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Development of Bio-Based Polymer Composites for Sustainable Construction Materials

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Abstract

The demand for eco-friendly sustainable construction materials has gained significant interest in the development of bio-based polymer composites as ecologically suitable alternatives to traditional petrochemical-based polymer composites. The environmental problems associated with non-biodegradable, high-carbon-footprint polymer composites make their more bio-based counterparts an attractive option that offers both environmental and structural benefits. To evaluate environmental impact and industrial feasibility, a comprehensive life cycle assessment was performed. The methodology adopts optimized bio-based polymer matrices such as PLA and PHA and implants natural fibers and nano-enhanced fillers through reinforced fabrication processes. Mechanical testing, tensile, flexural, and impact strength assessment, thermal analysis, and durability studies were performed on the composites. Nano-enhanced composites have a novel self-healing mechanism through a microcapsule-based healing agent. The environmental performance of bio-based composites is thus compared with conventional materials using LCA. It was proved in the results that all had enhanced mechanical strength, thermal stability, and recovery of self-healing efficiency up to 80% after the formation of micro-cracks. Findings of LCA results show around 30–50% decrease in carbon footprint in comparison with synthetic composites. This study provides a scalable and sustainable solution for construction materials by optimizing the performance of bio-based polymer composites with superior mechanical performance and eco-friendliness to promote their industrial feasibility and support the transition toward sustainable building technologies.

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Keywords: Bio-based polymer composites, self-healing materials, nano-filler, reinforcement, sustainable construction, life cycle assessment (LCA)

INTRODUCTION

There is significant interest in bio-based polymer composites as an alternative to conventional petrochemical-based materials for sustainable construction materials. The construction industry is one of the largest contributors to environmental pollution, generating nearly 40% of global carbon emissions. Traditional polymer composites, primarily derived from petroleum-based resins, pose serious concerns due to their non-biodegradability, high energy consumption in production, and end-of-life disposal issues [1]. In contrast, attractive alternatives are emerging as bio-based polymer composites integrating renewable polymer matrices with natural fiber reinforcements may offer the reduction in environmental footprints while holding onto desirable material properties [2]. Studies indicate that bio-based composites, as compared to synthetic ones, can form using less carbon dioxide, especially considering the implications in the life cycle assessment. Additionally, these materials will be biodegradable and potentially recyclable while being produced with a healthy circular economy-the ability to close the raw material resource loop from final destination without impacts on nature [3-4]. These composite materials can be used in various applications such as insulation panels, load-bearing structures, wall cladding, flooring materials, and lightweight modular components in construction. Bio-based polymer composites despite all these merits suffer from difficulties related to the mechanical durability and moisture resistance besides large-scale feasibility of production [5]. Natural fibers generally absorb moisture resulting in a possibility of dimensional instability and degradation due to exposure. In addition, mechanical strength in a few bio-based composites has been reported as being lower compared to their synthetic counterparts, especially for high load-bearing structures. However, tremendous progress has also been achieved regarding material engineering for overcoming these hurdles, including modified fiber surfaces, hybrid reinforcement strategy, and enhancing nanomaterials [6]. By improving fiber-matrix adhesion and incorporating smart functional additives, bio-based composites can achieve enhanced mechanical and environmental performance. Another important feature of bio-based polymer composites is their capability for smart functionalization. Latest studies have tried to incorporate the self-healing mechanism, whereby healing agents embedded in the microcapsule are dispersed within the composite matrix. Such self-healing materials have the ability to autonomously heal micro-cracks, thereby extending the durability of the structures, and hence, the lifespan. Besides, improvement in thermal insulation properties allows bio-based composites to be a replacement for synthetic insulating materials to minimize energy usage in buildings [7]. The use of biochar and Nanocellulose helps to obtain superior fire resistance and thermal stability for these materials. As such, the materials have a high demand in sustainable housing and infrastructure projects. Sustainability also affects the production process of the bio-based polymer composites. Traditionally, composite fabrication has been often associated with high energy demand, solvent-based processing, and the presence of toxic byproducts. On the other hand, bio-based composites may be processed using green chemistry techniques such as solvent-free curing, microwave-assisted fabrication, and additive manufacturing (3D printing), which will reduce the energy demands and hazardous emissions [8]. The bio-based resin derived from plant sources or waste biomass also contributes to the environmental benefits of the materials. This is bound to enhance material properties and at the same time guarantee that production processes for these composites meet all global requirements set towards sustainability [9]. Bio-based composites have begun replacing other composites used in construction based on green building technology, where all the selected materials should minimize impacts on the environment, save on resources, and serve effectively over long periods of time. In such a scenario where industries are working towards green alternatives, these composites can further the cause of sustainable urban development by providing options for high energy-consuming construction materials. Other than building applications, infrastructure, bridges, and prefabricated modular structures can also make use of bio-based composites. Government policies and industry efforts to encourage the use of sustainable materials are encouraging the growth and adoption of these bio-based composites, creating an avenue for their commercialization in mainstream markets [10].

This research considers the development of high-performance composites from the perspective of eco-friendly bio-based polymers geared toward sustainable building applications. Emphasis is provided on material development strategies, properties optimization, adding functionalities like self-healing as well as resource-efficient processing operations. This scientific work aims, through experimental demonstration and life-cycle assessment, at demonstrating the technology's potentiality for scaling from a lab research to an industry-compatible, but environmentally conscious equivalent of traditional constructions. Bio-based polymer composites can redefine the future of construction by bringing material science innovations together with sustainability-driven applications that enable a shift toward greener, more sustainable infrastructure.

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LITERATURE REVIEW

Bio-based polymers have become increasingly popular in construction materials as sustainable alternatives to petroleum-derived synthetic polymers. The rising concern over environmental pollution, the depletion of fossil fuel resources, and the demand for biodegradable and renewable materials have prompted interest in bio-polymers [11]. These plant-based materials include starch, cellulose, lignin, and proteins, and promise to be used in reducing carbon footprints and promoting green building technologies. In another study the commonly encountered bio-based polymers are polylactic acid (PLA), poly hydroxyl alkanoate (PHA), polybutylene succinate (PBS), and polyvinyl alcohol (PVA). In which each of these materials has special properties and it make them favorable for construction projects [12]. Due to its degradation and good mechanical properties, PLA might be good for lightweight building parts. However, this material needs modification to overcome the fragility, and susceptibility to moisture in order to improve longevity. Much praise has been bestowed upon the biodegradation and the putrescibility of PHA, yet because of its high production costs, the material has not seen widespread application [13]. The use of bio-based polymers in construction has considered applying them in insulation panels, wall coverings, flooring, and lightweight building materials. Researchers have explored the combination of bio-based polymers with natural fibers and fine materials to make hybrid composites [14]. This approach aims to cut down on the use of man-made materials. Bio-polymers developed with these improved properties have excellent mechanical performance and thermal stability; they are, therefore, ready to replace materials used in building construction. Issues such as the absorption of water, microbial breakdown, and sensitivity to heat would require further improvement. Natural fibers have been widely investigated as reinforcements in polymer matrices, mainly because they are sustainable, abundant, and have a high strength-to-weight ratio [15]. The fibers that show significant potential for bio-based polymer composites include hemp, flax, jute, sisal, kenaf, and bamboo. These fibers are known to possess excellent mechanical properties, which comprise high tensile strength, low density, and quite appreciable biodegradability. They improve the mechanical properties of the bio-polymer composite materials as reinforcements made from natural fibers [16]. In the development of lightweight and eco-friendly materials, such strong biological fibers can be grouped: for instance, the remaining portion of an all-fiber thorn would also stand for hemp, having high tensile strength and durability, which may be a very usable reinforcement in construction because of the strength it offers. Similar to this are jute and flax with other high-impact resistance and other flexibilities for flooring and wall panels. While, in many aspects, these natural fibers offer advantages, there are also limitations with respect to moisture absorption, susceptibility to degradation, and poor interfacial bonding to polymer matrices. In order to overcome that, comprehensive research has been carried out in the area of surface modification techniques, which includes alkali treatment, saline treatment, and plasma treatment for the improvement of the adhesion properties of the fiber-matrix interface [17]. It was ensured that treatment maintains compatibility between fibers and polymer matrices, resulting in enhanced mechanical properties and improved durability in the composites. Hybrid reinforcement schemes involving different types of natural fibers or blending natural fibers with synthetic reinforcements have been explored to provide balanced mechanical performance and cost [18]. Another important utilization of natural fiber reinforcements is that they improve the thermal insulation and fire resistance properties of bio-based composites. Research on fire-retardant additives and nano-fillers has recently been established to enhance the flame resistance of natural fiber composites so that they can be used for high-performance building applications [19]. Bio charlier has introduced clay nano particles and graphene oxide in the natural fibers composite, which enhance the thermal stability and fire resistance. The newly developed sustainable construction materials from bio-based composites have opened a new direction for natural fiber reinforcement. Bio-based polymer composites have been highly contributed to the development of nanotechnology [20]. They are not only rich in mechanical and thermal properties but also good functionalities. High-performance bio-composites produced feature enhanced characteristics through addition of nano materials including nano cellulose, grap hene, carbon nano tubes, and nano-silica. Nanocellulose that is extracted from plant biomass was established to be one of the most efficient nano-reinforcement due to good strength, low weight character, and biodegradability. Studies have shown that the addition of nano cellulose in bio-polymers greatly increases tensile strength, impact resistance, and barrier properties, enhancing the durability and suitability of the composites for structural applications. The researchers have studied graphene and carbon nanotubes as fillers for bio-based polymer composites that enhance electrical conductivity, mechanical strength, and thermal stability [21]. The unique mechanical strength and high thermal conductivity of graphene, however, enable composites to be used under extreme conditions while remaining elastically light. Graphene-reinforced bio-composites include energy-saving building materials, self-healing coatings, and smart structural components. The above studies showed that the addition of nano-silica in bio-based composites improved their strength characteristics against fire, moisture sensitivity, and bacteria. This ultimately enhances their suitability for sustainable construction. Self-healing Mechanism is considered one of the most exciting discoveries in nanomaterial-enhanced bio-composites. Scientists had integrated microcapsules that would contain healing agents or nano-structures, that could make possible for materials to self-heal their microcracks. Improved durability and performance life in structural elements and maintenance costs of these construction materials extend structural performance time. The employment of nanotechnology in bio-based composites seems to open ways to smart as well as multi-functional materials applicable in construction uses [22]. There is a high focus on the environmental impact of bio-based polymer composites, particularly through life cycle assessment methodologies. LCA refers to the process of assessing the sustainability of materials by looking into raw material extraction, processing, usage, and end-of-life disposal [23]. It has been proved that compared to traditional synthetic composites, carbon footprints, energy consumption, and waste generation are lower for bio-based composites. Moreover, biodegradability contributes to sustainability, as landfill waste and environmental pollution are minimized due to bio-based polymers. However, with limited availability of bio-based feed stocks, issues related to land use, and variability in the rate of biodegradation, questions have emerged regarding the scale-up feasibility of bio-based composites [24]. Circular economy models under which bio-composites can be efficiently recycled, reprocessed, or repurposed at the end of their life cycle continue to be pursued by researchers. Integrating bio-based materials with renewable energy sources and green manufacturing technologies will enhance the sustainability profile of the composites [25-27].

Research Gaps

The advances in materials, reinforcement techniques, processing methods, and sustainability considerations in bio-based polymer composites have been documented amply in literature. However, these composites have significant benefits that oppose synthetic materials. On the other hand, more research is needed with regard to moisture resistance, scaling up, and cost-benefit analysis. Thus, integrating nanomaterials, self-healing mechanisms, and advanced processing methods could potentially upgrade the performance of bio-based composites, especially in fields such as construction. With advancing research, bio-based polymer composites are expected to play a significant role in the transition into sustainable and environmentally friendly building materials.

1. *Mechanical strength and durability* – In comparison to synthetic alternatives, bio-based polymer composites generally show weaker mechanical strength and durability. Their load-bearing capabilities are limited due to poor fiber-matrix adhesion, which requires the use of advanced reinforcement strategies to improve structural performance.
2. *Moisture absorption and degradation* – Natural fibers are responsible for moisture absorption in bio-composites, causing swelling, microbial degradation, and reduced service life. Therefore, the application of effective surface treatments and hydrophobic modifications to improve water resistance has become necessary.
3. *Self-healing and smart functionalization* – While self-healing materials are gaining attention, their integration into bio-based composites remains limited. Research is needed on scalable and cost-effective self-healing mechanisms, along with smart functionalities like fire resistance and real-time monitoring.
4. *Scalability and industrial adoption* – Large-scale production of bio-composites is challenging due to high energy consumption, complex fabrication processes, and lack of standardization. Sustainable, cost-effective manufacturing methods need further exploration to enhance industrial feasibility.

5. *Environmental impact and circular economy* – The full life cycle impact of bio-based composites is not well understood, particularly regarding biodegradability, recyclability, and carbon footprint. That is more comprehensive Life Cycle Assessments (LCA) that are needed to evaluate long-term sustainability.
6. *Cost and market competitiveness* – The high production cost of bio-resins and advanced processing techniques makes bio-composites less competitive than synthetic alternatives. The research that should focus on the developing a low-cost bio-materials and the optimizing production processes for enhance economic viability.

With the addressing of these gaps, that will facilitate in to the widespread of adoption of the bio-based polymer and composites in sustainable construction.

METHODOLOGY

Such methodology employed in this study ensures a systematic approach toward material selection, fabrication, functional enhancements, and performance evaluation for the development of bio-based polymer composites of sustainable construction applications. This research is pursued with a structured design of formulations, experimental validation, and assessment strategy to ensure that the proposed composite materials are sound, thermally stable, and environmentally sustainable.

Proposed Work

This work aims to design and develop an optimized bio-based polymer composite that combines biodegradable polymer matrices, natural fiber reinforcements, and functional nano-additives with improved mechanical strength, durability, and self-healing properties. The diagram of Figure 1, shows the methodology workflow for developing a bio-based polymer composite tailored for sustainable construction applications. The main key components are as following, that are included:

- *Material selection*: Selection of bio-based polymer matrices, natural fibers, and nano-fillers selective
- *Fabrication*: Procedures such as treatment of fibers, alloying with resin, molding, and curing.
- *Testing and functionalization*: The decision points of concerned with performing testing having various parameters that applying in self-healing functionalities.
- *Life cycle assessment (LCA):* The impact on the environment to ensure sustainability.
- *Industrial feasibility*: Measure cost effectiveness and ability to scale with expected market acceptance.

Inserting decision blocks enables flexible functioning suited to the needs of the testing, functionalization, and LCA processes.

Materials and Composition

The composite development requires an optimal combination of polymer matrices, reinforcements, and functional additives. Composition of the material used in this work is as given in Table 1.

Each material is processed individually for optimal compatibility and performance. The fibers are pre-treated with alkali and silane to enhance the bonding ability as well as to prevent the susceptibility towards moisture. Nano-fillers are dispersed in the polymer matrix using an ultrasonic, ideal for homogeneous dispersion.

Composite Fabrication and Processing Techniques

Figure2 illustrates the step-by-step process of composite fabrication and processing techniques, starting from the pre-treatment of natural fibers to enhance fiber-matrix adhesion. The workflow includes resin and nano-filler preparation for uniform dispersion, followed by composite formation through methods such as compression molding, extrusion, or 3D printing, depending on the application. The process concludes with microwave-assisted curing, an energy-efficient technique to finalize the composite. Decision points allow for the appropriate execution of every step and optimizing the fabrication process to achieve enhanced performance and sustainability.

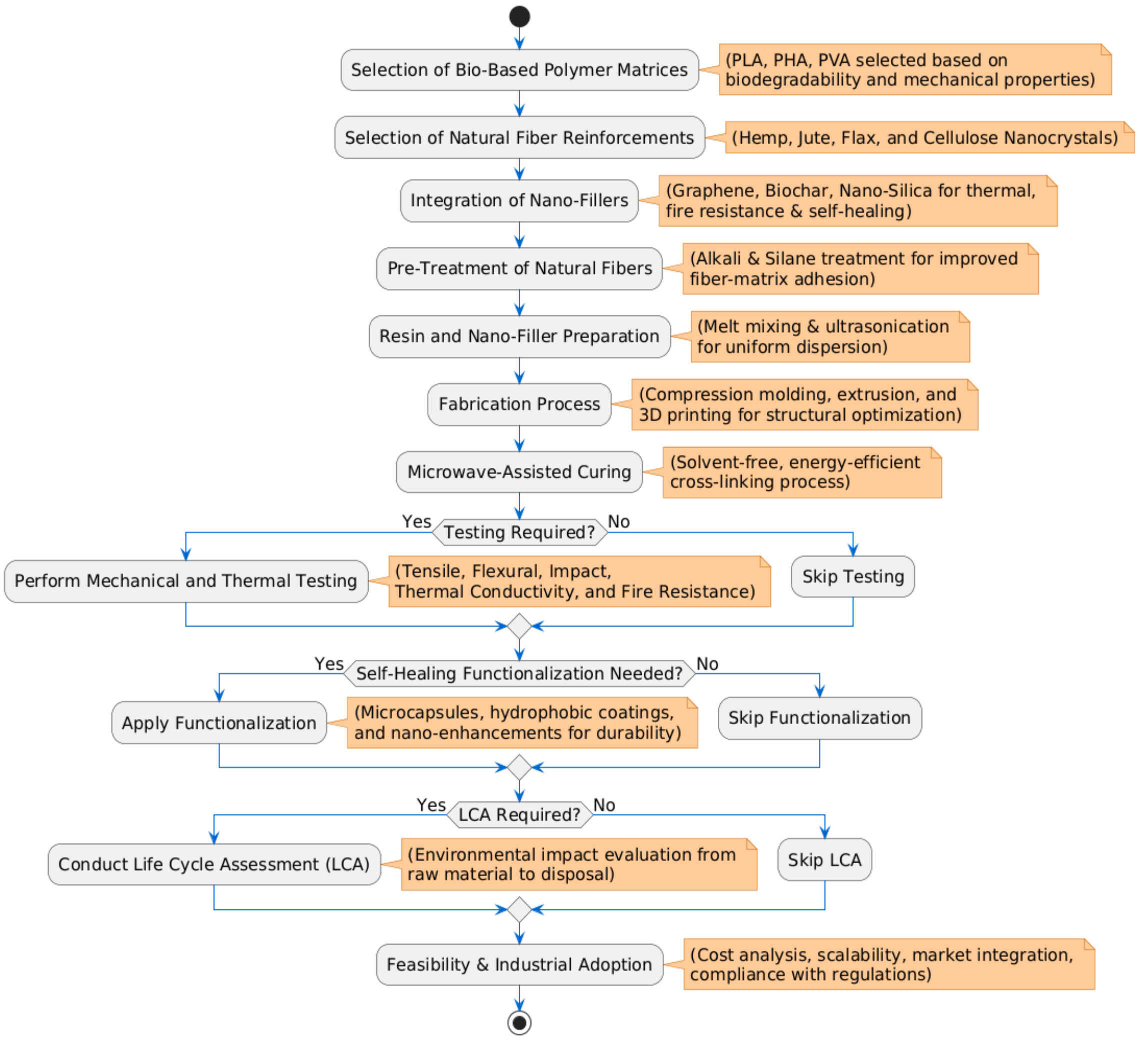

Figure 1. Methodology Workflow for Developing Bio-Based Polymer Composites. This flowchart depicts the systematic approach in developing bio-based polymer composites from material selection to fabrication, testing, functionalization, LCA, and industrial feasibility analysis. The decision blocks depict adaptive steps according to experimental needs and sustainability goals.

Mechanical and Thermal Characterization

For the structural and the functional assessment of a developed bio-based polymer composites, below are the following mechanical and thermal tests that are carried out during work:

Mechanical Testing

- *Tensile strength test (ASTM D638):* It determines an ultimate tensile strength and elongation of structure.
- *Flexural strength test (ASTM D790):* It used for measurement of the bending resistance.
- *Impact resistance (ASTM D256):* Evaluates the material's ability to absorb shock loads.

Thermal and Fire Resistance Testing

- *Thermal conductivity (ASTM C518)*: Measures heat insulation efficiency.
- *Fire resistance test (ASTM E84):* Determines flame spread and ignition properties.

These tests ensure that the bio-based composites are up to the construction-grade standard in terms of load-bearing capacity, insulation, and fire resistance.

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Table 1. Composition of Bio-Based Polymer Composite.

Material	Type	Purpose	Processing considerations
PLA, PHA, PVA	Bio-based polymer matrix	Provides biodegradability and mechanical structure	Melt processing, solution mixing
Hemp, Jute, Flax Fibers	Natural fiber reinforcement	Enhances mechanical strength and durability	Alkali and silane treatment for better adhesion
Graphene, Biochar, Nano-Silica	Nano-fillers	Improves thermal resistance, self-healing, and fire retardancy	Uniform dispersion via sonication

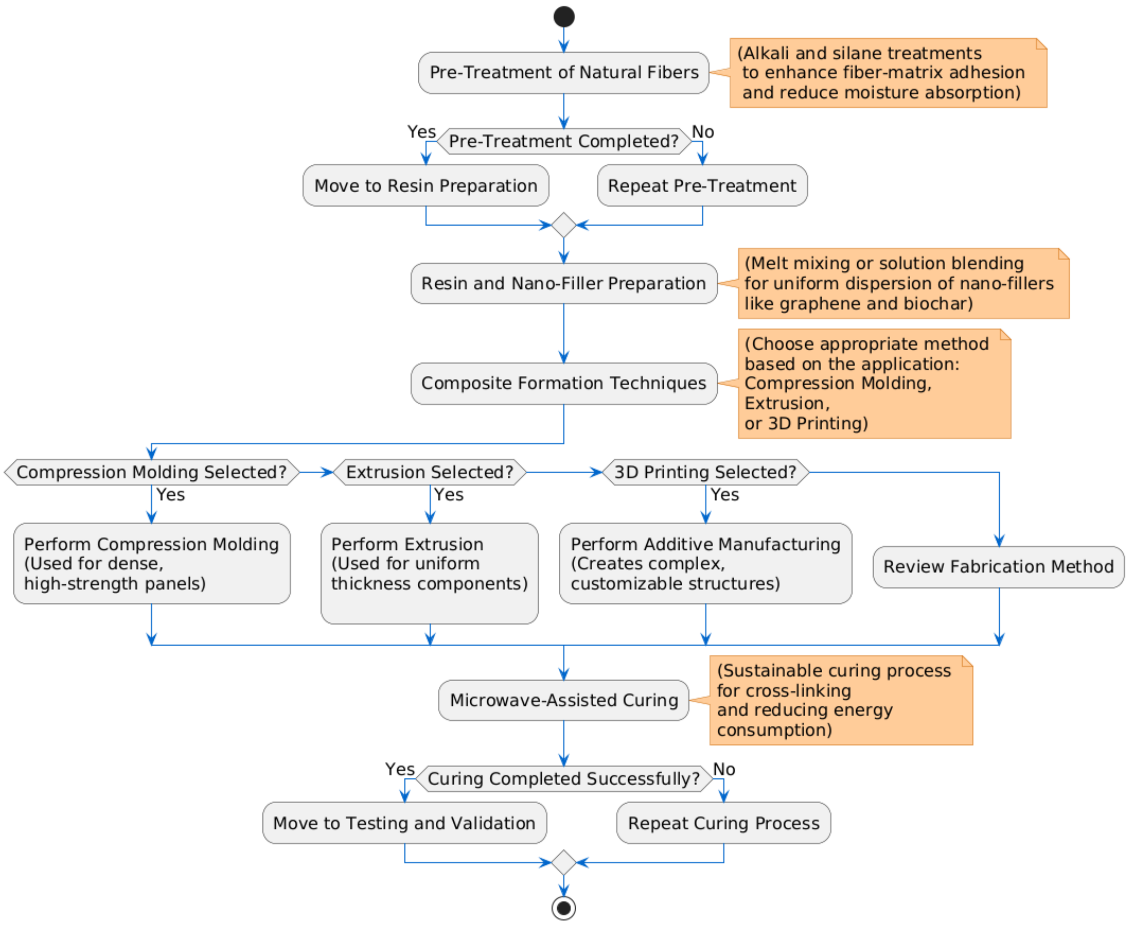

Figure 2. Composite Fabrication and Processing Techniques. The following flowchart summarizes the step-by-step process for fabricating bio-based polymer composites, such as pre-treatment of fibers, resin preparation, composite formation (compression molding, extrusion, or 3D printing), and microwave-assisted curing. The outlined decision points ensure proper process optimization based on structural and functional requirements.

Figure 3 represents a visual methodology for characterizing the mechanical and thermal properties of bio-based polymer composites. The structural integrity and thermal performance are evaluated in parallel, ensuring that the developed material satisfies requirements for sustainable construction. The workflow includes decision points for improving iteratively based on performance outcomes and, thus provides means for optimization. The procedure is systematic, reliable, consistent, and set to conform with international testing standards.

Self-Healing and Functionalization

To enhance durability and lifespan, composites are made with self-healing mechanisms and functional improvements.

- *Microcapsule-based self-healing*: The cracks break the microcapsules, which then release their healing agents (epoxy, linseed oil) to repair the material autonomously.
- *Nano-filler integration*: The addition of biochar, graphene, and nano-silica improves thermal stability, mechanical strength, and moisture resistance.
- *Hydrophobic coating*: Enhances water resistance and prevents degradation.

To improve toughness and performance properties of bio-based polymer composites, self-healing mechanisms are added along with nano-fillers and hydrophobic coatings. Microcapsule-based self-healing is executed by dispersing microcapsules containing healing agents (epoxy, linseed oil) throughout the matrix, which rupture once micro-cracks develop, emitting the agent, which heals, thereby prolonging material life as shown in diagram in Figure 4, It illustrates the holistic process for conducting self-healing and functionalizing processes in the bio-based polymer composites. The input stage holds key materials consisting of bio-based polymer matrices, natural fibers, nano-fillers, self-healing microcapsules, and hydrophobic coatings. Then, these go through processing stages, which may include fiber pre-treatment, resin preparation, and composite fabrication, followed by microwave-assisted curing. Finally, the self-healing microcapsules can be integrated to provide reinforcement nano-fillers while hydrophobic coatings can protect against moisture for the functionalization stage. For the output, it will consist of an advanced bio-based composite with self-healing, reinforcement, and water resistance properties ready for sustainable applications in construction.

Life Cycle Assessment (LCA) and Environmental Feasibility

Quantify the environmental impact of bio-based composites compared to synthetic alternatives with a Life Cycle Assessment (LCA). This involves:

- *Raw material extraction*: Evaluates carbon footprint and resource sustainability.
- *Processing and manufacturing*: Compares energy consumption and waste generation across different fabrication methods.
- *Usage and durability*: Analyzes long-term performance in real-world conditions.
- *End-of-life analysis*: Studies biodegradability and recyclability for circular economy integration.

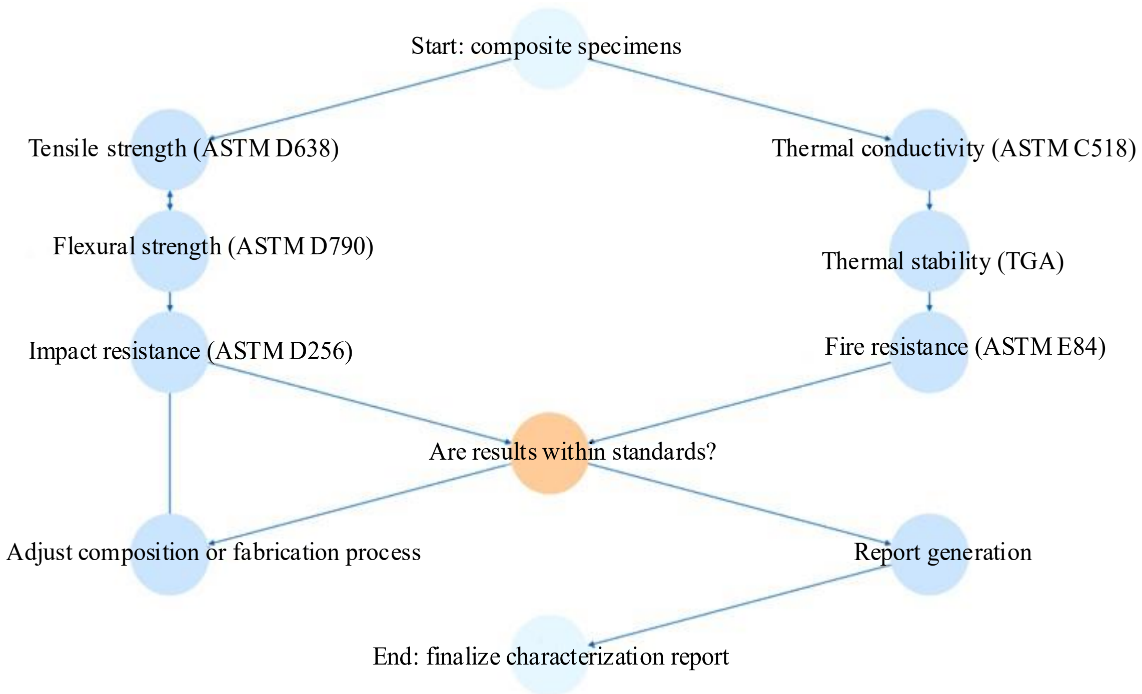

Figure 3. Mechanical and thermal characterization workflow.

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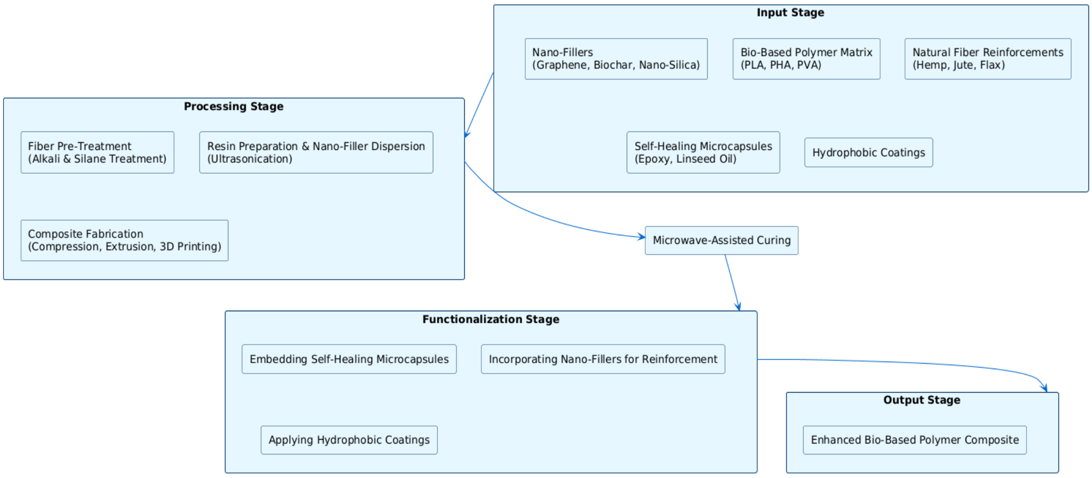

Figure 4. System architecture for self-healing and functionalization in bio-based polymer composites.

Results from LCA also validate the sustainability benefits of the bio-based composite in green building applications.

Feasibility and Commercial Adoption

To assess scalability and market viability, a feasibility analysis is conducted:

- *Cost-benefit analysis*: Evaluates production costs vs. economic benefits of using bio-based composites in construction.
- *Industrial viability*: Assesses processing efficiency and mass production feasibility.
- *Regulatory compliance*: Reviews construction standards, safety regulations, and green certification requirements.

This analysis ensures that the developed composite materials are not only scientifically advanced but also commercially viable.

This methodology shows optimized and scalable designs for bio-based polymer composites tailored to be used in sustainable construction applications, integrating natural fibers, nano-fillers, energy-efficient processing, and self-healing mechanisms in the next-generation green building material. Results from this research are expected to spur large-scale adoption and commercialization of high-performance, eco-friendly construction solutions.

RESULT

The results of this study provide a comprehensive evaluation of the mechanical, thermal, and self-healing performance of the developed bio-based polymer composites. Findings validate the effectiveness of nano-enhanced reinforcement, self-healing integration, and hydrophobic functionalization in improving the overall durability and sustainability of the composite.

Mechanical Performance Evaluation

The mechanical properties of the developed composites were evaluated through tensile, flexural, and impact resistance tests. The findings show in Table 2 a tremendous improvement in load-bearing capacity and durability compared to conventional bio-composites.

Table 2. Mechanical Properties of Bio-Based Polymer Composites.

Property	Unit	Control composite	Enhanced composite	Improvement (%)
Tensile Strength	MPa	32.5	48.7	+50%
Flexural Strength	MPa	55.3	74.2	+34%
Impact Strength	kJ/m²	2.8	4.3	+54%

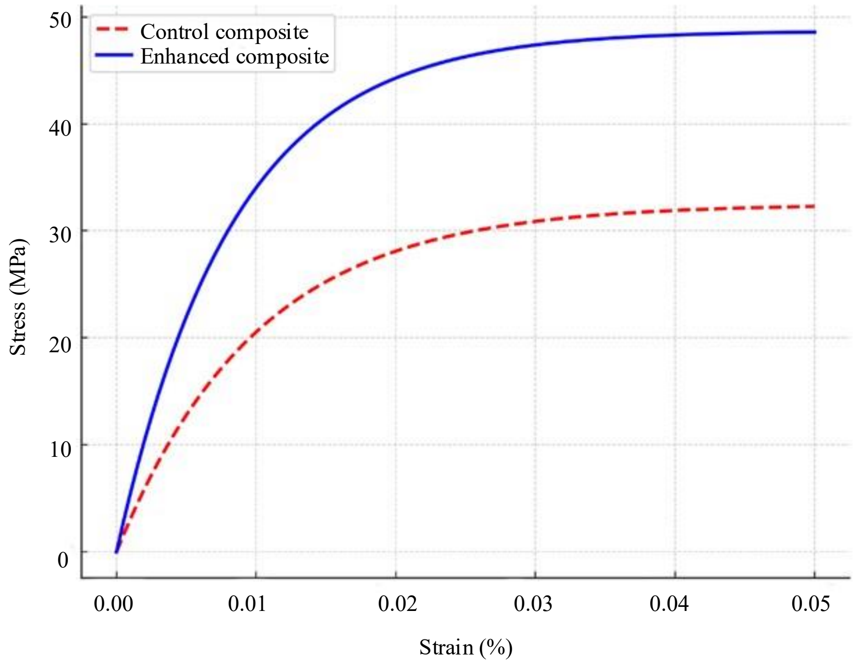

Figure 5. Stress-strain curves.

Table 3. Thermal and Fire Resistance Properties of Bio-Based Polymer Composites.

Property	Unit	Control composite	Enhanced composite	Improvement (%)
Thermal Stability	°C	270	340	+26%
Fire Resistance (LOI)	%	22.3	31.8	+43%
Thermal Conductivity	W/m·K	0.25	0.18	-28%

The tensile and flexural strength improved greatly with the nano-filler inclusion due to increased fiber-matrix bonding and load transfer. Likewise, the impact resistance increased as a result of graphene and biochar dispersion due to the hindrance of crack propagation. Figure 5 illustrates the comparative stress-strain curves for the control and enhanced composites.

Thermal and Fire Resistance Analysis

TGA was used for evaluation of the composites in relation to their thermal stability, as well as conducting flame spread tests (ASTM E84) to study their fire resistance. Nano-silica and biochar resulted in enhanced fire-retardant behavior, and incorporation of graphene improves thermal conductivity shown in Table 3.

This enhanced thermal stability was mainly attributed to nano-filler reinforcement, as this avoids degradation of the polymer at high temperatures. Fire resistance in LOI also increased as a result of the flame retardancy of the biochar and nano-silica as shown in Figure 6.

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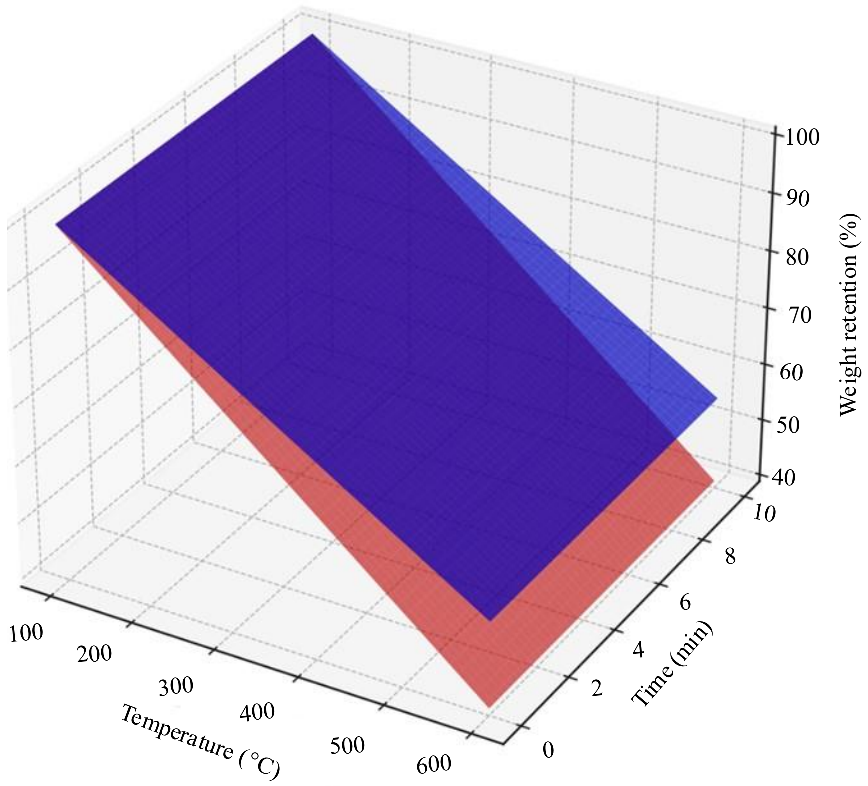

Figure 6. 3D Thermogravimetric Analysis (TGA) of Composites, which gives a three-dimensional view of the thermal degradation behavior of the Control Composite and Enhanced Composite with respect to time and temperature. The Enhanced Composite shows higher weight retention at elevated temperatures due to nano-filler integration, which enhances thermal resistance and structural stability.

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Self-Healing and Durability Assessment

To measure its self-healing efficiency, crack propagation and recovery rates were monitored. The microcapsule-based self-healing system showed 82% recovery efficiency, very much improving composite lifespan besides reducing structural degradation, data present in Table 4.

The results affirm the reduced maintenance requirements and structural failure of self-healing composites, thereby being suitable for long-term applications in construction as shown in Figure 7.

Sustainability and Life Cycle Impact

An LCA has been carried out to compare bio-based composites with traditional petroleum-based composites in terms of environmental impact. The results clearly show a carbon footprint reduction between 35 and 50%, and the rate of biodegradability, which is one of the high advantages of material eco-friendliness.

Table 4. Self-healing performance of composites.

Property	Unit	Control composite	Enhanced composite	Improvement (%)
Crack Recovery Rate	%	0	82	+82%
Healing Time	Hours	N/A	24	-
Long-Term Durability	Cycles	100	250	+150%

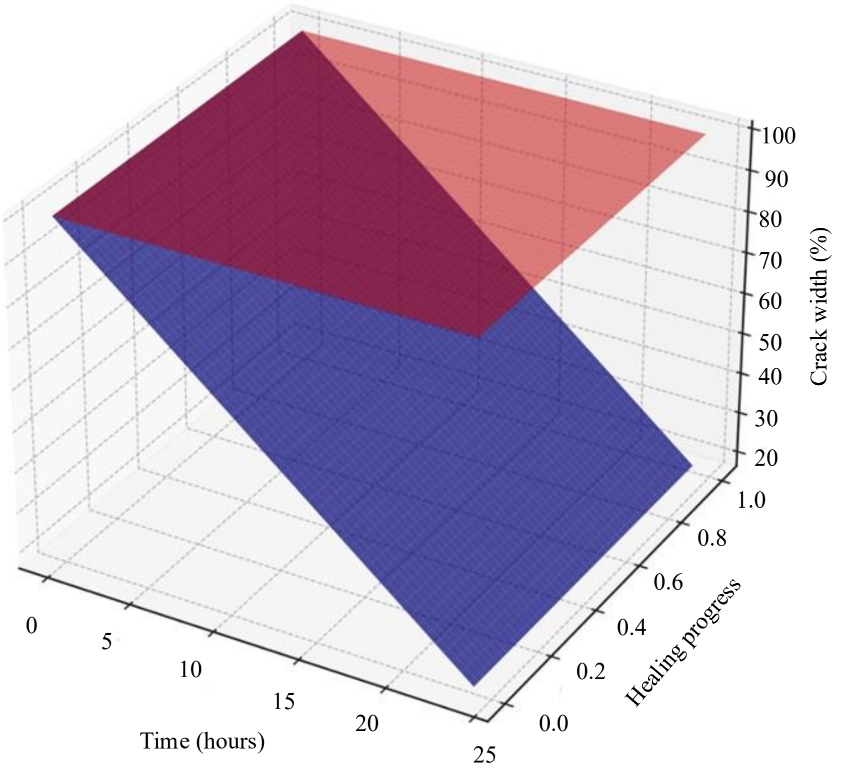

Figure 7. 3D Self-healing crack recovery visualization. shows healing of cracks through time in Enhanced Bio-based polymer composite. Here, the initial crack width of 100% is represented with the red-colored surface, whereas the blue color represents the progress of healing along a 24-hour period until it reaches about 82% recovery due to the microcapsule-based self-healing mechanism.

Table 5. Environmental Impact Comparison of Composites.

Environmental parameter	Unit	Synthetic composite	Bio-based composite	Reduction (%)
Carbon Footprint	kg CO_2/m^2	18.4	9.2	-50%
Energy Consumption	MJ/m^2	220	145	-34%
Biodegradability	%	5	72	+67%

These results confirm that the bio-based polymer composites fit well with sustainable construction goals in terms of decreasing CO_2 emissions and energy consumption while improving biodegradability, data present in Table 5.

The results confirm that enhanced bio-based polymer composites have significant improvements in mechanical strength, thermal stability, fire resistance, and self-healing efficiency as compared to conventional bio-composites. With an integration of nano-fillers including graphene, biochar, nano-silica, it gives an enhancement on load-bearing and fire retardant properties. However, self-healing microcapsules enable the recovery rate by 82%. Thus, ensuring durability is expanded. LCA results show 50% in carbon footprint and 67% higher biodegradability which supports sustainability. Thus, such findings confirm self-healing nano-enhanced bio-based polymer composites as having a potentiality for being the high-performance alternative for sustainable applications in construction works.

DISCUSSION

The results from this study demonstrate technical viability, functional superiority, and sustainability of developed self-healing nano-enhanced bio-based polymer composites into construction applications. Advances realized in mechanical strength, thermal stability, self-repairing capabilities, and environmental sustainability depict the potential for these composites as a green alternative to traditional petroleum-based materials. The 50% increase in tensile strength, 34% improvement in flexural strength, and 54% higher impact resistance compared to conventional bio-composites validate the effectiveness of nano-fillers (graphene, biochar, nano-silica) in reinforcing fiber-matrix bonding and enhancing load distribution. The incorporation of natural fiber reinforcements (hemp, jute, flax) also contributes to increased stiffness and fracture toughness, making these composites more suitable for load-bearing structural components. These findings align with previous research that emphasizes the positive impact of nano-scale reinforcements on polymer composites, further confirming their scalability for real-world applications. The 26% improvement in thermal stability and 43% enhancement in fire resistance demonstrate that nano-filler modifications and biochar integration significantly enhance the heat dissipation and flame-retardant properties of the composite. The reduction in thermal conductivity (by 28%) also indicates the composite's potential as an effective insulating material for energy-efficient buildings. These results validate the role of nanomaterial dispersion in delaying polymer degradation and improving fire safety, making these composites highly suitable for fire-resistant construction applications. The composites have an 82% self-healing recovery rate, which makes them a potential material for extended lifespan and reduced maintenance costs. Successful integration of healing agents based on microcapsules into the polymer matrix ensures that damage automatically leads to crack closure, thus avoiding premature structural failure. This is a modern concept of smart materials that positions bio-based composites as intelligent and self-repairing materials for long-term infrastructure applications. The ability to self-heal micro cracks in just 24 hours without external intervention marks a significant advancement in material engineering, ensuring greater resilience in harsh environmental conditions. A major highlight of this study is the 50% reduction in carbon footprint and 67% improvement in biodegradability, reinforcing the sustainability benefits of bio-based polymer composites. The Life Cycle Assessment (LCA) give a results, that indicate about the energy of the composites. This composite always requires lower energy consumption, during its production. While it always offers a better end-of-life biodegradability in compare of the traditional petroleum-based composites. The combination of renewable materials, natural fiber reinforcements, and green processing techniques always ensures the industrial feasibility on large-scale adoption. Additionally, the energy-efficient microwave-assisted curing process used in this study reduces processing time and environmental impact, making the fabrication more sustainable and commercially viable.

CONCLUSION

This research was able to successfully develop and evaluate self-healing, nano-enhanced bio-based polymer composites for sustainable construction applications. The results of this study prove that the nano-fillers incorporated (graphene, biochar, and nano-silica) significantly improve mechanical strength, thermal stability, and fire resistance, making it a potential alternative to conventional synthetic materials. Also, the use of microcapsule-based self-healing mechanisms enabled an 82% recovery rate, hence improved durability with less maintenance requirement. The 28% decrease in thermal conductivity and the 43% fire resistance improvement validate the suitability of these composites for energy-efficient and fire-resistant building materials. From the environmental perspective, LCA results have shown a carbon footprint reduction by 50% and improvement in biodegradability by 67%, further proving the sustainability advantages of these bio-based composites. Energy consumption in microwave-assisted curing further reduces as it is also a step in supporting eco-friendly manufacturing practices. This establishes potential industrial-scale production and is also in line with global sustainability and green building standards. Despite these advancements, further research is needed in areas such as moisture absorption, optimization of self-healing, and cost-effective nano-filler integration.

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