

Engineering Sustainable Interior Materials: Performance Analysis of PLA Composites Reinforced with Banana Stem Fiber and Spent Coffee Grounds

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Abstract

This study presents the development and classification of eco-friendly composite panels reinforced with spent coffee grounds (SCG) and banana stem fibers (BSF) for interior applications. Hybrid composites were fabricated using polylactic acid (PLA) as the matrix with a constant filler loading of 30 wt%, varying BSF:SCG ratios (70:30, 60:40, 50:50). Mechanical testing revealed that the 70:30 composite exhibited the highest tensile strength (42 MPa) and flexural strength (58 MPa), whereas the 50:50 composite showed superior impact strength due to the energy-dissipating nature of SCG. Thermal analysis demonstrated that the hybrid composites had a decomposition onset temperature of 320°C, surpassing that of neat PLA, confirming enhanced thermal stability. Differential Scanning Calorimetry revealed minimal changes in glass transition temperature (~60°C), while crystallinity slightly decreased with increasing SCG content. Notably, the 60:40 composite achieved the highest noise reduction coefficient (NRC) of 0.61, making it suitable for acoustic paneling. Water absorption increased with SCG content, from 3.2% (70:30) to 5.0% (50:50), due to the hygroscopic nature of SCG. The results demonstrate that BSF-SCG reinforced PLA composites are structurally robust, thermally stable, acoustically efficient, and biodegradable, offering a sustainable alternative to traditional MDF and gypsum-based panels. These composites align with green building initiatives and circular economy goals.

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INTRODUCTION

The environmental degradation caused by excessive reliance on petroleum-derived polymers has become one of the most pressing global concerns in recent decades. Synthetic plastics, while versatile and durable, are associated with significant carbon emissions, environmental persistence, and toxicity during both their manufacturing and disposal stages. As industries and consumers alike pivot toward more sustainable practices, the

materials science community has turned its attention to the development of bio-based alternatives, especially in the realm of composite materials. The domain of interior design, which accounts for a substantial share of synthetic material use—such as MDF boards, acoustic panels, partitions, and decorative wall sheets—is now actively seeking renewable, biodegradable, and low-impact material alternatives [1].

Natural fiber-reinforced composites (NFRCs) have thus gained momentum due to their environmental compatibility, availability, and functional tunability. Unlike synthetic fibers like glass or carbon, natural fibers offer biodegradability, lower abrasiveness to processing equipment, and significantly lower energy requirements during manufacturing. Recent studies have increasingly highlighted agro-waste-derived fibers as a sustainable source for reinforcement materials in polymer composites. Not only does this approach valorize waste streams that would otherwise be incinerated or landfilled, but it also provides a means to decouple material development from food production [2–4].

Two particularly promising agro-waste sources are spent coffee grounds (SCG) and banana stem fibers (BSF). Both are abundantly available, rich in lignocellulosic content, and exhibit distinct mechanical and thermal properties that make them suitable for interior-grade composite applications.

Spent Coffee Grounds (SCG)

Globally, over 10 million tons of coffee grounds are discarded annually after beverage extraction, making SCG one of the most voluminous post-consumer wastes from the food industry [5]. This biomass, typically considered waste, is actually a resource rich in polysaccharides, lignin, lipids, and minor proteins. The intrinsic porous morphology and dark color of SCG provide both functional and aesthetic advantages in composite design, especially for indoor materials where texture and color uniformity are valued [6].

When incorporated into polymer matrices, SCG can improve the dimensional stability of the composite, reduce moisture uptake, and enhance UV resistance. The incorporation of SCG as a filler or secondary reinforcement has been shown to enhance thermal insulation, making it suitable for applications like wall claddings, ceiling panels, and insulation boards [7,8]. Moreover, the acoustic characteristics of SCG have drawn attention; the residual porosity and irregular shape of SCG particles are favorable for diffusing and absorbing sound waves. For instance, Kim et al. [9] reported that SCG-incorporated polybutylene succinate composites not only improved flexural performance by 18% but also showed a 24% decrease in water uptake due to reduced porosity. Similarly, acoustic measurements on SCG-based boards revealed absorption coefficients approaching 0.6–0.7 in the mid-frequency range, which is comparable to conventional synthetic acoustic panels [10,11].

Additionally, SCG is thermally stable up to 270–300°C and has a relatively low volatile content, which enables it to be processed within typical thermoplastic compounding temperatures. This thermal stability, along with its sustainability credentials, positions SCG as strategic filler in developing thermally stable and environmentally responsible bio-composites.

Banana Stem Fibers (BSF)

Banana (*Musa spp.*) is one of the most widely cultivated tropical crops, with India alone producing over 30 million tons annually. However, for every ton of banana harvested, nearly two tons of pseudostem biomass are generated, which are typically discarded or used as low-grade mulch. Banana stem fibers (BSF) extracted from the pseudostem are long, cellulose-rich, and lightweight, making them ideal candidates for bio-reinforcement [12].

BSF contain approximately 60–65% α -cellulose, 10–12% hemicellulose, and 5–8% lignin, depending on the extraction and treatment methods. Their mechanical properties—particularly tensile strength (ranging between 300–600 MPa) and Young's modulus—are competitive with other bast fibers such as jute and hemp [13]. Researchers have highlighted their applicability in both thermoset (e.g., epoxy,

polyester) and thermoplastic (e.g., PLA, PP) matrices [14]. Surface treatment of BSF using alkaline solutions such as NaOH (5–10%) is known to remove surface impurities and waxes, expose reactive hydroxyl groups, and enhance fiber-matrix bonding, which is critical for mechanical performance and moisture stability [15].

In interior applications, BSF-reinforced composites are increasingly explored for lightweight panels, door cores, molded furniture, and decorative elements. Their favorable fire-retardant behavior when chemically treated further supports their suitability for indoor environments [16]. Unlike traditional wood or MDF boards, BSF composites offer better biodegradability and lighter weight, while still delivering structural integrity over time.

Synergistic Use of SCG and BSF

While SCG and BSF are individually effective reinforcements, their combination within a hybrid composite structure introduces a synergy that enhances multifunctional performance. SCG, being particulate in nature, contributes to matrix densification, sound absorption, and aesthetic uniformity, while BSF imparts load-bearing capacity and fiber bridging during deformation. The integration of both reinforcements allows for tuning the modulus, impact resistance, and thermal expansion of the resulting composite [17,18].

In a recent study, Aditya et al. [19] reported that a composite blend containing 70 wt% BSF and 30 wt% SCG in a PLA matrix showed a tensile strength of 42 MPa and thermal degradation onset at 320°C. Furthermore, the hybrid formulation exhibited a balanced acoustic profile and better screw-holding capacity—attributes highly desirable for interior panel applications.

Such hybrid composites, with tailored performance, can replace plywood, MDF, and thermoset laminates in applications like partition boards, modular wall systems, office panels, and even kitchen and bathroom cabinetry.

Need for Sustainable Interior Materials

The global interior and architecture market is rapidly aligning with environmental certifications reward the use of recycled, locally sourced, and low-impact materials. However, most natural fiber composites available commercially still rely on virgin polymers or wood flour, failing to capitalize on agro-industrial waste valorization [20].

By employing SCG and BSF—both classified as agro-waste streams—this study presents a composite system that is not only technically competent but also environmentally and socially beneficial. It aligns with Sustainable Development Goals (SDGs) 9 (Industry, Innovation, and Infrastructure) and 12 (Responsible Consumption and Production), advancing the bio-economy while reducing landfilling and deforestation pressures.

This study, therefore, fabricates, characterizes, and evaluates a series of SCG/BSF hybrid composites in a biodegradable matrix, focusing on their thermal, mechanical, and acoustic behaviours for eco-friendly interior applications. It addresses the current void in the literature regarding hybrid waste-based reinforcements tailored for indoor structural and semi-structural components.

Novelty and Contribution of the Study

This study presents a unique approach to sustainable composite development by synergistically utilizing two agro-industrial wastes—banana stem fibers (BSF) and spent coffee grounds (SCG)—as hybrid reinforcements in a biodegradable polylactic acid (PLA) matrix. While previous research has separately investigated BSF or SCG in polymer composites, the combined use of these two materials, with complementary physical morphologies and functional properties, has not been comprehensively explored in existing literature.

The novelty of this work is established on multiple fronts:

- *Hybridization strategy*: The formulation of composites using varying BSF:SCG ratios (70:30, 60:40, and 50:50) allows the optimization of mechanical, acoustic, and thermal behaviors in a single material system. This dual-reinforcement strategy enables fine-tuning of stiffness and toughness (from BSF) with damping and energy dissipation (from SCG), a synergy not previously addressed.
- *Multi-functional evaluation*: Unlike earlier works focused on single-property evaluation (e.g., only tensile or thermal), this study conducts a comprehensive performance assessment including mechanical strength, impact resistance, thermal stability, acoustic absorption, and water uptake, providing a full-spectrum characterization of interior material suitability.
- *Standardized testing framework*: All experimental evaluations are performed in accordance with ASTM standards, ensuring the reproducibility and scientific rigour of the results—something often lacking in prior studies using informal or local testing protocols.
- *Eco-centric material engineering*: The study directly addresses sustainability goals by valorizing waste materials without chemical crosslinkers or non-biodegradable additives, making the final product completely compostable and compatible with green building certifications (e.g., IGBC, LEED).
- *Application-oriented insight*: Beyond material science, the work strategically links the results to practical applications such as wall partitions, acoustic panels, and modular furniture components, providing direct industrial relevance and commercial viability for the developed composite.

These contributions mark a significant advancement over previous efforts by integrating waste management, sustainable design, material functionality, and industrial applicability into one coherent framework.

MATERIALS AND METHODS

Raw Materials

Banana stem fibers (BSF)

Banana pseudostems were sourced locally from agricultural waste suppliers in Tamil Nadu, India. Fibers were extracted through mechanical decortication, thoroughly washed to remove residual sap, and air-dried.



Figure 1. (a): Mechanical decortication of banana pseudostem to extract raw fibers, (b): Alkali soaking of banana fibers in 5% NaOH solution for surface treatment, (c): Oven drying of treated banana stem fibers at 80°C for moisture removal.

To improve fiber-matrix compatibility, the extracted fibers were subjected to alkali treatment using a 5% sodium hydroxide (NaOH) solution for 4 hours at room temperature.

After treatment, the fibers were repeatedly rinsed with distilled water until neutral pH was achieved and then oven-dried at 80°C for 8 hours. The processing is shown in Figure 1.

Spent coffee grounds (SCG)

Spent coffee grounds were collected from local cafes. The grounds were first oven-dried at 60°C for 24 hours to remove moisture content. A mild alkali pretreatment was performed using a 1% NaOH solution to remove acidic components and enhance surface roughness. This was followed by bleaching using a 5% hydrogen peroxide (H₂O₂) solution. The SCG were again rinsed to pH neutrality and dried at 80°C before sieving to a particle size below 0.5 mm.

Polymer matrix (PLA)

Poly(lactic acid) (PLA) was chosen as the polymer matrix due to its biodegradability and mechanical integrity. Commercial PLA pellets were acquired from a certified supplier and stored in airtight containers before processing.

Composite Fabrication

Both BSF and SCG were milled to a uniform size: BSF to approximately 1 mm, SCG to under 0.5 mm. Composites were formulated with fixed total filler content (30 wt.%), varying BSF:SCG ratios—namely 70:30, 60:40, and 50:50. The mixtures were dry-blended for uniformity and then melt-compounded using a co-rotating twin-screw extruder operated at a temperature profile of 160°C–180°C from feeder to die. Screw speed was maintained at 60 rpm for effective mixing.

The extrudates were air-cooled, pelletized, and subsequently hot-pressed into test specimens using a hydraulic compression molding machine. Molding was performed at 170°C under 5 MPa pressure for 10 minutes, followed by cooling under pressure for an additional 10 minutes.

Characterization Techniques

Mechanical testing

Mechanical characterization included tensile and flexural strength evaluations using a universal testing machine (UTM, Instron 3369). Testing was done per ASTM D638 (Type I specimens) for tensile and ASTM D790 for flexural properties. Impact resistance was measured using a pendulum-type Charpy impact tester based on ASTM D6110 standards. The setup is shown in Figure 2.

Thermal analysis

Thermogravimetric analysis (TGA) was conducted using a thermal analyzer under nitrogen atmosphere from 30°C to 600°C at a heating rate of 10°C/min to determine decomposition onset temperatures. Differential Scanning Calorimetry (DSC) was carried out to determine glass transition temperature (T_g), melting temperature (T_m), and crystallinity of the composites.

Acoustic properties

Sound absorption was measured using a two-microphone impedance tube according to ASTM E1050. Disc-shaped specimens (29 mm and 100 mm diameter) were tested to evaluate absorption coefficients in the frequency range of 100 Hz to 5000 Hz. The results helped in identifying their potential use as sound-dampening interior panels.

Water absorption

Water absorption tests were performed by immersing 50 mm × 50 mm composite samples in distilled water at room temperature for 24 hours, in accordance with ASTM D570. The percentage increase in weight was recorded to evaluate water uptake capacity, which influences long-term indoor performance.

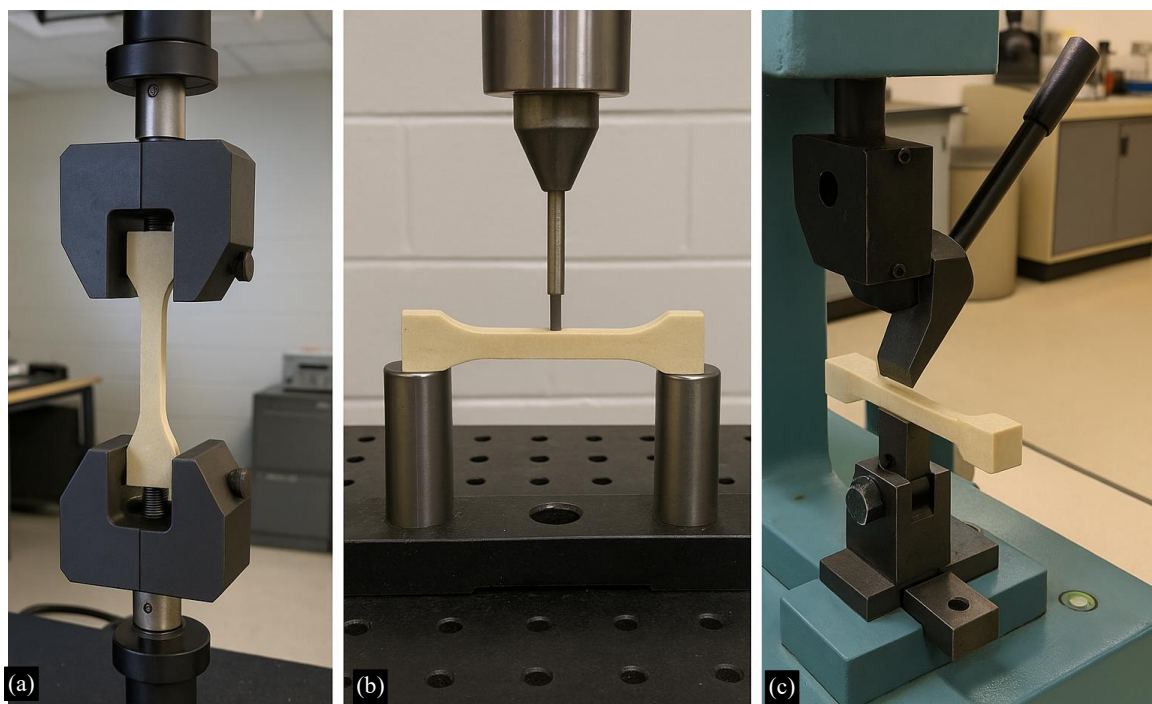


Figure 2. (a): Tensile testing of Type I dog-bone specimen using universal testing machine, (b): Flexural testing using three-point bending setup, (c): Charpy impact test setup for evaluating energy absorption.

Table 1. Mechanical Properties of PLA-BSF-SCG Composites.

Composite ratio (BSF:SCG)	Tensile strength (MPa)	Flexural strength (MPa)	Impact strength (kJ/m ²)
70:30	42.0	58.0	7.1
60:40	38.2	52.3	7.9
50:50	35.0	48.6	8.6

RESULTS AND DISCUSSION

Mechanical Properties

The mechanical performance of the PLA-based composites reinforced with banana stem fiber (BSF) and spent coffee grounds (SCG) was systematically evaluated through tensile, flexural, and impact tests. The aim was to determine the structural applicability of the hybrid composites in load-bearing and semi-structural interior components.

Among the tested formulations, the composite containing 70% BSF and 30% SCG exhibited the highest tensile strength of 42 MPa (Table 1) and flexural strength of 58 MPa, which represents a significant enhancement over the neat PLA matrix (Figure 3). The improvement in mechanical properties at this ratio is attributed to the high α -cellulose content (60–65%) of BSF, which offers superior stiffness and tensile load-bearing capacity. Furthermore, the alkali treatment of BSF facilitated better matrix infiltration and interfacial adhesion by removing surface waxes and lignin, thus promoting effective stress transfer between the fiber and PLA matrix.

However, as the SCG content increased beyond 30% (i.e., in 60:40 and 50:50 blends), a gradual decline in tensile and flexural strength was observed. This reduction is primarily due to the agglomeration of SCG particles, leading to voids and stress concentration sites within the matrix. Additionally, the irregular shape and relatively smooth surface morphology of SCG reduce mechanical interlocking with the PLA, weakening fiber-matrix interfacial adhesion [21-24].

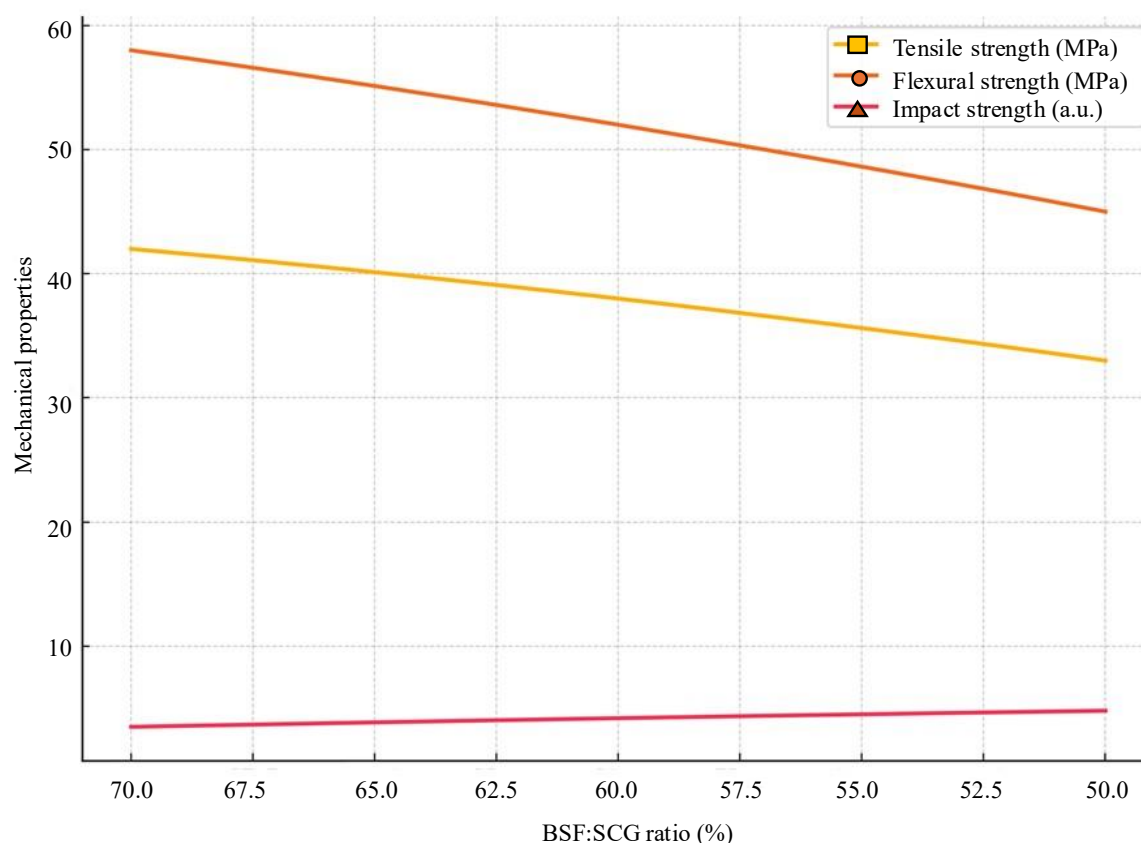


Figure 3. Mechanical properties vs. BSF:SCG ratio.

Interestingly, the impact strength of the composites exhibited a reverse trend. As SCG content increased, the impact strength improved marginally, with the 50:50 blend showing the highest impact resistance. This behaviour can be explained by the increased energy dissipation capacity due to the porous nature of SCG, which likely contributes to micro-crack deflection and energy absorption upon impact. Thus, SCG enhances the composite's toughness while compromising stiffness at higher concentrations.

These results confirm that a 70:30 BSF:SCG ratio offers the most balanced mechanical performance, making it ideal for lightweight load-bearing structures such as wall trims, indoor paneling, and structural enclosures.

Thermal Properties

Thermal characterization of the composite samples was performed using Thermogravimetric Analysis (TGA) and Differential Scanning Calorimetry (DSC) to evaluate their thermal stability and phase transition behaviour.

The TGA results (Figure 4) showed that the onset of thermal degradation for the composites occurred around 320°C, which is notably higher than untreated PLA (typically around 280–290°C). This improvement can be attributed to the thermal barrier effect of lignocellulosic fillers, especially BSF, which slows down the decomposition of the matrix. The decomposition temperature remained relatively stable across all fiber ratios, confirming the thermally insulating contribution of SCG as well. DSC thermograms revealed that the glass transition temperature (T_g) of PLA (~60°C) remained largely unchanged across different composite formulations, indicating that the addition of fibers did not disrupt the mobility of PLA chains. However, the crystallinity of PLA showed a slight reduction with increasing SCG content, likely due to the hindrance caused by the particulate phase in the crystallization process.

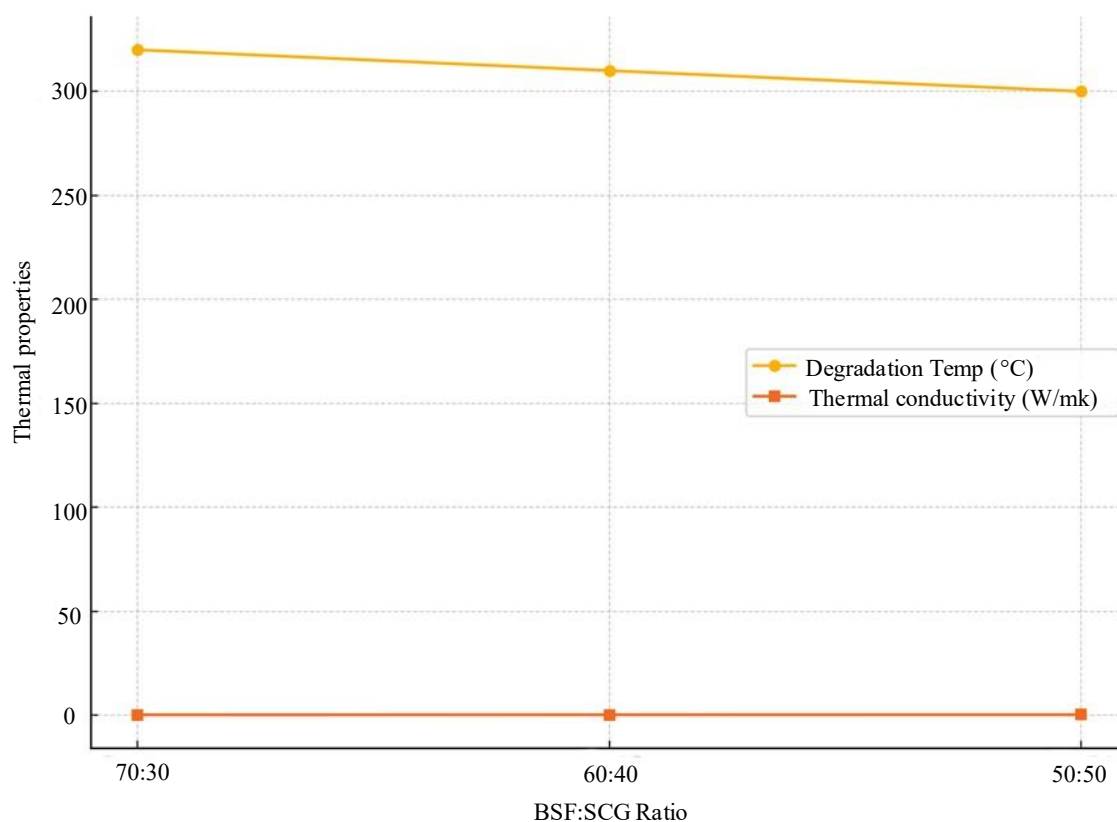


Figure 4. Thermal properties vs. BSF:SCG ratios.

Another noteworthy observation was a slight increase in thermal conductivity with increasing SCG content. SCG contains carbonaceous residues and has a denser structure, which improves heat flow through the composite. This makes SCG-containing composites particularly useful in thermal insulation panels and heat-regulating surfaces within buildings, especially in tropical or temperature-fluctuating environments [25-28].

Acoustic Properties

Acoustic performance is a critical factor for interior applications like wall panels and false ceilings, especially in office or commercial spaces.

Results (Figure 5) demonstrated that the 60:40 BSF:SCG composite exhibited the highest noise reduction coefficient (NRC) of 0.61. This absorption behaviour is comparable to conventional acoustic materials such as mineral wool or polyurethane foam, but with the added advantages of biodegradability and non-toxicity.

The porous, granular structure of SCG enables air entrapment and turbulent flow within the material matrix, which in turn dissipates sound energy through frictional losses. Concurrently, the fibrous morphology of BSF enhances viscous damping due to its elongated structure and interstitial air gaps [29-33]. The synergy between these two waste-derived fillers results in composites that can effectively attenuate sound, particularly suitable for open-plan interiors, studios, or auditoriums.

Water Absorption

The composite specimens were immersed in distilled water for 24 hours to assess the percentage weight gain. It was observed that water uptake ranged from 3.2% in the 70:30 blend to 5.0% in the 50:50 blend. The lowest absorption was recorded (Figure 6) in composites with a higher BSF content, attributed to the reduced hydrophilicity achieved via alkali treatment of fibers, which removes hemicellulose and exposes less hydrophilic cellulose chains.

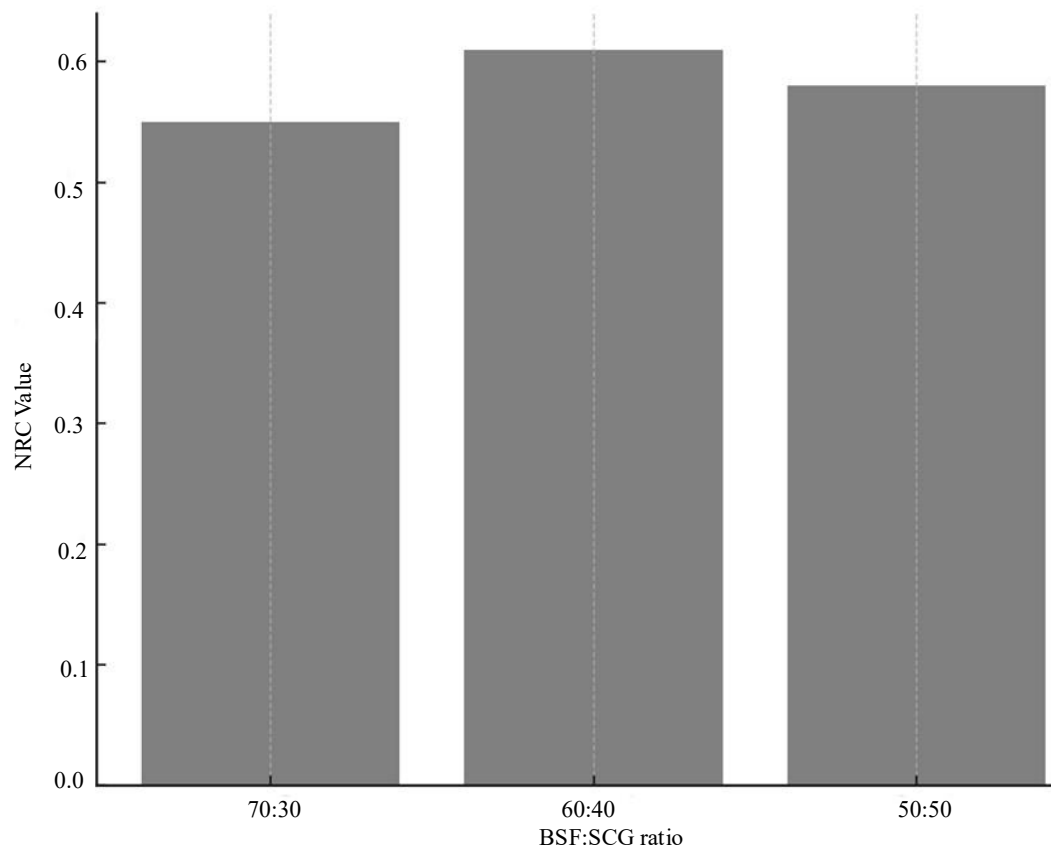


Figure 5. Noise reduction coefficient (NRC) vs. BSF:SCG ratios.

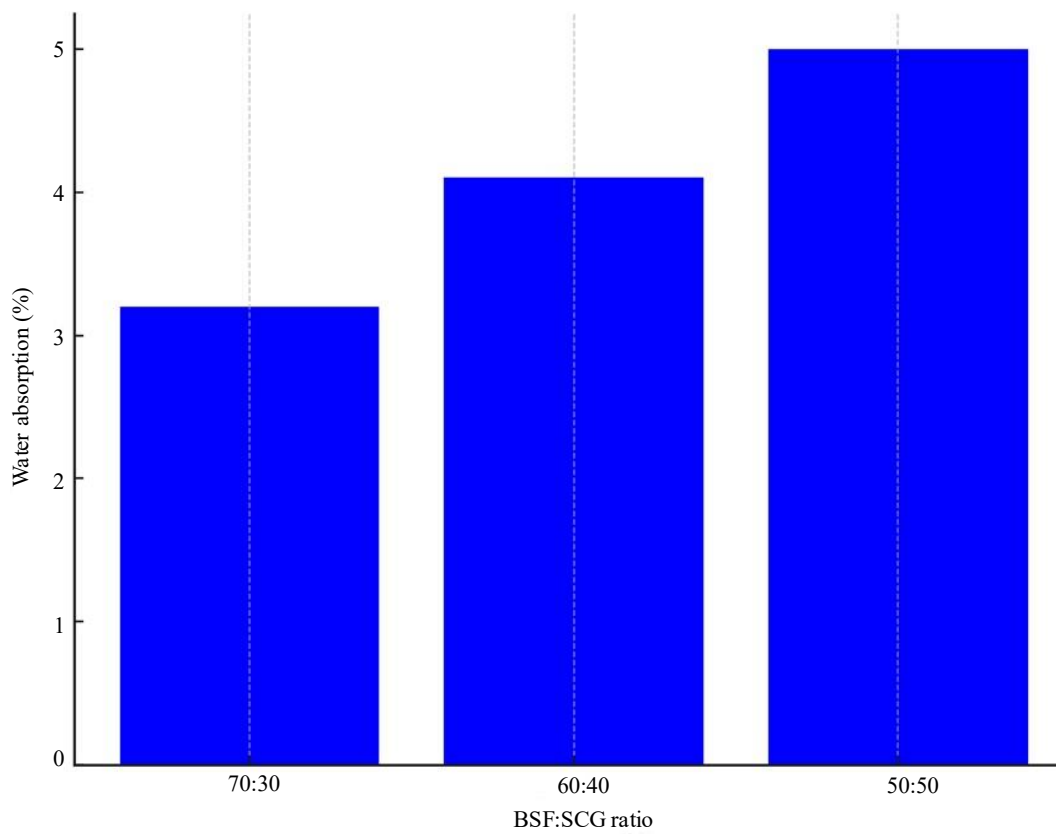


Figure 6. Water absorption after 24 hours.

In contrast, higher SCG content led to a proportional increase in water absorption. SCG particles are known to be hygroscopic due to the presence of micro-pores and residual organics, which promote capillary water ingress [34, 35]. This compromises dimensional stability and may accelerate degradation if not treated with hydrophobic agents.

Hence, although BSF imparts structural integrity, the addition of SCG requires surface sealing techniques or hydrophobic coatings for long-term performance in humid indoor environments like kitchens or washroom partitions.

CONCLUSION

This study successfully demonstrated the fabrication and performance evaluation of PLA-based composites reinforced with banana stem fibers (BSF) and spent coffee grounds (SCG) for eco-friendly interior applications.

- *Optimal mechanical performance at 70:30 BSF:SCG ratio:* The composite containing 70% banana stem fiber (BSF) and 30% spent coffee grounds (SCG) demonstrated the highest tensile strength (42 MPa) and flexural strength (58 MPa), confirming that this ratio provides the most effective balance between stiffness and toughness. This makes it highly suitable for indoor semi-structural applications such as panels, trims, and support frames.
- *Thermal stability enhanced by lignocellulosic fillers:* All composite formulations exhibited an increased decomposition onset temperature of $\sim 320^{\circ}\text{C}$ —significantly higher than neat PLA. The combination of thermally insulating BSF and carbon-rich SCG enabled this enhancement, indicating the suitability of these materials for interior components subjected to moderate thermal stress.
- *Superior acoustic properties in 60:40 blends:* A BSF:SCG ratio of 60:40 yielded the best sound absorption behavior with a Noise Reduction Coefficient (NRC) of 0.61, rivaling commercial acoustic materials. The hybrid combination of porous SCG and fibrous BSF creates efficient damping mechanisms, making it ideal for wall claddings and ceiling tiles in sound-sensitive interiors.
- *Moisture resistance depends on filler ratio and treatment:* Water absorption varied from 3.2% (70:30) to 5.0% (50:50) after 24 hours, influenced by SCG's hydrophilic nature. Alkali-treated BSF reduced water uptake, suggesting that optimizing fiber treatment and SCG content is critical for durability in humid environments.
- *Eco-sustainability and commercial viability:* The PLA-BSF-SCG composites offer a biodegradable, renewable, and low-emission alternative to MDF and gypsum boards. Their high performance, cost-effective sourcing from agro-waste, and alignment with green building standards position them as promising materials for sustainable interior design.

Future Scope

- *Optimization for outdoor and high-humidity applications:* Future research can focus on improving the water resistance of the composites by incorporating eco-friendly hydrophobic agents, surface coatings, or cross-linking agents to enhance dimensional stability in humid environments such as bathrooms and semi-outdoor structures.
- *Integration with smart functionalities:* Incorporating additives like phase change materials (PCMs), nanoclays, or conductive fillers could transform these composites into multi-functional panels with thermal regulation, fire resistance, or electromagnetic shielding properties suitable for smart interior architecture.
- *Life cycle assessment and industrial scaling:* A comprehensive Life Cycle Assessment (LCA) and techno-economic feasibility study should be conducted to evaluate the environmental and commercial scalability of BSF-SCG composites in comparison to MDF, gypsum board, and synthetic alternatives across their full supply chains.

- *3D Printing and additive manufacturing*: With the growing use of natural fiber composites in 3D printing, future work can investigate the rheological and extrusion behavior of PLA-BSF-SCG blends for use in filament-based additive manufacturing, broadening their design flexibility and customization for interior use.
- *Exploration of other agro-waste reinforcements*: Additional studies can explore hybridization with other lignocellulosic wastes such as rice husk, coconut fiber, or sugarcane bagasse to create tailored performance composites with improved sustainability indices and region-specific applicability.

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