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| RESEARCH ARTICLE

Thermal Conductivity and Structural Performance of Natural Insulation Materials in Refrigeration: A Review

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| ABSTRACT
The growing need for sustainable and energy-efficient refrigeration systems has sparked research into eco-friendly insulation options. This review looks closely at the thermal conductivity and structural performance of natural insulation materials, especially fiber-reinforced bio-composites, for refrigeration use. Traditional materials like polyurethane and polystyrene are efficient but create environmental issues and challenges at the end of their life. On the other hand, natural fibers like coir, jute, banana, hemp, sugarcane bagasse, and calabash provide low thermal conductivity, high porosity, and biodegradability, which support global sustainability efforts. The review is based on twelve peer-reviewed studies published between 2010 and 2025. It examines the behavior of composites concerning thermal conductivity, specific heat capacity, density, porosity, and compressive strength. Coir/jute and banana-eggshell composites show a good balance of thermal insulation and mechanical strength, while calabash-based composites are promising for low-temperature settings. However, challenges like moisture absorption and scalability still exist. The review suggests using optimization methods such as RSM and DoE for further improvements. In conclusion, bio-composites are viable candidates to replace synthetic insulators in refrigeration, as long as further research focuses on durability, fire resistance, and lifecycle cost.

| KEYWORDS
Natural insulation, Calabash composite, Refrigeration, Thermal conductivity, Structural performance, Coir/jute, Banana fiber, Sustainable materials, Epoxy composites.

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1. Introduction
The demand for environmentally sustainable and energy-efficient refrigeration systems has increased dramatically during the last decade (Gupta et al., 2021; She et al., 2018). This trend is being driven by worldwide activities aimed at lowering greenhouse gas emissions and reducing dependency on petroleum-derived commodities (Bhatkar et al., 2013). Refrigerators, freezers, cold storage facilities, and refrigerated transport systems fundamentally depend on thermal insulation to sustain low internal temperatures while concurrently minimizing energy expenditures (Dincer, 2017; Meng et al., 2024). Traditionally, this insulation has been supplied by petroleum-based synthetic materials such as polyurethane (PU) foam, expanded polystyrene (EPS), and extruded polystyrene (XPS), which are characterized by low thermal conductivity and relatively elevated structural integrity (Raja et al., 2023). Nevertheless, there is growing scrutiny directed towards these materials due to their environmental shortcomings, which encompass inadequate biodegradability, dependence on fossil feedstocks, and the emission of hazardous substances during both production and disposal at the end of their lifecycle. The incorporation of natural materials for thermal insulation in refrigeration applications has surfaced as a viable solution that harmonizes with both

ecological and economic goals (Chaturvedi et al., 2024). Natural fibers and agricultural residues, including coir, jute, banana, hemp, rice husk, sugarcane bagasse (Nyambo et al., 2014), and even calabash (Gono et al., 2020), have exhibited significant potential as cost-effective, renewable, and biodegradable substitutes for synthetic insulators (Rafiq et al., 2020). These materials generally display high porosity, low density, and advantageous fiber-matrix interactions, thereby enabling them to fulfill dual functions in thermal resistance and mechanical reinforcement (Onyenanu et al., 2024; Onyenanu et. al., 2015; K et al., 2025; Ejelonu et al., 2011; Omobuwajo et al., 2003; Magno et al., 2022). Furthermore, they can be formulated into composites utilizing either bio-based or conventional resins to augment their structural integrity, consequently broadening their applicability within refrigeration systems (Pawłosik et al., 2025).

A multitude of studies have investigated the thermal performance of these alternative materials. For instance, Ganasan et al. (2024) evaluated the mechanical, moisture absorption, and thermal stability of banana fiber/egg shell powder-based epoxy composites. Similarly, Veeraprabahar et al. (2022) developed natural coir/jute fibers hybrid composite materials for automotive thermal insulation applications. Karthik et al. (2025) explored the antibacterial, mechanical, and thermal properties of calabash fiber reinforced epoxy composite with natural fillers. Revista et al. (2015) worked on the thermal and energy evaluation of a novel polymer-ceramic composite as insulation for a household refrigerator. From their study, it was also found that at stable operating conditions, the energy consumption using the composite saves approximately 1.5%. Also, Alazzawi et al. (2024) worked on the comparative study of natural fiber-reinforced composites for sustainable thermal insulation in construction. Furthermore, these bio-composites frequently exhibit acceptable compressive strength, dimensional stability, and moisture absorption resistance. This shows that all of them are critical qualities for refrigeration systems that experience temperature cycling and condensation.

In spite of the promising advancements, several challenges remain unresolved. The absorption of moisture continues to be a significant issue due to the hydrophilic properties of lignocellulosic fibers, which may jeopardize thermal and mechanical performance over extended periods (Al-Maharma & Al-Huniti, 2019; Rangappa et al., 2022). Furthermore, there is an imperative for systematic optimization through methodologies such as Response Surface Methodology (RSM) and Design of Experiments (DoE) (Ezechukwu et al., 2025; Onyenanu et al., 2024) to meticulously refine composite formulations tailored for refrigeration-specific applications (Ukachi et al., 2024; Unya et al., 2025). In addition, concerns regarding scalability, the effects of long-term thermal aging, and the requisite fire retardancy persist as barriers to commercial implementation. This review endeavors to critically evaluate the thermal conductivity and structural performance of natural insulation materials utilized in refrigeration applications (Al-Homoud, 2005; Pásztory, 2021). It amalgamates contemporary literature regarding fiber types, composite formulations, and contextual applications. By juxtaposing natural composites with traditional insulating materials, the review delineates performance trade-offs, elucidates engineering innovations, and underscores prospective trajectories for the enhancement of sustainable refrigeration insulation systems.

2. Literature Review

The literature on natural insulation materials for refrigeration systems shows a growing shift toward sustainability and material innovation. Studies have focused on finding thermally efficient and structurally sound alternatives to synthetic insulators. Veeraprabahar et al. (2022) created coir/jute composites bonded with polyurethane, which demonstrated high thermal insulation at temperatures above 350°C. In a similar effort, Ganasan et al. (2024) developed banana-eggshell epoxy composites that achieved significant improvements in flexural strength and thermal resistance. Ogbonna et al. (2018) introduced calabash-PVC composites that provided insulation suitable for cold storage and thermos applications. Comparative assessments by Alazzawi et al. (2024) and Tasgin et al. (2024) measured performance metrics such as compressive strength, specific heat, and moisture resistance across different natural fibers. The lowest thermal conductivity (0.01467 W/mK) was reported by Ndagi et al. (2021) for a coir-sugarcane bagasse mix, making it a top-performing bio-insulator. A trend has emerged: no single material performs best in all areas. Mechanical strength, thermal efficiency, and environmental resistance often come at a cost to one another. As a result, studies suggest using hybrid materials, adjusting densities, and applying moisture-proof treatments. Methodological advancements using RSM and DoE are becoming more popular for optimizing composite formulations.

3. Methodology

This review employed a structured literature synthesis approach to assess the thermal and mechanical performance of natural insulation materials used in refrigeration systems. The goal was to find, compare, and criticise studies on materials such as natural fibres, agro-waste particles, and bio-based composites that can be used or adapted for thermal insulation in cold-chain, home, and industrial refrigeration.

3.1 Data Collection and Selection

The Scopus, ScienceDirect, and Web of Science databases were chosen for their comprehensive indexing of engineering, materials science, and energy efficiency research. These platforms are well-known for curating peer-reviewed, high-impact journals related to sustainable materials and thermal systems. A Boolean search approach was developed to retrieve studies that were highly relevant to the topic (Onyegirim et al., 2025 and Nwankwo et. al., 2025). The following search string was used:

- ("natural insulation material" OR "bio-based composite" OR "natural fiber insulation")
- AND ("thermal conductivity" OR "specific heat" OR "thermal resistance")
- AND ("refrigeration" OR "cold storage" OR "thermal panels")

The search was limited to literature published between 2010 and 2025, to ensure that recent advances in thermal performance characterisation and biocomposite creation were included. Only English-language articles from peer-reviewed journals and international conference proceedings were reviewed. An initial set of 417 publications was identified. Titles and abstracts were reviewed for their applicability to refrigeration-based thermal insulation using natural materials. The exclusion criteria included papers focused solely on building insulation, electrical insulation, or unrelated thermoplastics. A total of 12 articles passed preliminary relevance checks.

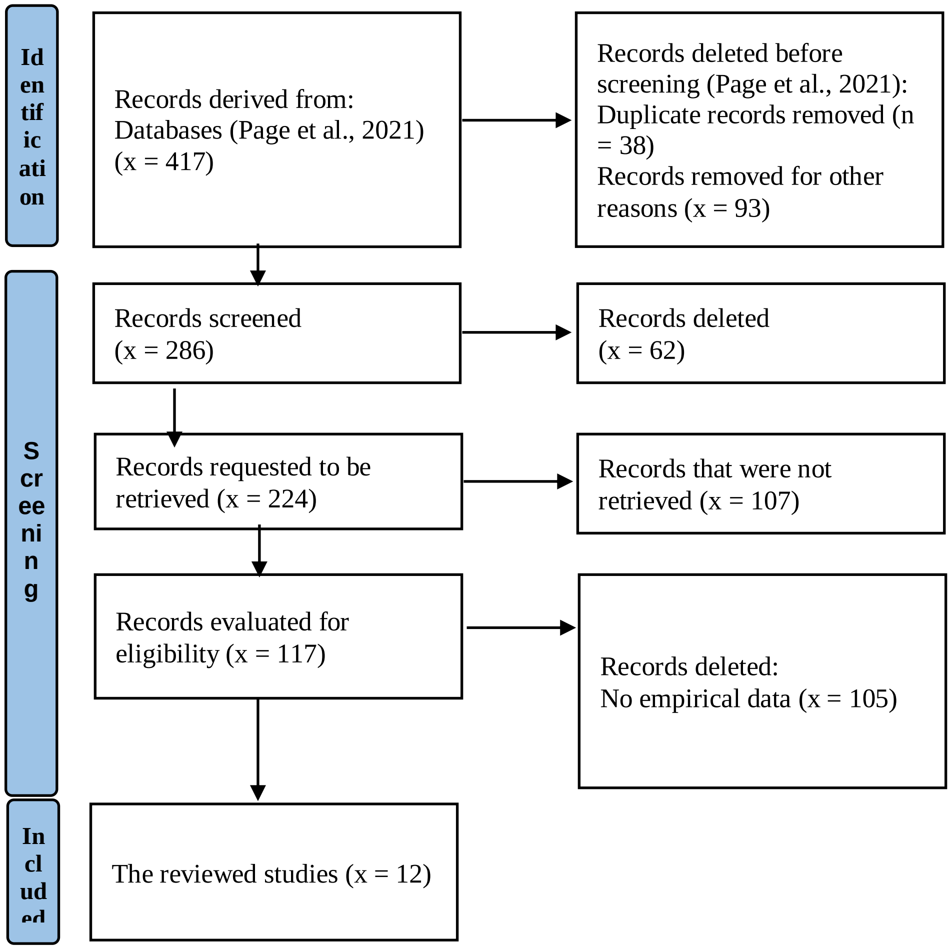

Figure 1: PRISMA Flow Diagram for the Process of Literature Selection (Source: Page et al., 2021)

3.2 Publication of Journals by Ranking

As illustrated in Figure 2, research interest in natural insulation materials for refrigeration has increased significantly, with a clear concentration of publications in recent years. Specifically, 5 of the 12 assessed publications were published between 2021 and 2024. Furthermore, the publication of these findings in high-impact publications such as Polymers, Materials Research Express, and the International Journal of Thermofluids highlights the topic's interdisciplinary relevance in materials science, mechanical engineering, and environmental research. These journals are frequently ranked in the Q1 and Q2 Scopus categories, reflecting scholarly rigour and impact. This increase reflects growing awareness about the environmental impact of synthetic insulators, as well as developments in bio-based composite technology.

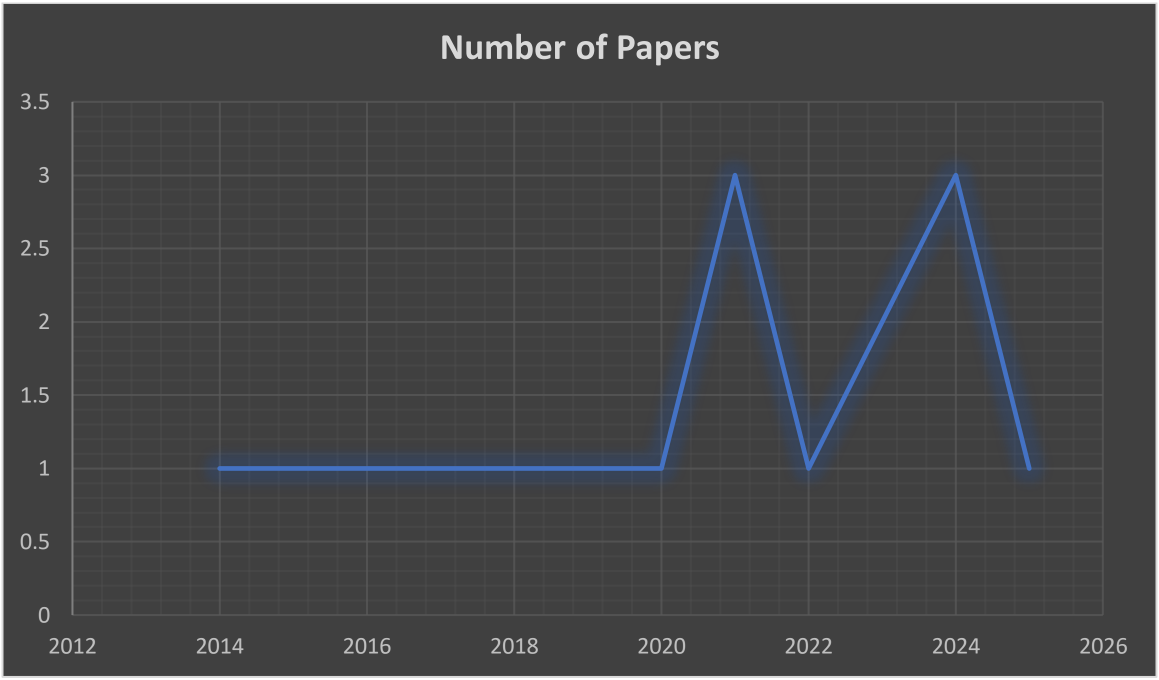

Figure 2: Graph of Journal Article by Year of Publication (Osobajo et al., 2017)

4. Reviews

To critically analyse improvements in natural insulation materials for refrigeration systems, this review combines and synthesises information from a number of peer-reviewed publications. Thermal conductivity, structural integrity, and adaptability for cold storage or refrigeration applications are all important considerations. Table 1 provides a full review of the selected publications, emphasising the types of composites tested, the experimental results, and significant performance measures given by various authors.

Table 1: Summary of Reviewed Studies on Natural Insulation Composites for Refrigeration Applications

Study Topic	Composites	**Details / Findings**	Citations
Development of natural coir/jute fibers hybrid composite materials for automotive thermal insulation applications	Coir/Jute with different blend proportions of raw materials mixed with rigid polyurethane foam as a binder	"The results showed that the porous natural coir/jute composites possess excellent performance in thermal insulation of high-temperature heat waves, especially above 350°C. The thermal insulation properties of these natural coir/jute composite materials are useful for the proper application in products such as interior lining materials for auditoriums, halls, apartments, automotive, aircraft, and ducts and enclosures for thermal equipment and insulation for machines."	(Veeraprabahar et al., 2022)
Mechanical, moisture absorption and thermal stability of banana fiber/egg shell powder-based epoxy composites.	Banana Fiber/Egg Shell Powder-Based Epoxy Composites	"Examination of the data revealed that in comparison to epoxy with no reinforcement, the addition of bio-fillers improved the thermal insulation (4 wt.% of CEP exhibits 0.052 W/mk), water absorption (4 wt.% of CEP produced 5.31%), flexural strength (20 wt.% of CEP exhibit 36.57 MPa), and modulus (12 wt.% of CEP exhibit 300.12 MPa) of the hybrids."	(Ganasan et al., 2024)
Thermal and energy evaluation of a novel polymer-ceramic composite as insulation for a household refrigerator	Polymer-ceramic composite material	"Based on the experiments, it is concluded that when using the composite, the average internal temperature of the fridge is increased by 1°C, for practical and design purposes, the refrigerator still functions below 3°C. It was also found that at stable operating conditions, the energy consumption using the composite saves approximately 1.5%. Despite these slight savings, the pyro-expanded perlite composite acts as a thermal isolating material. This material may exhibit better ease of use and thermal, energetic, and economic benefits, without omitting the environmental characteristics that they favor."	(Revista et al., 2015)
Comparative study of natural fiber-reinforced composites for sustainable thermal insulation in construction	Date palm, hemp, and jute fiber composites	"Our results show that the thermal conductivity of the composites ranges from 0.0514 – 0.084 W/m. K for different fiber loading is affected by the fiber content. Furthermore, at maximum fiber concentration (30 by weight), the highest heat capacity of the hemp composite was 1674 J/Kg.K. The 30 wt% of jute and date palm composites achieved a maximum compressive strength of 70 MPa and 64 MPa, respectively."	(Alazzawi et al., 2024)
Mechanical, wear, and thermal properties of natural fiber-reinforced epoxy composite: cotton, sisal, coir, and wool	Cotton, sisal, coir, and wool fibers.	"Thermal conductivity is highest at cotton composite (1.017 W/mK) and is lowest at coir composite (0.187 W/mK). Additionally, the highest specific heat was observed in the coir composite (26.313 MJ/m3K). Cotton demonstrated potential for efficient heat transfer, while wool outperformed in insulation. Sisal	(Tasgin et al., 2024)

fibers		displayed versatility for structural applications. Coir emerged as an effective insulator with energy-saving applications."	
Development of calabash (Lagenaria siceraria) – Polyvinyl chloride composite for thermal insulation	*Calabash (Lagenaria siceraria) – Polyvinyl chloride composite*	"The newly developed composite has lower thermal conductivity than polyvinyl chloride and can be used for such thermal insulation applications as low temperature thermal insulation limits of 15 °C to -75 °C refrigeration and cold rooms' insulations and for hot water and steam condensate as in thermo-flask applications."	(Ogbonna et al., 2018)
A review on the thermal characterisation of natural and hybrid fiber composites	Natural and hybrid fiber composites	"It is concluded that thermal analysis can provide useful information for the development of new materials and the optimization of the selection process of these materials for new applications."	(Neto et al., 2021)
Renewable natural resources reinforced polyurethane foam for use as lightweight thermal insulation.	Polyurethane matrix was incorporated with wood fiber, bamboo fiber, rice husk, and liquefied polyol.	"The thermal conductivity of the bio-based thermal insulation ranged from 0.045 to 0.065 $W.m^{-1}K^{-1}$, and the addition of the natural fibers increased mechanical strength. The prepared bio-based insulation showed great potential for building thermal insulations with particularly low thermal conductivity (less than 0.065 $W.m^{-1}K^{-1}$) and self-bearing strength."	(Shao et al., 2020)
Investigation of the thermo-physical and mechanical properties of coir and sugarcane bagasse for low temperature insulation	Coir and sugarcane bagasse	"Thermal conductivity test showed that 1.0 mm particle size coir mixed with sugarcane bagasse has the lowest thermal conductivity of 0.01467 W/mK, whilst that of 0.5 mm particle size has a thermal conductivity of 0.01472 W/mK. This is lower compared to the measured thermal conductivity of the polyurethane control sample of 0.01832W/mK/mK. Sample F (1.0 mm particle size,70% coir and 30% bagasse) with a thermal diffusivity of 5.15x10 $^{-5}$ m^2/s, water absorption capacity of 410 %, UTS of 0.219 MPa, Compressive strength of 0.583 MPa, Specific heat capacity of 1141.3 J/kgK and thermal resistivity of 68.16 W/m/K is most suitable replacement for polyurethane as low temperature thermal insulator."	(Ndagi et al., 2021)
A brief review on the mechanical and thermal properties of banana fiber-based hybrid composites	Banana fiber-based hybrid	"In this, it was inferred that the composite with 10% wt banana and 30% wt jute fiber possesses higher thermal stability and thermal conductivity when compared to the normal ones."	(Sivaranjana & Arumugaprabu, 2021)
Thermal conductivity of hemp concretes:	Hemp concretes	"The thermal conductivity of studied materials ranges from 90 to 160 mW/(m.K) at (23 degrees C; 50%HR).	(Collet & Prétot, 2014)

Variation with formulation, density, and water content.		It is shown that the thermal conductivity increases by about 54 % when the density increases by 2/3, while it increases by less than 15 % to 20 % from the dry state to 90% RH."

5. Discussion

The review of recent studies highlights the growing abilities of natural insulation composites in refrigeration systems. It focuses on thermal conductivity, specific heat capacity, and structural properties. These materials are not only good for the environment but also perform similarly to, and in some cases better than, traditional synthetic insulators like polyurethane foam and expanded polystyrene. Among the studies reviewed, coir and jute composites have shown particularly promising results. Table 2 presents the physical and thermal insulation properties of coir/jute composites (Veeraprabahar et al., 2022). It shows that composite sample S1C achieved a thermal conductivity of 0.112 W/mK and the lowest thermal insulation value of 0.02131, indicating excellent insulation ability. Figure 3 visually demonstrates the superior thermal insulation performance of coir-dominated composites compared to other configurations. These results support the use of coir/jute blends in refrigeration environments, especially in components like liner panels and inner walls. In comparison, banana fiber and eggshell powder-based epoxy composites reported by Ganasan et al. (2024) reached a slightly better thermal conductivity of 0.052 W/mK at 4 wt.% eggshell powder. While these values are better in terms of thermal performance, it is important to consider mechanical stability and moisture resistance. Coir/jute combinations still hold an advantage due to their porosity and composite density, as shown in Table 2. The study by Alazzawi et al. (2024) offers valuable insights into the specific heat capacity of date palm, hemp, and jute fiber composites. Figure 4 shows that hemp composites had the highest specific heat capacity at 1674 J/kg·K, greatly exceeding the baseline of neat epoxy at 1210 J/kg·K. Jute and date palm composites followed closely, with values ranging from 1253 to 1512 J/kg·K and 1325 to 1462 J/kg·K, respectively. A high specific heat capacity is crucial for insulation materials in refrigeration since it helps the material manage temperature changes and maintain internal stability. Although direct heat capacity values for the coir/jute samples from Table 2 are not listed, their relatively high thermal insulation efficiency suggests they have comparable thermal mass.

Another important aspect is the relationship between composite density and performance. Table 2 shows a range of density from 103.5 to 146.7 g/cm^3. Denser composites usually have higher thermal conductivity and better structural stability. For example, sample S6C/J, which has a density of 146.7 g/cm^3, measured a thermal conductivity of 0.146 W/mK and a good TIV of 0.06488. This trade-off emphasizes a key consideration in composite design: finding the right balance between insulation performance and mechanical strength. In comparison, calabash-PVC composites discussed by Ogbonna et al. (2018) show lower thermal conductivities than PVC alone and are suitable for refrigeration needs between 15 °C and –75 °C. While these composites offer more flexibility in thermal range, the available structural data is limited. Coir and sugarcane bagasse composites studied by Ndagi et al. (2021) have the lowest thermal conductivity in the dataset at 0.01467 W/mK. They outperform others in insulation potential, but their mechanical strength is moderate, pointing out another important trade-off. Although banana and sugarcane-based composites provide excellent thermal conductivity, coir/jute composites show more balanced performance in both thermal and structural aspects, particularly under changing refrigeration loads. Additionally, the high specific heat of hemp, illustrated in Figure 4, makes it a strong candidate for hybrid composite formulations that improve thermal mass without losing insulation.

The data indicate that no single material outperforms in all categories. Instead, composite design must be application-specific, taking into account conductivity, thermal inertia, density, and moisture resistance. The comparative results from Table 2, Figure 3, and Figure 4 demonstrate these materials' expanding practicality and give a foundation for designing insulating solutions employing natural composites in modern refrigeration technology.

Table 2. Physical and thermal insulation properties of coir/jute composites.

Sample ID	Thickness (mm)	Density (g/cm^3)	Porosity (%)	Air permeability (CC/S/C m^2)	Thermal conductivity (W/mK)	Thermal insulation (TIV%)
S1C	10.02	145.3	1.01	0.33	0.112	0.02131
S2J	12.01	134.9	1.71	0.31	0.123	0.04306
S3C/J	13.34	124.3	1.54	0.34	0.143	0.05568
S4C/J	11.50	103.5	1.93	0.35	0.132	0.07056
S5C/J	10.23	113.3	1.63	0.33	0.156	0.08725
S6C/J	12.10	146.7	1.82	0.39	0.146	0.06488

Source: (Veeraprabahar et al., 2022)

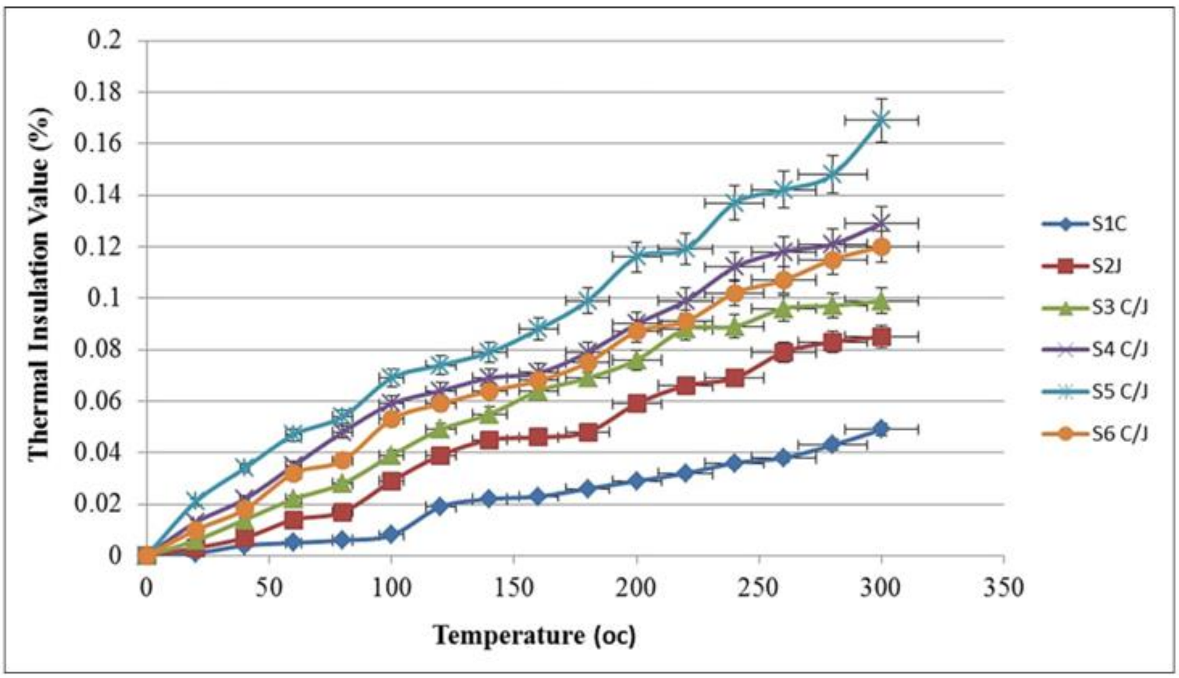

Figure 3. Thermal insulation analysis of composite materials (Veeraprabahar et al., 2022)

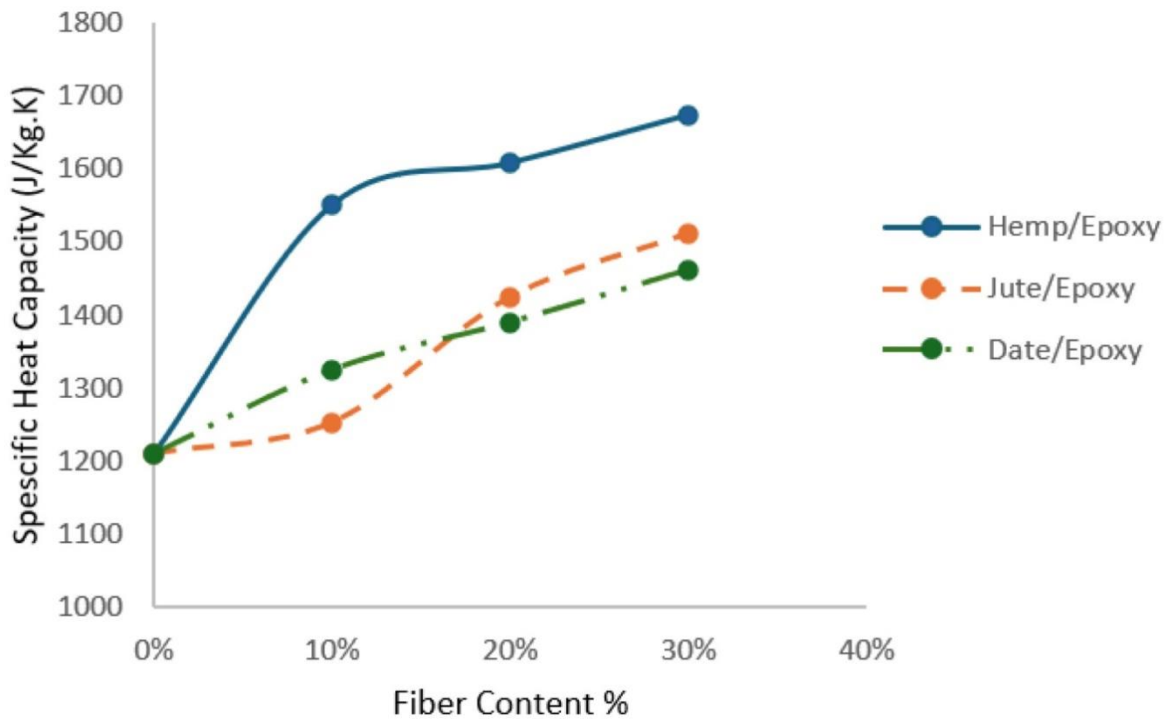

Figure 4. Heat capacity analysis for all-natural fiber composites (Alazzawi et al., 2024)

6. Conclusion

This review examines the thermal conductivity and structural performance of natural insulating materials in refrigeration systems, namely coir, jute, banana, hemp, calabash, and other bio-based composites. Natural fibre composites outperform synthetic insulators in terms of heat conductivity (varying from 0.01467 W/m·K for coir-bagasse to 0.112 W/m·K for coir-jute) and structural stability, making them suitable for refrigeration applications. Composites such as banana-eggshell epoxy and coir-jute polyurethane demonstrated low thermal conductivity and acceptable compressive strength, making them suitable for linings and panel insulation. Materials having high specific heat capacity, such as hemp, provide increased thermal inertia, which is essential for temperature stability in refrigeration conditions. However, difficulties like as moisture absorption, thermal ageing, and mechanical trade-offs persist.

Future research should focus on the development of hybrid composites, moisture-resistant treatments, and performance optimisation through statistical design methodologies. Lifecycle and cost assessments will be required for commercial viability. Natural insulating composites, with further refining, have the potential to play a significant role in the development of sustainable, energy-efficient refrigeration systems.

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