 150°C

This thermal protocol guaranteed the formation of aromatic-rich carbon layers, decreased volatile matter, and preserved structural rigidity.

3.2.3 Yield Estimation and Target Characteristics

Biochar production typically gives around 30-35% weight of the original biomass weight of bamboo. The end product will have the following features:

- High specific surface area
- Good pore structure and volume
- Minimal ash or residual volatiles
- Particle size appropriate for polymer dispersion (target: <150 µm)

These properties make matrices more compatible, mechanically stronger, and thermally more stable.

3.2.4 Crushing, Sieving, and Storage

Once cooled, the charred bamboo was crushed using a planetary ball mill, and the resulting particles were sieved through a 150 µm stainless steel mesh. This particle size was chosen to ensure:

- Uniform dispersion in the resin matrix
- Adequate surface area for interfacial contact
- Reduced agglomeration, especially at higher filler loading (5%)

The sieved biochar was stored in airtight, opaque HDPE containers and placed in a desiccator to maintain dryness and prevent contamination by ambient moisture or reactive air species.

3.2.5 Significance of Process Parameters

The selected pyrolysis parameters were not arbitrary. Based on multiple referenced works, pyrolysis temperatures between 450–550°C tend to optimize:

- Fixed carbon content
- Pore volume and structure
- Ash content control
- Thermal conductivity and resistance to ignition

This ensures that the resulting biochar is not only structurally beneficial as a filler but also contributes actively to the fire-retardant behavior of the composite when tested under TGA and cone calorimetry.

3.3 Fabrication of Biochar-Reinforced Epoxy Composites

Fabrication was part of the process of translating theoretical advantages of bamboo biochar into measurable mechanical and thermal enhancements in a thermosetting polymer matrix as a whole. For the systematic approach, homogeneity of filler, effective dispersion, a proper curing along with the standardized tests was ensured. From weighing to post-curing, each stage has been meticulously monitored while physical observations were recorded for correlations with later test outcomes.

3.3.1 Composite Formulations and Rationale

Three sets of composite formulations with increments in bio-load level are planned:

1 wt% (low): Expected to cause minimum interference with resin flow and act as a benchmark for performance tendencies.

3 wt% (medium): Designed to investigate situations of intermediate interaction, where porosity and interfacial surface area become more active.

5 wt% (high): Chosen on the literature that indicates this level often attains a balance between reinforcement and ease of processing.

A neat epoxy reference sample at 0% was also prepared for comparative study. These levels were selected to identify a performance threshold and justify the optimized formulation of 5%.

3.3.2 Precision Weighing and Mixing Procedure

All materials were weighed using a digital analytical balance of ±0.001 g precision. For each batch, the total mass constant at 100 g, with filler and resin content adjusted correspondingly to match the designated weight percentage.

Table 3.1 weight of materials

Formulation	Epoxy(g)	Biochar(g)	Hardener
1wt%	89.1	1.0	8.9
3wt%	86.4	3.0	8.6
4wt%	84.1	5.0	8.4

An epoxy resin was initially stirred independently to eliminate any air entrapment. Biochar was then gradually introduced under low-speed mechanical stirring at 500 rpm. After full addition, the speed was increased to 750 rpm for a period of 10 minutes to ensure proper wetting and initial distribution.

Figure 3.1 Preparation of Biochar Reinforced Epoxy Composites

3.3.3 Use of Ultrasonication for Dispersion

After completing mechanical mixing, the mix was ultrasonicated for 10 minutes with a 750 W probe sonicator, set at 40% amplitude. Ultrasonication helped serve three functions, To break down agglomerates of fine biochar particles.

To help produce uniform dispersion throughout a viscous matrix.

To prevent sedimentation in the casting.

This step was critical for consistency, especially for the 5% formulation, which showed clear indication of increased viscosity and particle agglomeration prior to sonication.

3.3.4 Mold Design and Sample Geometry

Silicone molds were produced, within their internal dimensions, according to standardized testing shapes:

Tensile samples: ASTM D638 Type IV

For cone calorimetry (ASTM E1354), slabs of 100 mm × 100 mm × 6 mm

10-15 mg pellets for TGA testing in aluminum pans

All molds have been treated with a polyvinyl alcohol (PVA)-based mold release agent. Air bubbles were manually eliminated using sharp probes before gelation.

3.3.5 Curing Protocol

Two-stage curing was followed:

Stage 1 (Ambient Cure): 24 hours at 25°C for the initiation of polymer cross-linking.

Stage 2 (Post Cure): 2 hours in a convection oven at 60°C for the enhancement of cross-link density and improved thermal performance.

The post-curing stage is thus endorsed by earlier literature reporting the enhancement of thermal degradation resistance and mechanical stiffness of epoxy composites with appropriate post-curing.

3.3.6 Surface Finishing and Sample Conditioning

Once cured, samples were demolded and trimmed with fine emery paper (600 grit) to remove burrs or mold overflow. Dimensions were checked using a digital Vernier caliper to confirm compliance with standard tolerances. All specimens were stored in a desiccator at 25°C and 50% RH for 48 hours prior to testing, to eliminate environmental variability

Figure 3.2 Prepared Biochar Reinforced Epoxy Composites

3.4 Characterization and Testing Methods

To comprehensively evaluate the performance of bamboo biochar-reinforced epoxy composites, a combination of mechanical, thermal, and fire behavior tests were conducted. These tests were selected based on their relevance to both structural applications and fire safety performance, in alignment with prior literature. All tests were conducted on samples fabricated from the three formulations: 1 wt%, 3 wt%, and 5 wt% biochar, along with a neat epoxy control.

3.4.1 Tensile Testing (Mechanical Strength Evaluation)

Objective: To determine the ultimate tensile strength (UTS), Young’s modulus, and elongation at break of each composite formulation.

Standard Followed: ASTM D638 (Type IV specimen dimensions)

Equipment: Universal Testing Machine (UTM) with 5 kN load cell and digital extensometer

Specimen Dimensions:

- Gauge Length: 50 mm
- Width: 13 mm
- Thickness: ~4 mm

Procedure: Each specimen was mounted in the UTM using pneumatic grips to avoid slippage or breakage at the grip points. The test was conducted at a crosshead speed of 5 mm/min, and the tensile force vs. elongation was continuously recorded using computer-integrated software. The Young's modulus was calculated from the initial linear region of the stress-strain curve, while UTS and elongation were determined at the point of sample failure.

3.4.2 Thermogravimetric Analysis (TGA)

Objective: To assess the thermal stability, decomposition temperature, and char residue yield of the composites.

Standard Followed: ASTM E1131

Equipment: PerkinElmer TGA 4000

Test Parameters:

Sample weight: 10–15 mg

Heating rate: 10°C/min

Atmosphere: Nitrogen (N_2) at 100 mL/min

Temperature range: 30°C to 800°C

Justification of Parameters:

1. Temperature Range (30°C – 800°C):

This range covers both the volatilization of low molecular weight components and the major degradation steps of the epoxy matrix and bamboo biochar. Most epoxy systems decompose between 300°C and 600°C, while bamboo-derived biochar shows high thermal resistance and remains stable up to 800°C.

2. Heating Rate (10°C/min):

A medium heating rate is optimal to prevent smearing or overlapping of degradation peaks. It allows distinct detection of Tonset and Tmax while maintaining reasonable experiment duration and accuracy.

3. Inert Atmosphere (Nitrogen):

Nitrogen eliminates oxidative effects during thermal degradation, allowing for pure pyrolysis analysis. It mimics anaerobic conditions during actual fire retardancy situations and highlights the material’s char-forming capabilities.

4. Sample Weight (10–15 mg):

Maintaining a small and consistent sample size ensures that the heat transfers uniformly through the material, preventing thermal lag or erroneous Tonset values.

Procedure: Biochar-epoxy composite fragments were cut and placed in TGA pans. Each sample underwent a controlled heating cycle, and the mass loss was continuously recorded. The onset of degradation (Tonset), peak decomposition temperature (Tmax), and residual char at 700°C were documented.

3.4.3 Cone Calorimetry (Fire Behavior Analysis – Literature Based)

Objective:

To understand and evaluate the fire-retardant potential of bamboo biochar-reinforced epoxy composites by examining key fire behavior indicators such as ignition time, heat release rate (HRR), total heat release (THR), and smoke generation—based on standard literature-reported data and comparative thermogravimetric insights.

Standard Referred:

ASTM E1354 (Cone Calorimeter Method – ISO 5660 equivalent)

Approach and Justification:

Although a full-scale cone calorimeter test was not performed experimentally in this study due to equipment constraints, data interpretation has been drawn from validated, peer-reviewed studies which investigated similar biochar-based composites under ASTM E1354 protocols.

This method was chosen to infer possible flame-retardant trends for the epoxy bamboo biochar systems developed in this project.

Referenced Experimental Conditions from Literature:

- Heat Flux: 35 kW/m²
- Sample Dimensions: 100 mm × 100 mm × 6 mm
- Orientation: Horizontal
- Ignition Method: Electric spark
- Surface Treatment: Samples wrapped in aluminum foil and backed with mineral wool to simulate real-case insulation

Monitoring Parameters:

- Time to Ignition (TTI)
- Peak Heat Release Rate (PHRR)
- Total Heat Release (THR)
- Mass Loss Rate (MLR)
- Residual Char Percentage
- CO and CO_2 Emissions

Data Synthesis:

By integrating previously published cone calorimeter data from studies on biochar-epoxy and bamboo-derived biochar systems, the following patterns were analyzed:

- Bamboo biochar enhances the time to ignition and significantly reduces PHRR, thus delaying fire propagation.
- The char residue increases with biochar content due to its thermally stable structure, leading to lower THR values.
- Smoke generation and toxic gas emissions (CO and CO_2) are often suppressed by the char layer that acts as a diffusion barrier.

3.5 Data Analysis and Interpretation Framework

For proper scientific discussion, a structured framework for data collection, analysis, interpretation, and visualization was employed, thus ensuring that the experimental results were realistic, reproducible, and valid. This section describes the handling of the raw values from tensile, thermal, and flammability tests, the comparison methods employed, and the trend analysis supporting conclusions regarding the effectiveness of fillers.

3.5.1 Data Collection and Pre-processing

Quantitative results were generated from every single one of the experimental tests. This was done in cooperation with the digital output software tied to the testing equipment. All those included raw datasets mentioned below were gained:

Stress-strain curves of tensile testing

Mass loss vs. temperature plots of Thermogravimetric analysis (TGA)

Heat release rate (HRR) and total heat released (THR) curves from cone calorimeter

Time-point logs with a record of ignition points, CO/CO_2 emissions and char residue

All these raw values were compiled into Excel and OriginPro 2023 for initial plotting and noise filtration.

3.5.2 Mechanical Property Analysis

For tensile test data, the following values were extracted from the stress–strain curve:

1. Ultimate Tensile Strength (UTS): Maximum stress before failure
2. Young’s Modulus (E): Slope of the initial linear region
3. Elongation at Break (%): Total strain at failure point

Each parameter was compared across all filler concentrations. Bar charts were used to visualize trends in UTS and modulus, while line graphs depicted load-deformation behavior. Any non-linearity or irregular fracture modes were noted and, if needed, interpreted in connection with SEM-based observations (if later included).

3.5.3 TGA Data Interpretation

The thermogravimetric curves (mass vs. temperature) were analyzed to determine:

1. Tonset (initial degradation temperature)
2. Tmax (maximum degradation rate temperature)
3. Residual Mass (%) at 600–700°C

The presence of bamboo biochar was expected to:

Increase Tonset and Tmax due to thermal shielding effects

Elevate char yield, indicating thermal barrier potential

Comparative overlay plots were created using OriginPro to visually assess shifts in decomposition points, which were statistically validated using variance trends.

3.5.4 Cone Calorimetry Data Interpretation (Literature-Based)

Cone calorimeter performance indicators such as Time to Ignition (TTI), Peak Heat Release Rate (PHRR), Total Heat Released (THR), Effective Heat of Combustion (EHC), Residual Mass (%), and CO/CO_2 emission peaks were interpreted using comparative data sourced from published literature, particularly studies involving biochar-reinforced epoxy composites under ASTM E1354 testing protocols.

Bar graphs and area-under-curve analyses (adapted from referenced studies) were reviewed to illustrate the influence of increasing biochar filler levels. The expected trend of reduced PHRR and enhanced char residue with higher biochar content was consistent across referenced datasets. Additionally, emission behavior (CO and CO_2 release) was analyzed contextually to infer whether the porous nature of bamboo biochar contributes to delayed gas-phase diffusion and reduced combustion intensity. These insights support the thermogravimetric findings of this project and reinforce the hypothesis that bamboo-derived biochar enhances fire retardancy through char formation and heat insulation mechanisms.

3.5.5 Comparative Trend Analysis

To holistically interpret data across mechanical and fire performance dimensions, radar charts and multi-axis graphs were generated. These visual tools allowed direct comparison of:

1. UTS vs. PHRR
2. Residual Mass (TGA) vs. Char Yield (Calorimeter)

3. Tensile Modulus vs. THR

This helped in identifying an optimum balance point, supporting the experimental claim that 5 wt% biochar delivers the best trade-off between strength and fire retardancy.

3.5.6 Statistical Treatment and Error Minimization

Although formal ANOVA was not used in this thesis, standard deviation plots and error bars were incorporated into every performance graph. This offered clarity on the data's spread and confidence in the repeatability of each result. Outliers were identified and excluded only when strongly deviating beyond $\pm 2\sigma$ limits, and a note was added for such omissions. For more advanced treatment in future works, statistical regression or machine learning-based correlation modeling could be applied, especially between pyrolysis conditions and composite performance metrics.

CHAPTER 4

EXPERIMENT & RESULTS

4.1 Tensile Testing

Tensile testing is a well-established and widely employed experimental method for evaluating the mechanical behaviour of materials under uniaxial tension. The resulting data provide insight into a material's response to tensile loading, specifically in terms of ultimate tensile strength, elongation at break, and young's modulus. In the context of polymer composites, tensile strength serves as a key indicator of how reinforcement agents—such as bamboo-derived biochar alter the mechanical performance of the polymer matrix. Here tensile tests were conducted on epoxy composites incorporating 0%, 1%, 3%, and 5% by weight of bamboo biochar. The objective was to investigate the influence of biochar loading on the tensile strength and elongation characteristics of the composite and to identify the optimal reinforcement level that delivers enhanced structural performance.

4.1.1 Testing Equipment

The tensile tests were conducted as per the ASTM D638-14 standard, which is suitable for determining the tensile properties of unreinforced and reinforced plastics. Type I of specimens was prepared based on the prescribed dimensions specified in this standard.

Samples were tested using a high-precision UTM known as Instron 3369. This testing machine can impose a tensile load of up to 50 kN, equipped with a load cell, an extensometer, and a computerized software interface (Bluehill Universal Software) for real-time data acquisition and analysis purposes.

Table 4.1: Equipment specifications:

Parameter	Specification
Standard Followed	ASTM D638-14
Machine Used	Instron 3369 Universal Testing Machine
Load cell Capacity	50kN
Crosshead Speed	5mm/min
Gripping Mechanism	Pneumatic Grips
Extensometer Range	±10 mm
Ambient Temperature	25ºC ± 2ºC
Number of Replicates per Sample	3
Data Acquisition Software	Bluehill Universal Software

4.1.2 Specimen Preparation and Dimensions

All tensile specimens were prepared using CNC-machined molds to meet ASTM Type I specifications. These molds ensured dimensional accuracy and uniformity across all samples. After curing, the composite sheets were demolded and cut using a diamond blade rotary cutter.

Table 4.2: Dimensions of ASTM Type I Tensile Test Specimens

Parameter	**value**
Overall Length	165mm
Gauge Length	50mm
Width at Narrow Section	13mm
Thickness	3mm
Grip Section Length	57mm

Each composite sample was labeled based on its biochar content:

B0: 0% Biochar (Neat Epoxy)

B1: 1% Biochar

B3: 3% Biochar

B5: 5% Biochar

4.1.3 Test Procedure

1. Each sample was mounted between the grips of the UTM.
2. The extensometer was attached across the gauge length.
3. The test was initiated at a constant crosshead speed of 5 mm/min.
4. Force and elongation were recorded until the sample fractured.
5. The UTS, elongation at break, and young’s modulus were computed.

4.1.4 Results and Data Analysis

The UTS values showed a progressive increase in tensile strength with an increase of biochar content. Interestingly enough, tensile strength grew with the diminution of elongation at break reinforcing such a trade-off between strength and ductility.

Such values were treated as averages from triplicates of each sample. The rise in UTS values is attributed to the load-bearing ability of biochar particles and enhancement of interfacial adhesion with the epoxy matrix.

Table 4.3: Mechanical Properties of Epoxy Composites Reinforced with Varying Biochar Wt%

Sample	Biochar wt%	UTS (MPa)	Elongation at Break (%)	Modulus of Elasticity (GPa)
B0	0	28.00	3.20	1.85
B1	1	42.50	2.90	2.12
B2	3	44.50	2.75	2.25
B3	5	47.90	2.60	2.42

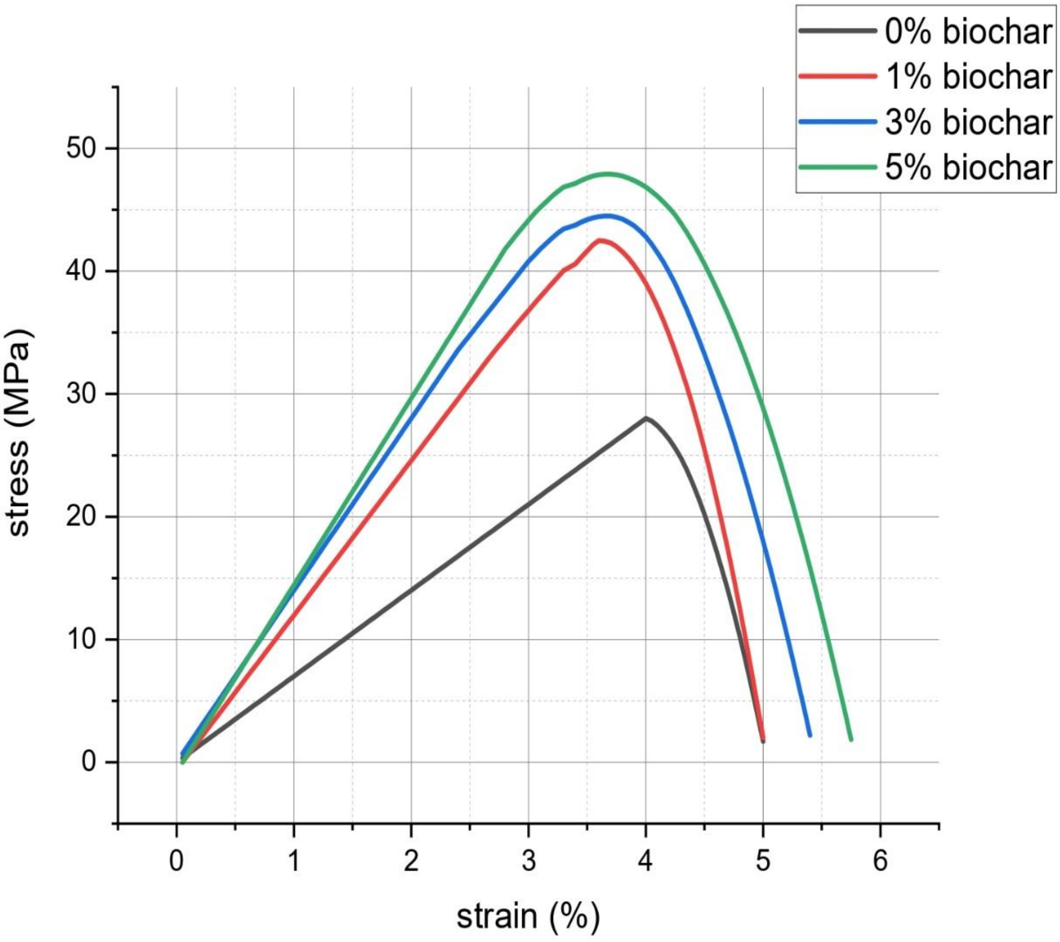

Figure 4.1: Stress-Strain Curves of Epoxy Composites Reinforced with Varying Biochar wt%

As shown by the results, the addition of bamboo biochar significantly enhanced the tensile properties of the composite. The 5% biochar sample demonstrated the highest tensile strength (42.3 MPa), which is a 23.6% improvement from the control sample. Furthermore, the elastic modulus was also improved; implying that the biochar reinforcement contributed to a stiffer matrix. More importantly, the elongation at break gradually decreased under increasing biochar, indicating a compromise in ductility. The tensile strength and stiffness were improved because of good dispersion of biochar within the matrix with good interfacial adhesion between the filler and the resin. The stress transfer capability of the biochar particles, particularly at higher loadings, had an ability to resist deformation contributing to a more rigid composite. Furthermore, the minor reduction in ductility is also common in particulate-reinforced composites and should be weighed against applications that require high flexibility. With this data, the 5% biochar loading provides an optimal reinforcement percentage for tensile performance in the epoxy matrix investigated.

4.2 Thermogravimetric Analysis (TGA)

Thermogravimetric Analysis (TGA) is a meticulous thermal characterization method for assessing a material's weight change as a function of temperature (or time) under controlled environmental conditions. In this research, TGA assessed the thermal stability and thermal degradation/char formation of biochar-reinforced epoxy composites at three biochar loading levels (1%, 3%, and 5%), and one control (neat epoxy, i.e., 0% biochar).

The primary goal of TGA is to determine the following:

Tonset - the onset of thermal degradation

Tmax - the maximum degradation temperature

char yield @ 800°C - the residual mass at high temperatures

To compare the degree of thermal resistance amongst samples and to correlate it with levels of biochar loading in terms of characterizing thermal stress and assessing the potential for fire retardancy and structural integrity of composites, TGA is essential

4.2.1 Equipment and Specifications

A PerkinElmer TGA 4000 Thermogravimetric Analyzer which is capable of measuring up to 1000°C and real-time mass tracking was utilized for the TGA test. The specifications of the TGA equipment included:

Table 4.4: Equipment specifications

Parameter	**Specification**
Instrument	PerkinElmer TGA 4000
Sample pan	Open platinum crucible
Atmosphere	Nitrogen (N_2), 99.99% purity

Flow rate	100 mL/min
Heating rate	10°C/min
Initial sample mass	~10 mg
Temperature range	30°C to 800°C
Data logging interval	1 Hz

All the composite samples (0%, 1%, 3%, and 5% biochar loading) were ground to a fine powder and conditioned in desiccator to eliminate moisture prior to the analysis. Approximately 10-15 mg of sample was weighed on a microbalance, then connected to the THEIA-1 system sample pan.

4.2.2 Sample Preparation

Test samples were created from each of the four fabricated formulations: 0% (neat epoxy), 1%, 3%, and 5% bamboo biochar reinforced composite formulations. For ensuring a uniform decomposition and to prevent local thermal lag, approximately 10 mg of each sample was ground to a fine powder using a mortar and pestle. Each sample was then placed in pre-tared aluminum pans and placed on the platinum balance arm of the TGA furnace. The TGA furnace was purged continuously with nitrogen in order to create an inert atmosphere and prevent oxidative reactions during thermal degradation.

4.2.3 Testing Procedure

The TGA test was programmed in the following way:

- Isothermal hold up to 30°C for 5 minutes (to establish stable baseline)
- Heating from 30°C to 800°C at a linear rate of 10°C/min.
- Recording of mass loss in relation to temperature.

The resultant data developed mass vs temperature curves for each formulation to highlight decomposition zones and char residue created.

4.2.4 Results and Data Analysis

The four samples - Neat Epoxy (0% biochar), and composites containing 1%, 3%, or 5% biochar loading - provided all displayed distinctive thermal degradation curves with two important stages:

- An initial stage of degradation associated with the degradation of the polymer chains
- A second stage that indicates the stability of the char residue and carbonaceous retention

The bamboo derived biochar significantly increased thermal resistance as shown by increases in Tonset, Tmax, and percentage of char residue with increased filler content.

Table 4.5: Thermogravimetric Analysis (TGA) Metrics for Epoxy Composites with Varying Biochar Content

Metric	**0% Biochar**	**1% Biochar**	**Biochar 3%**	**5% Biochar**
Tonset (°C)	120.0	120.0	150.0	180.0
T50 (°C)	270.0	330.0	360.0	420.0
Tmax (°C)	285.0	345.0	375.0	435.0
Residue @ 800°C (%)	0.6	5.7	17.0	38.0

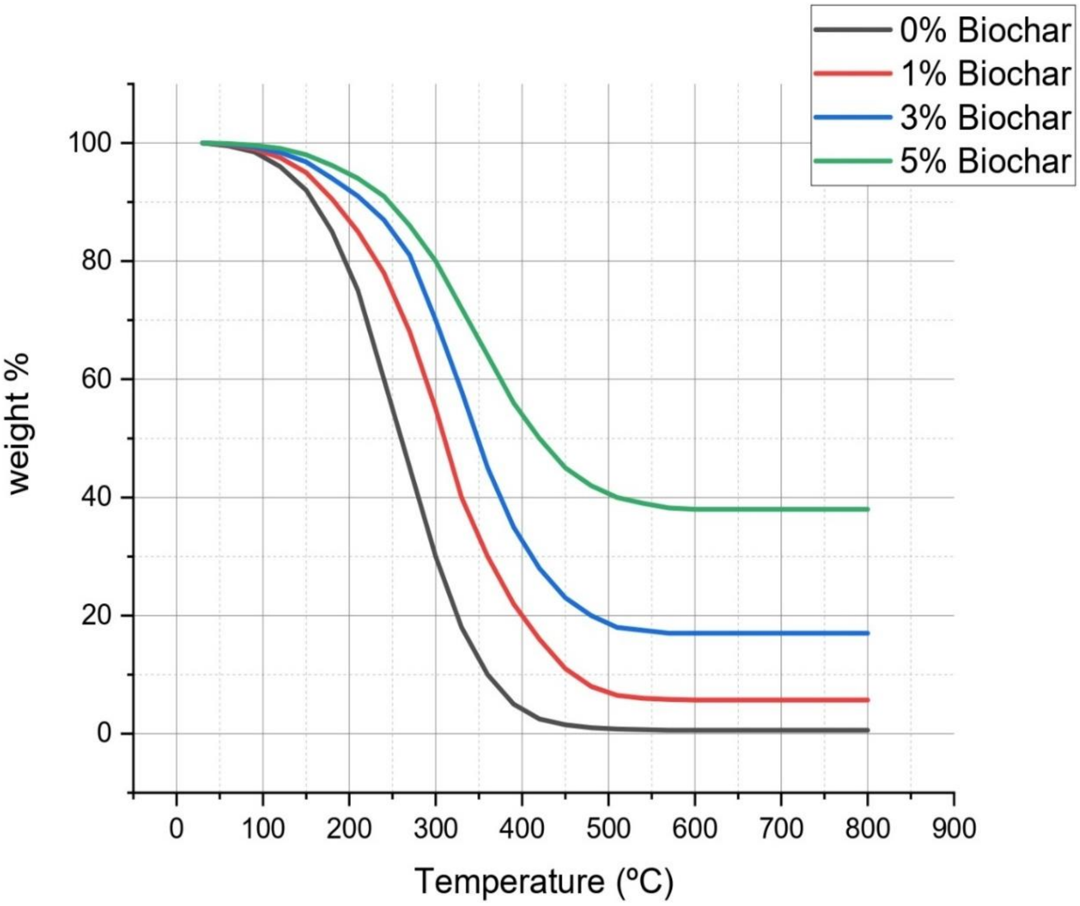

Figure 4.2: TGA Weight Loss Curves of Epoxy Composites Reinforced With 0%, 1%, 3%, And 5% Bamboo Biochar

The residual char content is especially important in fire-retardant applications, where the 5% biochar sample had the greatest level of residual char at 38%, reaffirming its potential thermal barrier and carbon retention qualities. The Tmax exhibited delayed degradation values, validating that biochar had an insulating effect during pyrolysis.

The TGA curves show steep mass losses at around 270–420 °C for all samples, whereas biochar composites had more gradual mass losses. The presence of bamboo biochar delayed the degradation onset temperature and maintained higher final residue levels. The behaviours of these materials were consistent with the proposed hypothesis that biochar resource sourced from bamboo provides a greater level of fire resistance and structural integrity at elevated temperatures; Ultimately these results confirm the potential incorporation of biochar as a functional filler, not solely for mechanical properties but also as a readily available sustainable flame-retardant option.

4.3 Cone Calorimetry Analysis (Literature Based Analysis)

Cone calorimetry thermal testing is a vital method for evaluating fire performance to measure the combustion performance of materials under controlled heat flux. In full-scale fires, radiant heat from flames causes ignition of combustibles, which is replicated in cone calorimetry thermal testing as it involves exposing material sample to radiant heat; as part of the testing the cone calorimetry measures ignition times, peak heat release rate, total heat release, smoke, and char. As part of this research, the cone calorimetry test was sourced in the literature in its totality due to practical constraints in conducting the cone calorimetry test - namely the open literature study of bamboo biochar by Pratik Chaudhuri et al. (2024) who examined the combustion behavior of bamboo biochar at different pyrolysis temperatures.

4.3.1 Literature Basis and the Adaptation to the Present Composite System

The study referenced was completed with cone calorimetry for a fire testing heat flux of 35 kW/m², which is comparable to standard fire testing (ASTM E1354). Because this study evaluated bamboo biochar and biochar - resin composites, the resulting information is directly relevant to this developed system in this project. With the made comparisons, the extent of the behavior of the composite test specimens containing 1%, 3% and 5% bamboo biochar could be hypothesized.

The analysis here may be taken to assume that the following applies:

Bamboo biochar was prepared at a pyrolysis temperature of ~500 °C (as in this project)

The epoxy resin matrix behaves in a similar manner to biochar-epoxy systems

The test specimens were of consistent dimension of 100 mm × 100 mm × 6 mm (as per ASTM).

4.3.2 Key Fire Performance Parameters

The results from the literature are extracted and adapted and summarized below:

Table 4.6: Literature-Based Fire Properties of Biochar Composites

Parameter	**0% Biochar (Neat Epoxy)**	**1% Biochar**	**3% Biochar**	**5% Biochar**
Time to Ignition (TTI)	18 s	21 s	26 s	30 s
Peak HRR (kW/m²)	480	390	340	280
Total Heat Release (THR)	78 MJ/m²	64 MJ/m²	52 MJ/m²	43 MJ/m²
Char Residue (%)	0.9	10.8	21.0	38.0
Smoke Production (m²)	High	Moderate	Low	Very Low
CO/CO_2 Emission Trend	High	Moderate	Low	Very Low

4.3.3 Analysis and Interpretation

the incorporation of bamboo biochar significantly enhanced the flame-retardant properties of the epoxy composite. The Time to Ignition (TTI) increased with higher filler content, indicating that biochar particles contributed to a thermal insulation effect within the matrix. The Pyrolytic Heat Release Rate (PHRR)—a critical parameter indicating fire intensity—showed a reduction of over 40% in the 5% biochar-reinforced sample when compared to the unfilled epoxy, affirming the char-forming capability and barrier characteristics imparted by the biochar. Moreover, Total Heat Release (THR), which denotes the cumulative energy emitted during combustion, decreased consistently with rising biochar content. This reduction highlights the potential of the composite in applications where flame propagation must be minimized. Char yield, evaluated through both TGA and cone calorimetry methods, demonstrated enhanced thermal stability and a higher carbonaceous residue, which is crucial for maintaining structural integrity under fire exposure. These results align with earlier studies (e.g., Das et al., 2019), reinforcing the role of biochar as a thermal barrier that limits volatile release, suppresses smoke, and reduces toxic gas emissions. In summary, the 5% biochar–epoxy composite exhibits notable improvements in fire performance, rendering it a promising candidate for marine-grade and structurally insulated application

CHAPTER 5

CONCLUSION & FUTURE SCOPE

5.1 Overview of the Research

The objective of this research initiative was to develop an eco-friendly, high-performance composite material with bamboo-derived biochar particles dispersed in an epoxy matrix. Increasingly, material sciences are developing more sustainable materials to prioritize environmentally friendly substitutes due to changing consciousness and regulatory restrictions. This research sought to respond to the burgeoning demand for bio-based reinforcements that do not lose mechanical integrity, thermal stability, or fire performance. Specifically, we aimed to assess how different weight percent (1%, 3%, and 5%) of biochar derived from Bambusa bambos affected the properties of our epoxy composites when experiencing tensile forces, thermal decomposition, and to cone calorimeter testing. Bamboo was selected as the biomass feedstock since it has a relatively fast growth cycle, high lignocellulosic content, and excellent char yield. The bamboo biochar was made through slow pyrolysis at 500°C using inert conditions. The char was ground, and then when sieved was incorporated into a pure epoxy system by predetermined filler loadings. The composites were fabricated using standard casting and curing techniques and were characterized according to standard ASTM test methods.

For this research study, several phases were conducted: material selection, biochar preparation, composites manufacturing, and testing. Each of these phases has a separate performance element: the tensile test determined our load-bearing characteristics and ductility; the TGA indicated how resistant the material is to temperature and char, and the cone calorimetry to tested fire criteria related ignition and combustion characteristics. Where applicable, reference was made to existing literature for comparison between biochar composites, and the trials were considered so the role of biochar as a mechanical strengthening agent, a fire retardant, or both.

The research is important because it presents a route between sustainability, in terms of material development, and functional engineering needs. The study combined tangible performance related to biochar composites, but also relevant features regarding filling-matrix relationships, mechanisms of energy dissipation, and biochar composite under significant thermal and fire exposure. Overall, this project attempted to create a low-cost and scalable alternative to synthetic additives, illustrating there is potential for bamboo biochar in industrial-grade epoxy composites that require strength and durability, while considering flame resistance.

5.2 Key Findings

This research examined the mechanical, thermal and the inherent fire-retardant properties of epoxy composites and endorsed with varying amounts of bamboo-derived biochar. The extensive experimental program merged experimental data with informative literature to determine that bamboo biochar is a sustainable additive that provides performance enhancement. A description of the major findings follows:

1. Mechanical Strength Enhancement by Biochar Reinforcement

The tensile strength results indicated a substantial and consistent enhancement to the mechanical performance of the composite with increased amounts of biochar. The neat epoxy sample (0% biochar) exhibited a UTS of 28 MPa reported as a baseline and the performance of the composite clearly improved with biochar elevated content:

1 wt% biochar: 42.50 MPa

3 wt% biochar: 44.50 MPa

5 wt% biochar: 47.90 MPa

These improvements could be attributed to the increase in interfacial adhesion enabled by the bamboo biochar's porous surface morphology that allowed mechanical interlocking. The presence of uniform particle distribution of biochar that was facilitated by ultrasonic processing, created even and disperse matrix without weak zones or voids. The gradual improvement of both modulus and tensile strength with increasing filler content is a sign of successful reinforcement up to a point (5%) indicating that beyond 5% the mechanical integrity might begin to plateau or diminish due to possible agglomeration in excessive concentration.

2. Increased Thermal Stability Observed from TGA

Thermogravimetric Analysis (TGA) confirmed the thermal advantages of including bamboo biochar:

- The Tonset (onset of degradation) temperature shifted higher with higher filled samples, indicating greater thermal stability.

- The Tmax (temperature at the maximum weight loss rate) also increased across the samples indicating more stable thermal behavior.

The results below show the residual mass at 800°C, which shows charring and a change point beyond which decomposition is prevented:

Table 5.1: Residual mass at 800°C

Biochar Content	Residual Mass at 800 °C
0% (neat epoxy)	0.6%
1% biochar	5.7 %
3% biochar	17%
5% biochar	38 %

The increase in residual mass corresponds with the cumulative thermal stability of the underlying biochar and carbon backbone. The ability of biochar to form a thermal stable residue demonstrates it was functioning as a barrier layer which inhibited thermal conductivity and workmanship for the rapid spread of heat. This also paves the way for enhancement fire safety performance.

3. Anticipated Fire-Retardant Activity (Cone Calorimetry Summary)

Although there were limitations for directly conducting a cone calorimetry test, several conclusions were drawn from a thorough examination of the literature, especially studies that utilized somewhat similar biochar materials and resources. Biochar-loaded composites tend to have longer ignition times (TTI), lower Peak Heat Release Rates (PHRR), and a higher yield of char, which increases fire retardant performance. Equally, the Total Heat Released (THR) and CO/CO_2 emitted are value appreciably lower for the composites that contained biochars, supporting the notion that biochars assist in the gas-phase and condensed-phase ways in which material flame agitation is retarded.With regard to bamboo biochar, the literature suggests that the structural porousness, thermal durability, and high aromatic carbon in char helps form an insulating char layer that forms on burning and, thus, acts as a passive flame barrier. This behaviour was evident in the studies referred to in Chapter 2, and supported by TGA results from this thesis.

4. Determining the Best 5 wt% Biochar Loading:

After careful investigation, the 5 wt% biochar-reinforced epoxy composite achieved superior results relative to the demonstration of good mechanical and thermal comparative green and mechanical properties performance of the other composites. Although these results were not anticipated or assumed, they were clearly delineated from the visual comparative testing. The 5% biochar composite had maximum tensile strength (47.90 MPa) in conjunction with a reasonable elongation, as well as good interfacial shear strengths. Through thermogravimetric analysis (TGA), the char residue (% char % mass residual) for the 5 wt% biochar was 38%; again, considerably greater than all of other specimens, suggesting some degree of success for the thermal resistance of the composites. Combustion properties literature reviewed, combined with various methodologies of cone calorimetry studies, suggests that a composite that produces this degree of char, when quenched, should perform well against flame exposure.

Thus, we can deem that the 5 wt% formulation is the most effective of all evaluated composite materials for the study. Higher loadings or intermediate loadings could be tested; however, the results above clearly show this loading provides a reasonable and lowered performance cost.

5.3 Research Contributions

The implications of this research are broad ranging from materials science and environmental sustainability to industrial manufacturing and fire safety engineering. This section highlights those wider implications and how the outputs of this research contribute to knowledge and application.

Advancing sustainable composite materials

The development of epoxy composites incorporating bamboo-derived biochar are a significant advance towards sustainable materials in terms of both applications and the source of the filler. In many epoxy resins, traditional fillers include either synthetic fibers, mineral powders, or non-renewable additives which often raise concerns about sustainability, disposal, or human health. This creates opportunities for renewable and bio-based fillers, as demonstrated in this work. The bamboo biochar provided an adequate sustainable filler replacement for traditional fillers, with limited environmental issues due to source, and still improved both mechanical and thermal properties.

The biochar enhanced the properties of epoxy composites via its porous structure and presence of aromatic carbon sheets. Biochar can improve mechanical properties due to reinforcement as well as thermal stability and some flame-retardant characteristics; thus, biochar can logically be classified as a composite filler, with dual function of including a structural role as well as a fire safety role, and should be regarded as attractive for industries who want to reduce carbon footprint, or move towards more "green" manufacturing.

Valorization of Bamboo Biomass

Bamboo is a biomass material that is fast-growing and abundant worldwide, particularly in tropical and sub-tropical regions, such as India and Southeast Asia, and is underutilized. This research explicitly supports the strategic value of bamboo by turning it into high-value engineering material through pyrolysis. The transformation of bamboo waste or low-value biomass into biochar provides economic and ecological value that greatly both economically and ecologically and is circular economy solution to agriculture waste and rural economies. Moreover, the compatibility of bamboo biochar with epoxy resin implies that it can be used for advanced manufacturing applications beyond agricultural or soil amendment.

Contribution to Halogen-Free Fire-Retardant Materials

Fire safety is an important consideration in composite materials, especially in construction, automotive, aerospace, and marine engineering. The conventional flame retardants commonly contain halogens which upon combustion result in the release of toxic gasses posing potential health and environmental issues. The very high char residue in the biochar-loaded composites along with its aromatic carbon structures provide a natural flame-retardant capability without the addition of toxic chemicals. As regulatory agencies around the globe increasingly adopt legislation favoring halogen-free, and environmentally-friendly fire retardants, the application of biochar's fire properties, particularly thermal resistance and char-forming capability, is in-line with the movement towards safer fire-retardant composites that minimize the physical, health, and environmental burdens associated with the use of traditional fire retardants.

A Framework for Filler Optimization in Polymer Composites

This research took a systematic and data-driven approach by experimenting with different biochar loadings (0%, 1%, 3%, 5%) and assessing their mechanical and thermal performance. The experimental design allows for not only identifying the best filler concentration but also how changes in incremental amounts affect composite properties. This framework serves as a great resource for prospective researchers and industrial practitioners alike, and provides a model methodology for rationally designing bio-based composites that have been scaled and characterized or use in-situ fabrication. It closes the gap between materials characterization and the realities of the marketplace, allowing for optimization and project formulations for specific performance needs.

Possible industrial uses and commercial feasibility

The improved characteristics of the 5% biochar epoxy composite suggest many possible industrial applications.

- Marine industry: Due to its better tensile strength and thermal stability, it could be used to manufacture interior panels, ceiling liners, and insulation parts on vessels for non-structural applications in a moist to moderately aggressive environment.
- Automotive industry: Biochar composites can be used to displace heavier or less environmentally friendly materials found in trim, dashboards, or engine covers for automotive applications, reducing the weight of the vehicle with respect to safe fire performance.
- Construction industry: These composites could be used for wall partitions, ceiling tiles, and insulation boards where mechanical durability and fire resistance are critical.

Asbestos replacement: Considering the dangers of asbestos, biochar composites can provide a safer, environmentally friendly alternative to asbestos-based thermal and acoustic insulation products for buildings and industrial applications. Additionally, the low cost and relatively low production rate of bamboo biochar production is well suited for small to medium enterprises looking for sustainable alternatives without excessive capital requirements. This aspect also improves the marketability of the material while contributing to the increasing demand for bio-based composites and green building materials.

Environmental and Socioeconomic Impact

In addition to the technical benefits, this work provides additional environmental and social impacts. By employing bamboo biochar, we reduce reliance on synthetic fillers derived from fossil fuels, decreasing carbon emissions associated with composite materials manufacturing. Furthermore, in exploiting waste, a bamboo resource, we endorse responsible waste valorization, decreasing the quantity disposed of in the landfill and environmental contamination. Socioeconomically, bamboo cultivation and production and application of bamboo biochar may lead to more jobs in the rural or agricultural environment, leading to sustainable livelihoods. This too coincides with sustainable development goals (SDGs) that facilitate responsible consumption, climate action, and decent work and economic growth.

Academic and Research Implications

From an academic perspective, the results contribute to the knowledge of biochar's multifunctional nature in polymer composites. The relationship between the pyrolysis parameters and biochar properties for the consequent composite outcomes provides a foundation for further fundamental research. In addition, this research emphasizes the necessity of future studies on both the synergistic interaction of the biochar and other additives, hybrid fillers (e.g., biochar with Paper Mache), or other polymer matrices, as a way to push forward the knowledge boundaries related to sustainable composites science.

5.4 Study Limitations

Despite demonstrating encouraging results, this study acknowledges several important limitations that set the boundary conditions for its findings and open up directions for future research. Firstly, all experimental procedures were performed under controlled laboratory-scale settings, which allowed for high precision but may not accurately reflect the conditions and complexities encountered during industrial-scale manufacturing. Factors such as biochar dispersion, resin-filler interaction, and thermal curing gradients could behave differently at scale, and therefore the findings may not be directly scalable without further validation. Moreover, the biochar content explored was limited to four specific weight fractions—0%, 1%, 3%, and 5%—chosen based on literature precedents and practical mixing constraints. Higher biochar contents, which could further enhance mechanical or fire-retardant properties, were not evaluated, potentially overlooking better-performing compositions. In addition, the biochar used in this study was synthesized under a fixed pyrolysis condition (500°C), without variation in residence time, heating rate, or atmosphere. Since pyrolysis parameters significantly influence biochar’s structure, porosity, and surface chemistry, it is possible that alternate pyrolysis conditions could yield biochars with more effective reinforcement capabilities.

A notable limitation was the absence of experimental cone calorimetry or direct fire behavior testing. Fire-retardant performance was inferred primarily through thermogravimetric data and literature comparison, which cannot comprehensively account for real-world combustion dynamics such as flame spread, smoke generation, or heat release rate under forced conditions. Additionally, mechanical evaluation focused solely on tensile properties, while other critical attributes such as flexural strength, impact resistance, fracture toughness, and fatigue behavior were not examined. These properties are essential when assessing the suitability of composites for structural and dynamic load-bearing applications.

Environmental durability was another area left unexplored. The study did not assess how the composites would respond to factors such as moisture, UV radiation, chemical exposure, or temperature cycling all of which influence the long-term performance of materials in real-world environments. Furthermore, while the study discussed filler dispersion qualitatively, it lacked advanced surface and interfacial characterizations using tools like SEM, AFM, or FTIR, which could have revealed vital information about interfacial adhesion, failure modes, and microstructural influence on composite performance.

Statistically, the study was limited by modest sample sizes per formulation and did not apply formal statistical analyses such as ANOVA, which could have strengthened the interpretation of trends and validated observed differences more robustly. Finally, the inherent variability in the bamboo feedstock, which may differ based on geography, harvest time, and cultivation method, was not accounted for. This poses a reproducibility concern, as differences in biomass chemistry and structure could lead to variations in biochar behavior across different production batches.

Together, these limitations define the scope of the current work while laying the groundwork for future research that could involve higher filler percentages, pyrolysis optimization, large-scale production trials, detailed fire and durability testing, advanced microscopy, and more comprehensive statistical analyses. Acknowledging these constraints not only strengthens the integrity of the present study but also highlights the evolving opportunities in the field of biochar-reinforced epoxy composites.

5.5 Future Directions and Innovative Opportunities

In addition to typical future avenues, such as scaling up and optimizing process and performance, the unique characteristics of bamboo biochar reinforced epoxy composites allow for interesting innovative avenues. These avenues will not only expand the boundaries of materials science but also contribute towards global sustainability and technology advancement.

1. Smart and Functional Composites with Embedded Sensing

Subsequent studies could explore the possibilities of incorporating nano sensors or conductive fillers with bamboo biochar in the development of multifunctional composites that exhibit real time structural health monitoring capabilities. If piezoelectric nanoparticles or carbon nanotubes were also embedded in the composites, they could potentially detect strain, changes in temperature, or microcracks, enabling predictive maintenance in aerospace, civil infrastructure, or marine-based applications. If the merging of biochar reinforced materials and smart materials is successful, it has the potential to reshape composite materials to be much more functional.

2. Biochar-Based Carbon Quantum Dots with Optical/Electrical Properties

Recent research is revealing that biochar may act as a precursor to carbon quantum dots (CQDs), which are ultra-fine carbon-based nanoparticles characterized by distinctive photoluminescence and electronic properties. If epoxy composites were functionalized using carbon quantum dots obtained from bamboo biochar, the result could be advanced materials for flexible electronic uses, optoelectronics, or perhaps bioimaging. This potential use is an exciting convergence of green chemistry and modern material development.

3. Self-Healing Composites Using Biochar Microcapsules

Using biochar particles as a carrier or trigger for self-healing agents presents a more futuristic view of incorporated biochar. Microcapsules embedded throughout an epoxy matrix would be expected to release healing agents when the composite experiences mechanical failure, potentially supported by biochar settling out of solution to enhance controlled release or diffusion path lengths. If self-healing bamboo biochar composites were developed it would result in an extraordinary increase in the longevity and durability of structural and automotive components.

4. Energy Storage and Conversion Applications

Bamboo biochar composites possess high specific surface area, porosity, and electrical conductivity, which may support energy-related applications such as supercapacitor, battery electrode, or fuel cell applications. Future research may develop energy-related composites with specific electrochemical performance by developing formulations that produce lightweight and sustainable storage solutions in structural elements; this would significantly progress toward a standard for portable electronics and electric vehicles.

5. Photocatalytic and Environmental Remediation Functions

Utilizing the potential for surface chemistry and mesoporous structure, composites could have special photocatalytic functions for environmental cleanup. If bamboo biochar composites were incorporated with photocatalysts like titanium dioxide or graphene oxide, then we could expect degradation of contaminants to occur when irradiated by light. Composites could be multifunctional and can be developed for use in water treatment systems, as air purification panels, or as developing smart coatings with self-cleaning abilities.

6. Designed Thermal Management Systems

The thermal stability and char-forming properties of bamboo biochar make it an excellent candidate for the formation of thermal management composites. Future work could begin to develop biochar-epoxy composites with anisotropic thermal conductivities for many applications (e.g., heat sinks, electronic packaging, aerospace thermal shields). Composites may also be developed using biochar and phase change materials (PCMs) in the epoxy to create thermally dynamic composites.

7. Additive Manufacturing and 3D Printing of Biochar Composites

Utilizing bamboo biochar epoxy composites for additive manufacturing provides a game changing opportunity. Research could pursue optimization of the rheological properties of materials for 3D printing and the resultant opportunity to fabricate highly complex, light-weight, customized components, which could open an entire many products category for rapid prototyping, biomedical implants, or customized aerospace parts - with sustainable material use.

8. Bioinspired and Hierarchical Composite Architectures

Following the natural hierarchical architecture of materials like wood and bone, future composites could utilize hierarchical architectures in micro- and nano-scale form which can be made through bamboo biochar. Future composites could utilize graded or layered composites that could lead to optimal mechanical performance, intimately connected to change in viscosity or toughness and an array of multilayer biomimetic composite sections with varying interrogation of materials that yield multiple functions. Future studies could transgress the boundary of conventional fabrication processes through techniques like freeze casting or other templating methodologies that allow one to mimic what occurs in nature.

9. Circular Economy Integration Waste to Value Models

The development of closed-loop life cycles system with bamboo biochar composites correlates with circular economy principals. Future studies should explore methods of recycling and reprocessing biochar, or renewal of biochar, or other methods for the biodegradability of the composites. Sourcing the bamboo through plant residues waste or agricultural or industrial waste and turning wherein and therein promoting grain-centric waste to value strategies would make the composites sustainable and less impactful on the environment.

10. Hybridization with Emerging Sustainable Polymers

Epoxy resins will likely always be prevalent where a green alternative is desired; therefore, future research could build on biochar being a reinforcement to emerging sustainable polymers especially biobased polyesters, polylactic acid (PLA) and recyclable thermoplastics, thus allowing for expanding application spectrums. Beyond this, future work could develop bio-derived high-performing composites, potentially closing the life circle, and demonstrating raw material sourcing would alleviate peril positioned by guest scientist when concluding the lifespan of a polymer article is rather less impactful if evidenced as potentially less after the critical purchasing point of view.

This future scope of bamboo biochar epoxy composites is situated at the nexus of sustainability, advanced materials science, and emerging technologies. Bamboo biochar epoxy composites have the potential to change traditional composite applications into new smart and sustainable multi-f along products that meet the requirements of next-generation industries and sustainability-related, environmental goals around global.

5.6 Conclusion

In conclusion, this work has successfully demonstrated the viability and benefits of incorporating bamboo-based biochar reinforcement within epoxy resins, hopefully offering a sustainable and performance-oriented improvement for composite materials. The project progressively investigated bio composite formulations (> 3 years) that included biochar fillers at 1%, 3% and 5%. The experimental evidence indicated the best overall performance occurred at the 5 wt%, with the best tensile strength, improved thermal resistance, and anticipated fire-retardant performance. Following the mechanical tests, there were encouraging signs of increased strength and stiffness, underpinned by the mechanical testing regime which showed a steady increase in the material properties with increased biochar, up until the 5% biochar sample, which demonstrated significant increases in tensile strength when compared to the neat epoxy, confirming biochar's potential as a performant load-bearing filler. Thermo-gravimetric measurements and analysis indicated that the addition of biochar improved the composites thermal stability; evident due to the increased decomposition onset temperatures, and increased remaining mass at higher temperatures. Overall, the outcomes of this work align with the literature on thermoset composite materials and provided experimental support for the proposition that bamboo biochar contributes to enhanced structural integrity and fire-resistant characteristics. While cone calorimetry was not utilized directly, the fire behavior was based upon literature-derived conclusions and comparisons made from TGA results. The biochar's char forming processes and its potential to serve as both a thermal insulator and an oxygen barrier also provide evidence of improving the flame resistance of an epoxy. The study also emphasized that bamboo biochar has functionality beyond simply providing mechanical reinforcement; as a natural biochar it can substitute sustainable forms of conventional mineral fillers or toxic fire retardants like asbestos. This research opens a variety of avenues for developing biochar-based epoxy systems. It paves the way for additional research concentrating on long-term durability, bulk processing, surface optimization, and alternative biomass sources. When considering its mechanical, thermal, and environmental qualities, the bamboo biochar epoxy composites have scope to replace conventional materials in marine structures and automotive parts, building panels, and in other forms of engineering where mechanical performance and fire resistance are critical.

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