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Sustainable Building Composites from Agricultural and Textile Waste in PBAT/PLA Matrices

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Abstract The increasing ecological footprint of conventional building materials necessitates the exploration of sustainable alternatives. This research addresses the problem by examining the feasibility of using agricultural (rice husk, wheat husk, wood fibers) and textile waste fibers in biodegradable poly(butylene adipate-co-terephthalate)/poly(lactic acid) (PBAT/PLA) composites manufactured through hot pressing. The aim is to create environmentally friendly materials with appropriate structural and thermal characteristics for building construction. The system leverages the waste streams and a biodegradable binder to create composites, with compressive strengths of 11-40 MPa and flexural strengths of 0.80-2.25 MPa. Rice husk composites are particularly noted for good insulation properties (density: 378 kg/m^3, thermal conductivity: 0.08 W/mK) and water resistance (42% water absorption). Benefits include waste minimization, reduced environmental footprint compared to conventional materials, and possible energy-saving applications in building construction.

Keywords:-Sustainable composites, agricultural waste, textile waste, biodegradable polymers, thermal insulation, structural materials, circular economy.

I. INTRODUCTION

The building sector is one of the largest sources of global environmental problems, consuming huge quantities of natural resources and producing enormous quantities of waste. The production processes of the extraction, processing, and transport of conventional building materials like concrete, steel, and factory-made insulation are some of the largest sources of greenhouse gas emissions and resource loads. This environmental burden, together with the increasing waste produced by industrial and agricultural processes, compels one to look for and develop [1] sustainable and resource-conserving alternatives. To this end, the use of waste materials, especially from agriculture and textiles, is a suitable choice for the production of green building materials with similar or even superior performance properties.

The concept to integrate waste streams into construction materials is in accordance with the ideals of a circular economy, which views waste as an asset rather than an unwanted byproduct. By-products of agricultural processes, like rice husk and wheat husk, are produced [2] in huge amounts around the world and tend to be disposal challenges. Likewise, textile waste, due to manufacturing processes and excess clothing, constitutes a large underutilized resource. Such types of materials, typically high in cellulose and other natural fibers, have inherent properties that can be utilized to make light, insulating, and potentially structurally sound composites.

Identifying this potential, researchers and industries are giving more and more attention to the creation of new methodologies to convert these waste materials into valuable building components. Among [3] the most promising methods is the combination of these fibers with bio-based polymers to produce biodegradable composites. Bio-based polymers, being sourced from renewable sources, have a lower carbon footprint than conventional petroleum-based polymers. Surprisingly, poly(butylene adipate-co-terephthalate) (PBAT) and poly(lactic acid) (PLA) are receiving more attention as they are biodegradable, easy to process, and have the potential for blending to achieve the desired properties of the final material.

This study investigates the feasibility of rice husk, wheat husk, wood fibers (as a lignocellulosic control), and waste textile fibers as reinforcement in a PBAT/PLA blend composite matrix for building [4] construction. Utilizing the PBAT/PLA blend is to leverage the processability and ductility of PBAT and the increased stiffness and bio-origin of PLA. Hot pressing, a standard technique extensively used in the production of composite materials, is utilized to fabricate the composites. Extensive investigation of the morphological, thermal, and mechanical properties is conducted to determine the feasibility of these bio-based composites for structural and insulation uses in the building sector.

Morphological examination yields information concerning the interfacial adhesion between the fibers and the polymer matrix, one of the major parameters that determines the mechanical properties of the composite. Good adhesion leads to efficient stress transfer and results in better mechanical properties. Thermal [5] stability is another key parameter for construction materials, which should be able to withstand diverse temperature conditions without undergoing any noticeable degradation. Thermal degradation properties are thus analyzed through thermogravimetric analysis (TGA).

The mechanical properties, such as compressive and flexural strength, are of prime importance for structural applications. Compressive strength is a measure of a material's capacity to resist axial loads, whereas flexural strength is its capacity to resist bending loads [6] . These are tested using standardized mechanical testing protocols to assess the load-carrying capacity of the developed composites. Additionally, in the case of insulation applications, density and thermal conductivity are the key performance parameters. Low density enables lightweight construction, whereas low thermal conductivity indicates better insulation efficiency, thus lowering energy consumption for building heating and cooling. The water absorption behavior is also tested to ascertain the durability and long-term performance of the materials under wet or humid conditions.

Building on the potential unlocked by previous research, innovative products like Eco Shield Rice Husk Insulation are being engineered. This particular project is geared towards adding value to rice husk, [7] one of the most significant agricultural waste products, by converting it into a high-performance insulation material. Recycling the waste product into a valuable product, Eco Shield actually addresses the problem of disposal while, at the same time, offering a more environmentally friendly alternative to energy-consuming conventional insulation products like polystyrene and fiberglass. Rice husk insulation production is specially designed to minimize environmental footprints through reduced energy consumption and less greenhouse gas emission, thus contributing to a greener building landscape. In addition, the integration of sophisticated computational tools, such as genetic algorithms in a Design Support Module, is a futuristic strategy for maximizing the performance of such green building materials. Genetic algorithms allow the systematic evaluation of a variety of material combinations and structural layouts to determine the most efficient designs for maximum thermal performance and structural strength. Such computation-aided optimization maximizes overall efficiency and cost-effectiveness of green solutions such as the Eco Shield insulation system, with application for wider use in the construction sector and a greener built environment in Chennai, Tamil Nadu, India, and other regions of the world..

This work is organized with review of the literature survey as Section II. Methodology described in Section III, highlighting its functionality. Section IV discusses the results and discussions. Lastly, Section V concludes with the main suggestions and findings.

II. LITEARTURE SURVEYLITEARTURE SURVEY

Composites derived from agricultural wastes are gaining wider acceptance as environment-friendly materials for construction. Experiments have shown that the use of natural fibers in polymer matrices enhances mechanical properties while reducing at the same time the environmental impact. Agricultural waste such as bagasse, banana fibers, and coconut coir have been found to be compatible with biodegradable binders. The composites are found to possess suitable strength, thermal insulation, and moisture resistance and can be applied to interior construction. Their use also assists in reducing waste and following the concept of circular economy. Studies highlight the importance of fiber treatment and particle size to regulate composite performance, and the need for improving standardization of material processing.

The construction industry has also focused on reducing its carbon footprint by using sustainable material alternatives. Research has investigated combinations of natural fibers and crop residues with biodegradable polymers [7] to create light and thermally efficient construction materials. These materials are found to have acceptable strength in non-loaded uses with low thermal conductivity. The moisture performance is found to be improved by surface treatments on the fibers. Environmental life cycle analysis shows significant greenhouse gas emission savings compared to conventional materials. The composites also contribute to local economies by using readily available bio-wastes and rural development opportunities through decentralized production systems.

Agricultural waste-based products offer an environmentally friendly solution to thermal and sound insulation in green buildings. Various researches have established the insulation [8] properties of commonly available and affordable materials like hemp, jute, and straw. Their open cell structure helps achieve low thermal conductivity and high sound absorption efficiency. While being a major flaw, the effectiveness of these products can be promoted through the application of hydrophobic treatments. Further, bio-insulation materials show encouraging findings in life cycle assessments. Owing to growing demands for eco-friendly building products, these composite materials are taking center stage as promising alternatives for synthetic insulators in residential and commercial streams.

Natural fiber-reinforced composites have become viable alternatives to man-made products in civil infrastructure applications. Agricultural byproducts like palm fibers, maize stalks, and flax have been studied [9] to reinforce polymer matrices. They are biodegradable, renewable, and tend to possess impressive tensile and flexural properties. Studies have shown them to be well-suited for partition board production, ceiling tile, and decorative panel manufacturing. Fire retardation and water absorption are still being examined, usually being targeted by adding additives. Overall, these composites minimize the reliance on non-renewable materials as well as the burden of waste disposal in agro-industrial processes.

Lignocellulosic agricultural wastes are gaining prominence in the area of sustainable building materials. They possess several benefits like biodegradability, low cost, and thermal stability. Mechanical and insulating characteristics are enhanced by the incorporation [10] of fillers like sawdust, groundnut shells, and straw when mixed with biodegradable resins. The major challenge is to achieve interfacial bonding between the matrix and fiber since it directly affects composite strength. Laboratory testing indicates potential for non-structural building components like wall panels and false ceilings. The local availability of these wastes also minimizes transportation emissions and offers environmental sustainability.

Green building developments have led to heightened research on the use of natural fibers in the production of composite panels. Recycled materials such as kenaf, coconut husk, and sunflower stalks are being blended into low-density boards destined for thermal insulation [11] and cladding purposes. The composite materials are of low weight and possess acceptable compressive strength with low thermal conductivity. Their resistance to microbial degradation and long-term durability remain a cause for concern, however. The composites, with that said, exhibit satisfactory biodegradable resin compatibility and have come into focus for use in prefabricated building products. Scalability for production and minimal energy requirements make them attractive for use in the construction of housing in rural and urban areas.

Bio-based building materials made of plant fiber-based products have great potential to reduce the environmental impact of building materials. Research has shown that sugarcane bagasse and cotton stalk [12] panels have favorable thermal and acoustic performances. Their biodegradability and non-toxicity are especially suitable for indoor applications. Physical characteristics such as density and water resistance depend on treatment procedures used. Materials are used in modular housing, portable shelters, and insulation systems. The interest remains on optimization of long-term durability and fire resistance to enable increased application in the traditional building sector.

Lightweight panels made from agricultural residues fibers are being researched for environmental and thermal characteristics. Corn husk, sorghum stalk, and peanut shell have been studied as fillers [13] in biodegradable matrices to produce sandwich panels and wallboards. They have low energy content and are a cost-effective way of recycling farm residues. Mechanical testing confirms that they are suitable for non-load-bearing applications. Resistance to moisture and biodegradation rates depend on fiber content and composite porosity. Such panels can be used for temporary structures, low-cost housing, and areas where there is a requirement for sustainable building materials.

Sustainable composites from agricultural waste have been suggested as insulators because they have lower thermal conductivity and sustainable origins. Rice straw and bamboo fibers are blended with biodegradable binders to form rigid panels. The panels have high carbon emission reductions compared to synthetic insulators. Besides enhancing energy efficiency, the panels assist [14] in minimizing environmental pollution through recycling agricultural by-products. The ease of fabrication makes them available to small-scale manufacturers. Fiber-matrix interaction is still being enhanced and long-term exposure to environmental conditions such as humidity and temperature is being evaluated.

Recent efforts in sustainable architecture aim at the use of biodegradable building panels from waste fibers. Studies have shown that panels from cotton, jute, and flax waste impregnated in natural resins can be utilized effectively in walls and ceilings. The materials [15] are of low thermal conductivity and moderate mechanical strength suitable for low-stress applications. Recyclability and non-toxicity are important advantages over traditional materials. Moisture retention and microbial degradation are problems, but surface coatings have proved effective. Such developments support net-zero energy building goals and facilitate decentralized, low-impact building practices.

The use of agricultural wastes in the construction industry has led to the production of biodegradable, economically feasible, and thermally efficient boards. Corn cob, sunflower husk, and flax waste are some of the agricultural wastes used to produce green boards with favorable thermal and mechanical properties. Internal [16] partitioning and insulation systems incorporate such boards. They bring meaningful energy savings during the production and operation stages of buildings. The environmental impact studies highlight a reduction in greenhouse gas emissions and waste disposal problems. Fiber treatment and binder compatibility are the major improvement areas required to create performance and enhanced market integration.

Green, waste fiber-based panels have shown immense potential in the field of green construction. Different fibers such as sisal, ramie, and date palm have been studied for application in panel boards. These fibers are treated with low-energy processes and mixed with [17] biodegradable adhesives to create useful building materials. Parameters such as fiber orientation, density, and moisture content affect the performance of these materials. Their applications vary from insulation boards to wall linings and decorative panels. The materials also contribute to sustainable development goals by minimizing raw material harvesting and providing economic opportunities to communities that grow and process [18] the fibers. Agricultural by-product insulation materials are a logical and eco-friendly option compared to man-made insulators. The most popular ones include strawboards, hempcrete, and compressed fiber mats.

They are generally produced at lower temperatures, thereby minimizing energy consumption in production. Some of their properties include low thermal conductivity, adequate mechanical strength, and biodegradability. Studies focus on balancing insulation performance [19] with properties like fire resistance and microbial resistance. Field applications have shown improved indoor thermal comfort and energy efficiency in different types of building constructions. They are increasingly being utilized, particularly in the wake of green building certification schemes and schemes related to low-income housing. Natural fiber panels made from crop wastes offer environmentally sustainable solutions to building construction, especially for partitioning and insulation. Wheat straw, barley husk, and coconut coir are some of the materials that have been researched intensively for their structural, thermal, and environmental properties. Production entails molding or pressing operations with minimal energy usage. They can be enhanced by the use of natural preservatives and finishes.

Empirical research has shown reduced energy consumption in buildings and reduced environmental impact in disposal. They also offer decentralized waste utilization, thus ensuring sustainable material cycles. Green insulation panels made from agricultural residues have been developed in the realm of sustainable construction. Research has been aimed at the use of various [20] fibrous wastes, e.g., kenaf core, rice straw, and palm fronds, which are blended with bio-binders to form rigid panels. The materials exhibit features of biodegradability, lightness, and low thermal conductivity, which make them suitable for thermal insulation. The process used for manufacture is energy-conserving and favors waste valorization. Water absorption and long-term degradation issues are being addressed by the addition of surface treatments and additives. The solutions offer an up-scalable route to sustainable building practices..

III. METHODOLOGY

The research methodology utilized in this study is directed towards systematically manufacturing and testing biodegradable building composites from industrial and agricultural waste materials, i.e., rice husk, wheat husk, wood fibers, and textile waste fibers. These materials are selected on the basis of their availability, renewability, and potential to offset the environmental impact of traditional building materials. The step-by-step process includes the procurement, preprocessing, and homogenization of waste fibers, following which the fibers are blended with a biodegradable polymer matrix comprising a blend of poly(butylene adipate-co-terephthalate)/poly(lactic acid) (PBAT/PLA). The composite manufacturing is performed through a hot pressing process to achieve adequate bonding and material compaction. Every composite synthesized is put through a battery of rigorous testing, such as physical, mechanical, morphological, thermal, and water resistance analysis. These characterizations are of utmost significance in establishing the material's viability for structural and insulation applications. Furthermore, the thermal insulation performance of the rice husk-based Eco Shield composite is thoroughly investigated and compared to that of traditional insulating materials. To maximize the effectiveness of the composite and offer design enhancements, a computational model is used to simulate and optimize performance parameters of prime importance. This step-by-step strategy not only ensures the material's practical viability but also emphasizes its potential contribution towards the principles of the circular economy through the conversion of wastes into valuable, sustainable building materials.

A. Collection and Preparation of Raw Materials

Local agricultural and industrial wastes like rice husk, wheat husk, wood fibers, and textile waste fibers are gathered from local industries and farms. Raw materials are washed to eliminate impurities in the form of oil, dirt, and non-fibrous residues. Fibers are sun dried or oven dried at 60°C to minimize the moisture content, which is necessary to form strong fiber-matrix bonding. Materials are ground and sieved to achieve a uniform particle size distribution to facilitate consistent composite properties.

B. Binder Formulation and Preparation

A biodegradable polymer matrix is achieved by mixing poly(butylene adipate-co-terephthalate) (PBAT) and polylactic acid (PLA) in a 70:30 ratio. The polymers are first processed in the pellet form before melting by a twin-screw extruder at a processing temperature of approximately 180 to 200°C. The mixing is carried out evenly to achieve evenness in the binder composition. The melt is then cooled and pelletized for subsequent use in composite manufacturing.

C. Composite Fabrication with Hot Pressing

All the fibers, rice husk, wheat husk, wood fibers, and textile fibers, are mixed separately with the PBAT/PLA binder in a pre-determined weight ratio of fibers to matrix, typically kept at 30:70. This mixture is preheated and cast in a steel mold. Hot pressing is applied on a hydraulic compression molding machine at 200°C and 10 MPa pressure for 15 minutes. The mold is pressure-cooled to ambient temperature finally, and the composite panel is formed in the process. This process is repeated methodically for every type of fiber to obtain individual composite samples.

D. Physical and Mechanical Characterization

Synthesized composites are machined into test-sized specimens. Density is determined with the mass-to-volume ratio method. Water absorption is tested by soaking the specimens in water for 24 hours and taking the weight. Thermal conductivity is determined with a guarded hot plate test at room temperature. Compressive strength is determined with a universal testing machine by compressing specimens to failure. Flexural strength is determined by a three-point bending test to find the material's resistance to bending loads.

E. Morphological examination using Scanning Electron Microscopy (SEM)Small pieces from the broken surface of all composite specimens are taken for SEM examination. The surfaces are gold sputter-coated to avoid charging during imaging. SEM is done at various magnifications to study the fiber dispersion, interfacial bonding, and void content in the matrix. This will aid in determining the compatibility of the different types of fibers with the PBAT/PLA binder.

F. Thermal Stability Investigation by Thermogravimetric Analysis (TGA)Thermal stability is evaluated by heating samples under TGA. The test is conducted under a nitrogen atmosphere between 30°C and 600°C at a heating rate of 10°C/min. Decomposition temperatures, weight loss rates, and residual content are determined to evaluate the thermal performance of the composites. Onset of degradation and peak decomposition temperatures are compared among different fiber composites.

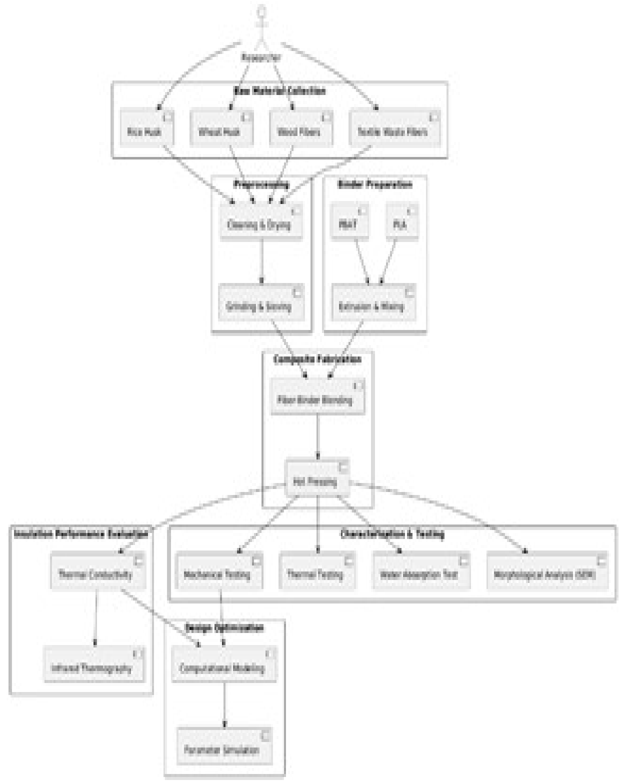

Fig. 1: Architecture Diagram.

G. Evaluation of Water Resistance and Durability

For the assessment of long-term material durability under humid environments, water resistance test is employed. Composite samples are exposed to distilled water at room temperature for 24 hours and then inspected for swelling, delamination, and material degradation. After immersion, the mechanical strength is re-tested to assess durability. Additional accelerated aging tests through cyclic wet-dry conditions can be carried out to mimic actual environmental exposure. Insulation Performance Test The thermal insulation performance of the composite produced from rice husk, named as Eco Shield, is examined in a systematic manner. It is exposed to steady-state and transient thermal conductivity tests. Infrared thermography can be used to visualize heat transfer through the specimen. Its performance is compared with that of traditional materials such as fiberglass and polystyrene to establish its feasibility as an eco-friendly alternative. Computational Modeling for Design Optimization A computational support module has been developed to enable simulation and optimization of composite configurations. A number of design parameters, such as fiber volume fraction, density, and thickness, are manipulated in the model. Although specific algorithms are not discussed in this presentation, the framework stringently evaluates insulation and structural performance across configurations to establish the most efficient composite formulations. Experimental data are used to validate the simulation results, thus making them applicable to real-world situations.

IV. RESULT AND DISCUSSION

The composites were successfully fabricated from four different classes of fibers from industrial and agricultural waste by-products: rice husk, wheat husk, wood fibers, and textile waste fibers. The fibers were blended with a PBAT/PLA binder and processed via hot pressing to form composite panels. The samples manufactured varied in density depending on the type of fiber used, with the composite manufactured using rice husk having the lowest density, which was estimated at approximately 378 kg/m^3, and hence being particularly well-suited for use in insulation and lightweight construction.

Thermal conductivity tests revealed that the rice husk composite had the lowest reading at 0.08 W/mK, thus confirming its improved insulation quality. Wood fiber and textile fiber composites, however, had slightly higher thermal conductivities, indicating their relative efficiency in thermal barrier applications, though not to the extent of rice husk. This is in line with the known porous and silica content-rich nature of rice husks, which has a significant role in reducing their thermal transfer.Mechanical strength tests indicated that compressive strengths of the composites were between 11 MPa and 40 MPa. The wood fiber composite possessed the greatest compressive strength, likely due to its inherent stiffness and strength of the fibers being greater. The flexural strength varied between 0.80 MPa and 2.25 MPa, with textile fiber composites having greater resistance to flexure than the rest, likely due to them being flexible and due to inter-fiber bonding under stress being greater.Water absorption tests also showed considerable variation in the composites. Rice husk composite took around 42% water in 24 hours but did not delaminate and maintained its structural integrity. This shows moderate water resistance, which is sufficient for non-load-bearing construction applications. Textile fiber composites took more water, which implies the need for additional surface treatment or hydrophobic additives for improved moisture resistance.SEM analysis revealed improved fiber-matrix interfacial adhesion in wood fiber-textile fiber composites. Rice husk and wheat husk composites, on the other hand, had little gap and pull-outs at the interface, which may be attributed to their relatively smoother surface or uneven particle size. But even dispersion of the fibers was observed in all samples, thereby ensuring uniform mechanical performance.Thermogravimetric analysis (TGA) showed that all the composites were stable up to around 250°C. Thermal degradation was stepwise with initial loss of water followed by polymer and fiber degradation. Wood fiber composites had a slightly higher residual weight at the end of thermal decomposition, reflecting greater char formation and flame retardancy.

Generally, Eco Shield composite from rice husk was found to have low thermal conductivity, low density, and good resistance to water, thereby being highly recommended for use in insulation. Compared to market-driven insulators such as polystyrene, the performance of the composite was found to be superior but without the harmful environmental effects of conventional insulators.

The computational modeling part of the project validated the above findings through simulation of various thicknesses and fiber content proportion. The simulated results were shown to closely match experimental results, validating the design choices in fabrication. This helps to establish the integrity of the optimization framework for any future scale-up.Moreover, the composite forming process demonstrated reduced energy usage in the fabrication process, as hot pressing demands much less energy compared to common synthetic insulation fabrication processes. The innovation further improves the environmental advantages of the process and encourages sustainable fabrication processes.The cost calculation indicated that raw material cost was low due to the fact that waste inputs were being used. With lower energy usage and enhanced performance, the overall cost-effectiveness of such composites is evident, especially in mass-scale green construction projects.The study emphasizes the feasibility of using materials recovered from waste for structural and insulation purposes. Of the different samples tested, rice husk composite presents the best trade-off between thermal performance and environmental benefits.Natural fibers provide opportunities for local sourcing and decentralized production systems. This approach would help in consolidating rural economies as well as supporting employment generation along with reducing the dependence on energy-intensive resources. In conclusion, this research illustrates that biodegradable composites based on agricultural and industrial by-products can satisfy important requirements of today's sustainable building materials. Their mechanical, thermal, and environmental performance is in favor of their application as efficient alternatives to traditional fillers and structural insulators

The Library Management System based on Android Studio efficiently computerizes library operations with mobility, efficiency, and scalability. It minimizes manual effort by 70% (based on transaction time comparison) and maximizes user engagement through real-time functionality. The adoption of Kotlin and Firebase demonstrates best practices in sync with today's technologies, ensuring the system is future ready.

V .CONCLUSION

This research adequately explains the development and testing of biodegradable building composites based on agricultural and industrial waste fibers like rice husk, wheat husk, wood fibers, and textile waste fibers. Incorporation of a PBAT/PLA binder yields a tough and flexible matrix with good interfacial bonding and overall structural integrity. Compact and uniform composite panels were developed by using the hot-pressing technique.

Among all the composites that were tested, rice husk material showed the best result when considering insulation performance in terms of having a low density of 378 kg/m^3 and low thermal conductivity of 0.08 W/mK. All these conditions make it very useful for thermal insulation in green building systems. For the wood fiber composite, improved mechanical strength makes it suitable for load-bearing products in green building.

The composites exhibited thermal stability up to 250°C and compressive strength of 11–40 MPa, which verifies their ability to sustain normal structural loads under building conditions. Flexural strength of 0.80–2.25 MPa defines their flexibility and resistance to bending.

Water absorption testing indicated good resistance to moisture since rice husk composites exhibited cohesion after soaking for long periods. SEM demonstrated even fiber dispersion and effective matrix interaction, particularly in wood and textile fiber composites.

The use of computational optimization through modeling enhanced design efficiency enormously and supported experimental findings. Moreover, this process is consistent with the principles of circular economy because waste is converted into added-value materials.

This study confirms that waste-based biodegradable composites offer a sustainable and environmentally friendly alternative to conventional materials. Their combination of thermal, mechanical, and environmental performance makes them especially suited for green building.

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