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Pineapple Leaf Fiber Composite Material for Thermal Insulation: An Overview

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Abstract
The natural fiber composites have made considerable headway among materials vying for sustainable and eco-friendly requirements. Among these fibers, pineapple leaf fiber (PALF) is highlighted for its lightweight properties, biodegradable dispositions, and superior mechanical strength. This review outlines advanced potential in thermal insulation using PALF composites by analyzing their structural composition, extraction methods, and compatibility with various matrices. The effect of fiber treatment, alignment, and hybridization of PALF with other natural fibers in thermal insulation performance has been studied. This report also discusses about thermal insulation efficiency. While PALF composites emerged as an eco-friendly alternative for thermal insulation, with some drawbacks, such as susceptibility to moisture absorption and long-term durability. This paper discusses these issues along with suggestions for future research aimed at enhancing PALF composites for practical thermal insulation applications.

Keywords: Pineapple Leaf Fiber (PALF), Thermal Conductivity, Thermal Diffusivity

Introduction

With a byproduct of Pineapple cultivation we get the Pineapple Leaf Fiber which can be utilized to create composite material which can be used for manufacturing a insulation material which can help to get thermal properties that are needed to be achieved from a goof insulation material. Here, Pineapple Leaf Fiber (PALF) can help to create a sustainable solution that can be implemented for thermal insulation for various applications. Pineapple Leaf due to its low thermal conductivity helps to reduce the heat transfer rate. Additionally, it has more specific heat capacity, which allows it to absorb and store the heat effectively and can help to regulate the temperature. The composite is made by creating a sandwich layer of Pineapple Leaf Fiber with Phenol Formaldehyde as a binding resin. The resin used also helps to enhance the thermal properties of the material to be manufactured. And after manufacturing the specimen can be tested for the various thermal properties tests for getting the optimum level values.

Literature Review

Pineapple Leaf Fiber as a an alternative for Insulation

Leaf fiber of pineapple (PALF) is the natural bast-fiber resource manufactured from leaf units of the pineapple plant, classified as the Bromeliaceae family. Pineapple tags had been over the years thought of

as agricultural waste, which was either burnt or disposed, thus exposing the environment. Lately, with the escalating need for sustainable materials, prospects for a PALF as a laundered product for a whole variety of appliques have become prominent. Its high tensile strength, lightweight nature, and biodegradability make it a promising material in various industries, including construction, textiles, and composites [4].

PALF is majorly composed of cellulose (70–80%), hemicellulose (10–15%), lignin (5–12%), and trace amounts of waxes, pectin, and water-soluble components. PALF is characterized by high cellulose content, providing the required tenacity for high performance in tensile and other mechanical properties, while lignin and hemicellulose in it influence both fiber-stiffness and fiber-bendability. Because of PALF's unique microfibrillar structure, its aspect ratio is high, thus suitable for enhancing the strength properties of a composite.

PALF posses various properties such as thermal and mechanical as a raw material for composite material:

- High Tensile Strength: PALF have a very high tensile strength as compared to some natural fiber as well such as jute and coir.
- Light weight: PALF has light weight as compared to some other synthetic fiber and can be used at place where weight reduction is critical factor.
- Biodegradability: Since it is a plant based fiber so it can decompose easily and can be recycled without any harm to the environment.
- Thermal Resistivity: It possess a good thermal resistance property which makes it a ideal natural material as an alternative in the field of thermal insulation.

Studies has also shown that PALF has more good properties as compared to some natural based fibers such as jute, coir etc. such material provide impressive amount of flexural strength. PALF when combined with matrices such as epoxy and polyesters show impressive amount of mechanical and thermal properties.

The construction industry has long remained one of the largest energy and resource users, presenting itself as the critical territory where sustainability materials need to be integrated. PALF composites appeared to have been experimented to be accepted in replacement of conventional building materials such as wood, concrete, and steel. Their low thermal conductivities make them suitable for such applications as insulation panels, roofing sheets, and partition walls; indeed, they can help in aiding energy-efficient building designs. A study explained the effectiveness of PALF composites in preventing heat leakage in buildings, especially in tropical and subtropical regions[2]. The study suggested that PALF's porous structure and very high cellulose content add significantly to the insulation property. The study done in the field to determine the mechanical properties of composite made from kenaf fiber and PALF fiber with varying fiber weight compositions. The results show that the tensile properties of kenaf fiber-reinforced PP composites improve with increasing fiber content. The highest tensile strength was observed in composites with a fiber content of 30 wt%, while composites with a fiber content of 10 wt% showed the lowest strength. However, the tensile strength dropped when the fiber content was beyond the critical limit of 30 wt. %. Composites with 40 wt. % and 50 wt. % fiber content exhibited tensile strengths of 14.45 MPa and 12.74 MPa, respectively, which were 8.72% and 19.52% lower than those with 30 wt. % fiber content. These results align with previous studies that suggested the optimum fiber content for composites was 30 wt. % [12]. The above study suggests that the PALF composite have excellent mechanical properties which helps them to be used in the manufacturing of insulation material

as insulation material also needs to with stand the tensile forces which applies on the material during its life time and during operations.

Thermal Insulation Properties of PALF composites

Thermal Insulation is a critical property in the field of energy storage and industrial application. Within various material PALF has outshined as a prominent material for use due to its impressive thermal conductivity natural structure etc. Various studies showed that untreated natural PALF has thermal conductivity of 0.034 – 0.039 W/mK. Compared to foam[1]. Whereas alkali treated fiber provide much less conductivity as that of untreated fiber due to low content of cellulose and lignin which affects the fibers ability towards moisture absorption [4]. Enhancing thermal properties can also be done by adding silica and alumina which acts as thermal barriers and can help in reducing the thermal conductivity property of the material. Similarly, nanoclay particles also contribute to the improved mechanical and thermal properties of the composites so that it can be employed at high temperature applications [1]. The value of thermal conductivity of the of fibre is measured to be equal to 0.21W m^{-1} K^{-1}. The value of thermal conductivity of pineapple leaf fibre is lower as compared to PF matrix (0.34 W m^{-1} K^{-1}). As the thermal conductivity of PF matrix composite decreases due change in the fibre content in the PF matrix and use of PALF by 15% of weight lead to the decrease and the value of thermal conductivity of the material as compared to the PF composite material[11]. The thermal conductivity value goes on decreasing as the percentage of the fiber goes on increasing. Some other research done with a combination of different natural fiber composite reveals that the value of thermal conductivity for long time duration is very low as the composite was made from 60% banana, 32% pineapple fiber and 8% jute fiber for a thickness of 15mm slab/plate the results for the thermal conductivity was found to be almost equal to 0.002 – 0.003 W m^{-1} K^{-1} for the cycle time of 300 seconds [18] . The value of thermal conductivity goes on decreasing. Further paper suggests that the use of use of pineapple leaf fiber particulates in the pineapple composite material by 7.5% leads to the increase in the thermal degradability temperature of the composite by 8.13%. The study concludes that the increase the particulate content in composite lead to increase in thermal stability of the material. From DTG curve analysis the peak value of the material moves from -0.452% to -0.440% at a temperature of 401 to 459 C respectively[20].

Research Gap

The Pineapple Leaf Fiber (PALF) emerges as a sustainable and most prominent natural fiber alternative in thermal insulation field. This section lights on gaps in existing literature and provides input on the field in which further research should be done further.

Limited Study on Thermal Properties: Most studies available are mostly done in mechanical properties such as tensile strength, impact resistance, and water absorption capacity of PALF composites [1]. But a very few studies are done on the thermal properties of the material such as thermal conductivity values through systematic experimentation are done. A research done in 2022 noted that while PALF exhibits promising thermal conductivity values, systematic experimental studies comparing PALF composites to conventional insulation materials such as fiberglass or polyurethane foam[3].

Lack of Fire Retardant studies: Current studies lack in fire retardant properties of PALF composites. While researchers have done research in this field but with some other material, they have done research

on materials such as jute and coir rather than PALF [3]. Developing a Fire retardant based PALF composite remains a open research field.

Insufficient advancements and physical modifications in material: The hydrophilic property is major drawback of PALF for reduced thermal efficiency and long term durability. While alkali treatments, silane coupling agents, and other surface treatments have been explored to improve fiber-matrix adhesion, their effects on the thermal insulation properties of PALF composites remain underexplored [4]. Also some advance modification techniques such as plasma treatment use nanomaterials have been widely studied for natural fiber not PALF. An another highlighted the potential of incorporating nanofillers like silica and nanoclays to enhance thermal stability, yet such innovations are still in their infancy for PALF composites[5].

Long term Performance Assessment: The environmental sustainability of PALF is mentioned but there is rarely any study on Life Cycle Assessment (LCA). While a paper emphasized the low carbon footprint of PALF-based materials, there is limited data quantifying the environmental impact of their production, use, and disposal [5]. Additionally, studies investigating the long-term performance of PALF composites, especially in outdoor or high-humidity conditions, are minimal.

Comparative Studies with other Natural Fiber: The studies with various other natural fiber based composites are also limited. The studies including thermal properties comparison are limited in this field.

Study to fiber degradability: More research should be done in the field of fiber degradability as the of the untreated fiber based composite have a thermal degradability range of 34-36% at 270 to 280 ºC [19]. The above mentioned degradability test were conducted to determine the loss of thermal properties of the composite due to prolonged temperature exposure which leads to the decrease in the properties of the material and limited study covered in this area.

Methodology

The study reviews a detailed review of present literature fig1. review on PALF composites for thermal insulation purpose. The methodology adopted is on comprehensive analysis of industrial and academic publications available. The following steps are conducted for methodology:

Definition of Research scope: It focused on potential of PALF in thermal insulation. The area of interest includes: chemical and structure of fiber, thermal properties of the fiber, extraction process and potential application and challenges in various industries.

Literature Search and selection: It includes searching for publications , journals and papers on ScienceDirect, Google Scholar etc with keywords such as Pineapple Leaf Fiber (PALF), Natural Fiber Composite, PALF thermal properties, etc. The paper include chapter published from 2015 to 2024.

Value Extraction and processing: The various findings such as composition, thermal properties value, comparative analysis data all are gathered and organized in a detailed manner.

Analysis and Findings: After evaluation of results such as thermal conductivity value, gaps, advancements these all are incorporated and discussed in the context of implications in PALF composite suitability in thermal insulation.

Limitation: This review is limited by the availability of literature on PALF composites. Some findings rely on broader studies of natural fiber composites, which may not fully reflect the unique properties of PALF.

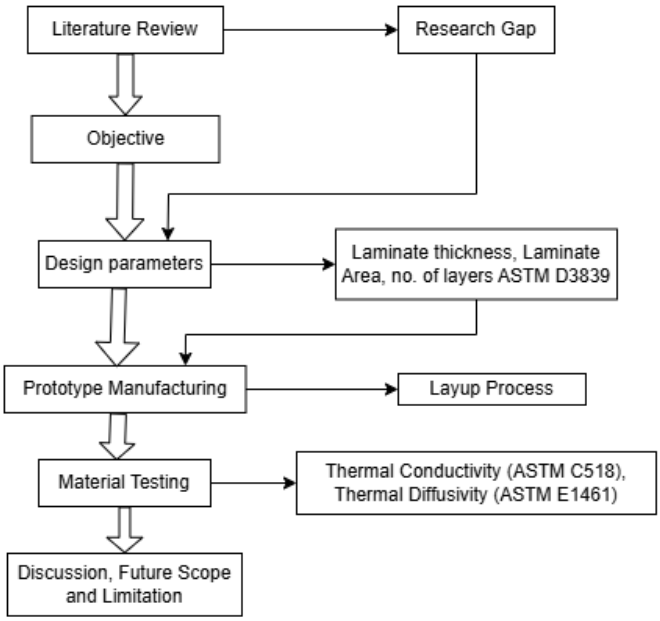

Figure 1: Proposed methodology

Future Scope

The future of the PALF based thermal insulation material lies in the solving current challenges and applying new innovative modification such as nanomaterials such as alumina and silica which improves the stability and thermal properties of the material. The PALF based composite material can also be utilized in the field of thermal insulation and it can create a good alternative for the some conventional insulation material such as glass wool. PALF based composite gives a wide scope in the field of thermal insulation as the material properties can be further enhanced by addition of alumina and silica which help to improve thermal properties as well as help in providing a good flexural strength as well which can improve its durability and improve the life of the composite material and deliver the optimum performance as compared to some other conventional insulation material.

Discussion

PALF has emerged as most dominant material for insulation material having a immense amount of potential for research and applications. The properties such as tensile strength, thermal properties, biodegradability provides a promising future in the field of industrial application.

Despite various obstacles such as moisture absorption, durability etc advancement in treatment, nanomaterials, hybridization and many more can improve the overall performance of the material. Future research should be more based on improving durability, improving properties, fabrication methods and more which will prove the credibility of PALF as a revolutionary insulation material.

In conclusion, PALF composites represent a transformative step toward sustainable thermal insulation materials.

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