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Development of Plant Based Insulating Materials for Thermal Energy Applications

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Abstract

The growing demand for energy-efficient and environmentally sustainable building materials has intensified research into renewable alternatives to conventional synthetic thermal insulators. This study investigates the development and performance evaluation of plant-derived insulating materials produced from Jute (*Corchorus spp.*), Banana stem (*Musa spp.*), and Kola leaves (*Cola spp.*) as sustainable substitutes for commonly used synthetic insulation materials such as fiberglass, polyurethane foam, and polystyrene. Unlike synthetic insulators, which are often associated with high embodied energy, environmental persistence, and disposal challenges, plant-based materials offer significant advantages including renewability, biodegradability, affordability, and reduced ecological footprint. A controlled laboratory experimental framework based on the Guarded Hot Plate (GHP) technique was employed to determine the key thermophysical properties of the developed insulation materials. Parameters evaluated included thermal conductivity, thermal resistivity, specific heat capacity, and thermal diffusivity, which collectively govern the heat-transfer behavior and thermal storage characteristics of insulation systems. Experimental results revealed significant variations in thermal performance among the investigated biomaterials. Jute exhibited the most favorable insulation characteristics, recording the lowest thermal conductivity of 0.077 $W\ m^{-1}\ K^{-1}$, the highest thermal resistivity of 0.325 $K{\cdot}m\ W^{-1}$, and the lowest thermal diffusivity of $1.132 \times 10^{-5}\ m^{2}\ s^{-1}$. These properties indicate superior resistance to heat transfer and establish Jute as a promising candidate for eco-friendly building insulation applications. Banana stem and Kola leaves demonstrated moderate insulating performance but exhibited comparatively high specific heat capacities of 1671 $J\ kg^{-1}\ K^{-1}$ and 1204 $J\ kg^{-1}\ K^{-1}$, respectively, highlighting their potential suitability for thermal energy storage and temperature-buffering applications. The findings demonstrate the technical feasibility of utilizing agricultural by-products as effective thermal insulation materials and support their adoption in sustainable thermal management systems, particularly in resource-constrained and environmentally sensitive regions.

Keywords

Plant-based Insulation Materials;
Sustainable Thermal Insulation;
Thermal Conductivity;
Natural Fiber Composites;
Agricultural Waste Utilization.

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1.0 INTRODUCTION

The development and evaluation of thermal insulating materials from plant-based raw materials are necessary because of their multifaceted benefits. Plant-based raw materials are renewable and biodegradable. Their utilization as thermal insulation supports environmental sustainability by reducing reliance on non-renewable resources and lowering carbon emissions (Biyada *et al.,* 2023). The growing demand for sustainable insulation materials especially for domestic indoors has led to increased interest in plant-based raw materials for thermal insulation applications (Ahmed and Sarkar, 2022). Utilizing such fibers contributes to a reduction of negative environmental footprints (Rahman *et al.,* 2022).

Moreover, these raw materials are non-toxic, making them healthier and safer for indoor applications compared to most of the conventional synthetic insulators. Natural fibers are considered viable alternatives to synthetic insulators like polystyrene or fiberglass in their natural form. This is because of their abundance, renewability, physical property and biodegradability. Utilizing natural fibers would create new income streams for farmers and simultaneously lowers the demand for the costly synthetic thermal insulators (Savio *et al.*, 2019). Thus, there is a critical need to develop and evaluate plant-based insulation materials that can advantageously challenge their continuous usage.

Considering the urgency in the demand for the development of sustainable plant based insulating materials, several research works were carried out globally to optimize the efficiency of thermal systems. Siciliano *et al.*, (2023) worked on "sustainable wood-waste for thermal insulation in building energy savings"; Marin-Calvo (2023) worked on "Rice-husk-based thermal insulation boards"; Luamkanchanaphan (2012) and his team worked on "Narrow leaf cattail (Typha) fiber as thermal insulation" ; Canto *et al.,* (2021)– conducted research on the "Performance of cassava Starch-Based Insulation"; Binici *et al.,* (2014) researched on Lightweight construction materials from cotton waste and fly Ash with the aim of producing lightweight thermal insulators from agricultural waste and Korjenic *et al.*, (2011) investigated "Natural fiber insulation plates" among several others.

Optimizing thermal efficiency requires the selection of suitable materials that exhibit low thermal conductivity, high durability, cost effectiveness, low environmental effect and mechanical stability (U.S Department of energy, 2017). Insulating materials play a crucial role in energy conservation and thermal management in buildings, appliances, and industrial systems. In facts, the thermal properties of insulators justified their performance and efficiency. In this research, plant-based raw materials (*Jute plant, Banana stem,* and *Kola leaves*) were selected for use due to their abundance, sustainability, low environmental impact, non- toxic, porosity.

2.0 MATERIALS AND METHODS

(a) *Sample Preparation*

The insulation sample were prepared based on physical and mechanical production techniques. these involves the physical manipulation of the materials through cutting, grinding, and shaping the plant based raw materials non synthetically. The production techniques were aimed at retaining the chemical and natural compositions of the materials (Maraveas, 2020).

The based insulation materials after the collection from farm were mashed such that their porosity is preserved. The mashed materials were then mixed with distilled water in a ratio of 4:1 by weight and mechanically stirred to obtain homogeneity in their natural composition. The homogeneous mixture was then cast using cylindrical mold. The cast was allowed to cure at room temperature for 24 hours to ensure complete binding of the materials. After the curing, the sample was carefully removed from the mold and got trimmed to the desired circular disk dimensions for testing. (That is the dimension that fit the guarded hot plate apparatus). Finally, the samples were conditioned at a temperature of 30^{0}C for another 8 hours in drying oven until moisture content were completely removed before thermal conductivity test.

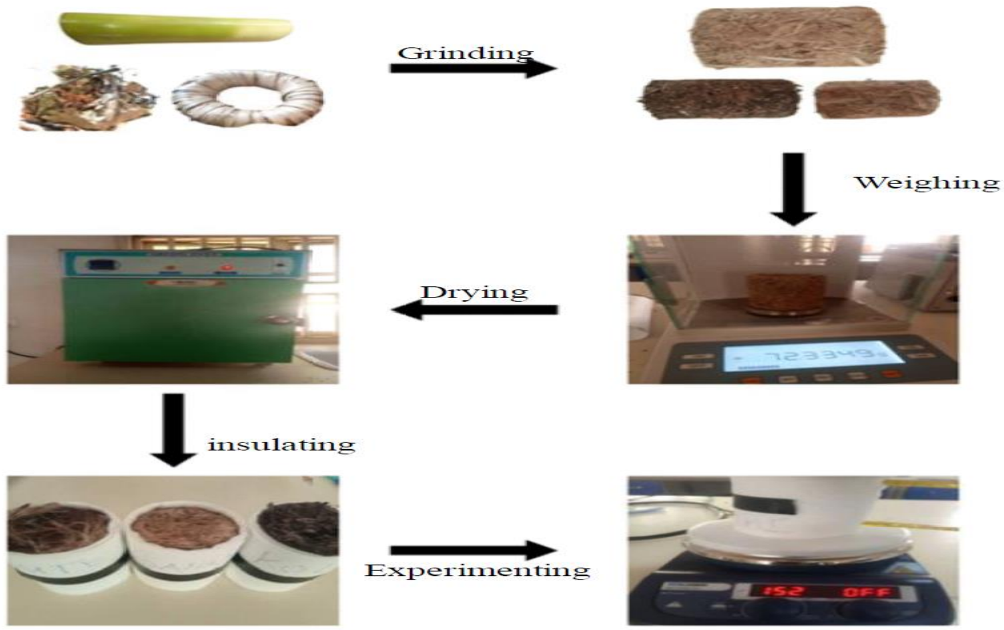

Figure 1: Sample Preparation stages

(b) Experimental Setup and Procedures

The Guarded Hot Plate (GHP) apparatus (Figure 2) was adopted for thermal conductivity measurement due to its simplicity and accuracy.

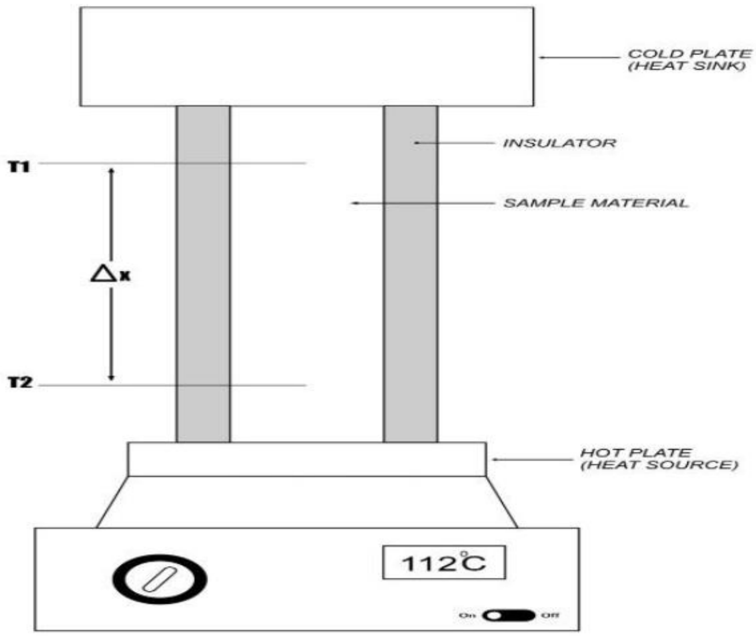

Figure 2: Improvised GHP apparatus

Figure 2 gives the experimental setup consisting of electric hot plate (70°-120°) that provided the heat flux **Q**, a cold plate container of equal dimension placed directly opposite to the heat source and above the sample which has been sandwiched between them. The cold temperature of the plate was maintained (10° -20°) by continuous application of ice/cold water throughout the duration of the experiment. This is to enable effective temperature difference between the hot and the cold plates.

The insulation sample sandwiched between the hot and cold plates was placed securely to the exclusion of air gaps between the plates and the sample material. A guarded insulation papers were installed to prevent any form of heat loss around the sample and to ensure only one-dimensional heat flow through the sample. A thermometer T_2 was inserted deep into the sample material at the bottom near the hot plate to determine hot side temperature (T_H) and thermometer T_1 was also inserted into the sample conveniently from above, just below the cold plate to record cold side temperature (T_C). The physical dimensions of the sample: thickness, Δx (m), Radius, r (m) and mass, m (kg) (using meter rule, Vernier caliper and weighing balance respectively) measured and recorded in Table 1 alongside the calculated surface area A (= πr^2), volume of disk V (= $\pi r^2 \Delta x$) and density, ρ (m/V).

The set up was then allowed to remain ON until it reached steady-state condition (i.e. until the heat flow through the sample and the thermometers variations stabilized and remained constant). The time taken for this was noted. At the steady-state condition, the hot side temperature (T_H) from T_2 and cold side temperature (T_C) from T_1 were carefully observed, measured and recorded. Also, the voltage (V) and current (I) from main power supply were measured and recorded. These procedures were repeated for the different processed samples (banana stem, jute plant and kola leaves).

(c) Theory and Analysis

(i)Thermal conductivity (k-value): this is the primary measure of the materials insulating efficiency. It is calculated based on Fourier's law of heat conduction using equation (1)

$$K=\frac{Q\Delta x}{A(T_H-T_C)} \quad (1)$$

where **K is** the materials thermal conductivity, **Q** heat flow rate, Δx sample material thickness, T_H hot side temperature, T_C cold side temperature. Lower values of **K** indicate better insulation performance of the material

(ii) Thermal Resistance per Unit Area (R-value): R-value is an important thermal property that measure how well insulating material resist heat flow. Higher R-values represent better insulating performance (Ashrae, 2017). It is a ratio of materials thickness, Δx to its thermal conductivity, K and is determined using:

$$R = \frac{\Delta x}{K} \quad (2)$$

(c) Specific Heat Capacity: Specific heat capacity of a material is the amount of heat needed to raise the temperature of 1kg of the material by 1K (or 1^0C). A good insulator has a higher specific heat capacity because it takes time to absorb more heat before it actually heats up (temperature rise) to transfer the heat. Specific heat capacity is measured from equation (3)

$$c = \frac{E}{m\ (T_H-T_C)} \quad (3)$$

E= IVt is the thermal energy input, m is the sample mass and T_H -T_C the temperature difference. Where I is the current (A), V is voltage (V) and t is time in seconds.

(d) Thermal diffusivity: this determines the time required for materials to attain thermal equilibrium and is estimated from insulation material's density (kgm^{-3}), ρ, calculated thermal conductivity, K and the specific heat capacity of the samples, c as:

$$\alpha = \frac{K}{\rho c} \quad (4)$$

Low thermal diffusivity means that the material takes longer time to reach thermal equilibrium, which is desirable quality for insulation materials, as they can store and resist changes to heat (Incropera *et al.*, 2013).

3.0 Results and Discussion

(a) Physical Quantities of the Sample Materials

The physical dimensions (thickness, radius and mass) as carefully measured and their calculated areas, volumes and densities are recorded in Table1.

Table 1: Measured and calculated samples physical quantities

Sample	Δx (m)	r (m)	A (m^2)	Vx10^{-3}(m^3)	M (kg)	ρ (kgm^{-3})
Jute	0.025	0.30	0.283	7.075	0.0613	8.664
Banana stem	0.025	0.30	0.283	7.075	0.0723	10.223
Kola leave	0.025	0.30	0.283	7.075	0.0976	13.790

(b) Guarded Hot Plate Experimental Result

Thermal conductivity experiment was carried out using improvised GHT method in a controlled laboratory setting and parameters such as voltage, current, time to reach steady-state temperature, heat input, heat energy, and temperature difference across each sample were recorded in Table 2.

Table 2: Measured quantities from thermal conductivity experiment

Sample	V (V)	I (A)	t (s)	Q (W)	E (J)	T_2 (°C)	T_1(°C)	Δx (m)
Jute	150	0.48	55.20	72	3,974	96.0	13.5	0.025
Banana stem	171	1.14	51.47	194.94	10,033	99.0	16.0	0.025
Kola leave	170	1.11	48.57	188.7	9,165	95.0	17.0	0.025

Evaluated Thermal Insulation Properties of the Processed Sample Materials

Using the result of the experiment from Tables 1 and 2, the thermal properties of each sample material were calculated using equations (1), (2), (3) and (4). These properties are essential for assessing insulation performance of the materials. They determine how effective each material can resist or conducts heat and how well it stores and transfers the thermal energy.

Table 3 Thermal Properties of the three processed plant-based insulating materials

Sample	K ($Wm^{-1}K^{-1}$)	R (m^2KW^{-1})	c ($Jkg^{-1}K^{-1}$)	α x10^{-5}(m^2s^{-1})
Jute	0.077	0.325	785	1.132
Banana stem	0.206	0.121	1671	1.205
Kola leave	0.213	0.117	1204	1.282

Thermal properties of the developed insulation materials

From the results in Table 3, Jute has the lowest thermal conductivity (0.077 $Wm^{-1}K^{-1}$), followed by Banana stem (0.206 $Wm^{-1}K^{-1}$) and Kola leaves (0.213 $Wm^{-1}K^{-1}$). This revealed that Jute is the most effective for reducing heat transfer and the best insulating material among the three. Also, Jute sample has the highest thermal resistance value per unit area (0.325 m^2KW^{-1}) thereby supporting its superiority as thermal insulator compared to Banana stem and Kola leaves that have thermal resistance values of 0.121 $m^2.KW^{-1}$ and 0.117 $m^2.KW^{-1}$ respectively. The lowest value of α (1.132 x 10^{-5} m^2s^{-1}) observed in Jute sample is a desirable property for insulation materials because it means heat spreads slowly in Jute material than others. Kola has the highest value (1.282 x 10^{-5} m^2s^{-1}). The results also show that Banana stem has the highest specific heat capacity (1671 $Jkg^{-1}K^{-1}$) which implied its ability to store more thermal energy than Jute and Kola samples. Jute having (785m^2s^{-1}) stored least thermal energy. Based on the analysis, Jute demonstrated the best performance as thermal insulator. It had the lowest k-value, highest R-value, and lowest diffusivity, even though its heat storage ability was not good as compared to Banana stem. This makes Jute sample suitable for use in applications where heat flow is the main priority. Banana stem having the highest heat storage capacity, is useful in systems where thermal buffering is needed, although its insulation performance is weaker than Jute; kola leaf had moderate values and can serve as an alternative where there is no better performance insulator.

Considering the classification of thermal insulators based on thermal property values (U.S Department of energy, 2017), it is clear that excellent insulators like VIP, aerogel, fiberglass, polyurethane and cellulose supersedes the three plant-based insulators for their unique thermal conductivity (< 0.05

$Wm^{-1}. K^{-1}$). Jute with a k-value ($0.05 < k < 0.1$) $Wm^{-1}. K^{-1}$ is found to be the most effective among the three agriculturally based material insulators. However, it may not be applicable in high performance insulations but lied in category of good insulators and can be compared with some insulators like cork, perlite, mineral wool for their similar thermal conductivity values. Banana stem and Kola leaf with k-value ($0.1 < k < 1$) $Wm^{-1}. K^{-1}$ are moderate insulators and had less performance in comparison with widely used synthetic insulators. They are less suitable for thermal resistance purposes in high-performance application.

Observing the specific heat capacities, developed plant insulators, particularly Banan stem (1671 $Jkg^{-1}. K^{-1}$) and Kola leaves (1204 $Jkg^{-1}. K^{-1}$) have shown impressive heat absorption capabilities that is higher than many synthetic insulators. This property makes them useful in scenarios where thermal buffering is more important than outright insulation, that is where temperature fluctuations is not needed. On the other hand, Thermal diffusivity values for the plant-based are a little bit higher than the synthetic ones. this revealed that heat poorly penetrates through them when compared to the excellent performance insulators.

4.0 CONCLUSION

Although, the three developed plant-based insulators (Jute, Banana Stem and Kola leaf) are less efficient than excellent synthetic insulators in literature, it can favorably compete with some good synthetic insulators in terms of performance. These synthetic materials, though effective, are often associated with drawbacks including high production costs, environmental pollution, flammability, health risks, and poor biodegradability. The plant-based insulators are uniquely advantageous for being biodegradable and renewable materials offering lower cost and reduced environmental impact. Among the three materials studied, Jute emerges the most promising alternative insulator for its relatively low thermal conductivity, high thermal resistance and diffusivity value. Besides, it is locally available.

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