



Sodom Apple (*Calotropis procera*) Fibre as a Sustainable Thermal Insulator: Performance Evaluation for Low-Carbon Thermal Storage Systems

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Abstract

Thermal insulation materials are critical to energy-efficient thermal management systems, impacting food preservation, vaccine cold chains, and building energy use. While expanded polystyrene (EPS) foams dominate insulation applications due to low thermal conductivity and lightweight structure, they present significant environmental challenges, including non-biodegradability, microplastic generation, and high embedded carbon. This study evaluates *Calotropis procera* (Sodom Apple) fibre as a sustainable, bio-based alternative for thermal storage. Mature fruits were harvested in Maiduguri, Nigeria, fibres were extracted, cleaned, sun-dried, and compacted to $<32 \text{ kg/m}^3$ bulk density. A double-walled aluminium storage box with a 25 mm insulation cavity was fabricated, and steady-state conduction was modeled using Fourier's law. Thermal retention tests benchmarked the Sodom Apple fibre system against conventional EPS enclosures over 300 minutes. The bio-based insulation sustained temperatures above 60°C for 5 hours, achieving 84.7% of EPS performance ($k = 0.066 \text{ Wm}^{-1}\text{K}^{-1}$, $R_{\text{ins}} = 0.379 \text{ m}^2\cdot\text{K/W}$). The fibre's hollow tubular morphology and air entrapment suppress convection and reduce radiative transport, providing functional equivalence under operationally relevant durations. These findings demonstrate that lignocellulosic fibres can deliver practically viable thermal performance while significantly reducing environmental impact, supporting the development of circular, low-carbon thermal management systems.

Keywords: *Calotropis procera*; Sodom Apple fibre; bio-based insulation; thermal retention; sustainable materials; circular economy; energy efficiency

Introduction

Thermal insulation materials sit at the nexus of energy efficiency, materials sustainability, and climate mitigation. Across food preservation systems, vaccine cold chains, decentralized medical logistics, thermal packaging, and building-integrated energy systems, insulation performance directly governs energy demand and carbon intensity. Globally, thermal management accounts for a substantial fraction of final energy use, and inefficiencies in containment and storage amplify upstream energy losses. Consequently, the development of next-generation insulating materials is not merely a materials challenge but a systems-level sustainability imperative.

Currently, petrochemical foams such as expanded polystyrene (EPS) are widely employed in insulation applications because of their low thermal conductivity ($\approx 0.030\text{--}0.040\text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$), lightweight nature, and ease of fabrication. However, the environmental externalities of these materials are increasingly untenable. EPS is fossil-derived, non-biodegradable, prone to fragmentation into microplastics, and difficult to recycle at scale. Life-cycle analyses consistently highlight its embedded carbon, persistence in landfills, and ecological toxicity, particularly in regions lacking formal waste management infrastructure (Khairulmaini *et al.*, 2020; Cosentino *et al.*, 2023). As global material consumption accelerates, the cumulative environmental burden of petrochemical

foams has catalyzed urgent interest in bio-based alternatives.

Lignocellulosic fibres have recently gained attention as renewable alternatives for thermal insulation. Materials such as kapok, hemp, jute, sisal, flax, and coconut coir exhibit low bulk density, extensive porosity, and thermophysical properties comparable to synthetic foams, while offering advantages in biodegradability and reduced embodied energy, (Baraniak *et al.*, 2023; Sun *et al.*, 2023; Le *et al.*, 2023). These materials leverage hierarchical microstructures—cellulose fibrils embedded within hemicellulose–lignin matrices—to entrap air and suppress conductive heat transfer. More recently, fibres derived from *Calotropis procera* (Sodom Apple) have attracted attention due to their distinctive hollow tubular morphology and ultra-low bulk density. The fibre's large internal lumen and thin cell walls promote high air entrapment and interfacial thermal resistance, which collectively reduce effective thermal conductivity through phonon scattering and reduced solid-phase conduction pathways (Musa *et al.*, 2024; Handayani *et al.*, 2024; Perini Muniz *et al.*, 2025; Singh *et al.*, 2025). From a heat transfer standpoint, insulation performance is fundamentally governed by conductive transport under steady-state conditions, with secondary contributions from radiation and, in highly porous systems, internal convection. For a homogeneous layer, Fourier's law defines the heat flux as:

$$q = -k\nabla T$$

and for one-dimensional steady conduction across a slab of thickness L :

$$Q = KA \frac{(T_i - T_o)}{L}$$

where k represents thermal conductivity, A the cross-sectional area, and $T_i - T_o$ the imposed temperature gradient (Çengel, 2007). The thermal resistance of the material is thus:

$$R_{th} = \frac{L}{KA}$$

For porous bio-based fibres, the effective thermal conductivity k is not solely a material constant but a multiscale property governed by fibre density, pore size distribution, tortuosity, and interfacial contact resistance. In such systems:

Experimental characterization of Sodom Apple fibre by Musa *et al.* (2024) reported a thermal conductivity of $0.066 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ at moderate packing density, situating it within the performance envelope of lightweight natural insulators. Although marginally higher than EPS, this value is comparable to other lignocellulosic materials and may be further reduced through densification control, fibre alignment strategies, surface treatments, or hybrid multilayer configurations. Importantly, bio-based fibres offer substantial advantages in renewability, biodegradability, and regional availability, which may offset slight thermal performance differentials when evaluated through a life-cycle or circular-economy lens.

Addressing these gaps requires a multidisciplinary synthesis that bridges materials science, heat transfer physics, environmental assessment, and application-driven design. This review therefore critically examines Sodom Apple fibre and comparable bio-based insulators through a systems-oriented framework. By integrating mechanistic heat transfer modeling, thermophysical datasets, and sustainability metrics, the study positions biomass-derived fibres not merely as substitutes for petrochemical foams, but as enabling materials for low-carbon thermal management infrastructures aligned with global decarbonization and circular economy objectives.

Material Selection and Thermophysical Rationale

Material selection was guided by thermophysical efficiency, structural integrity, and environmental sustainability. The insulated enclosure comprised:

1. Aluminium alloy 1100-H14 (inner and outer shells)
2. *Calotropis procera* (Sodom Apple) fruit fibre (insulation core)
3. Stainless steel fasteners and silicone sealants

Aluminium was selected for corrosion resistance and formability. Given the thin wall thickness, its thermal resistance contribution is negligible:

Thus, system performance is dominated by the insulation layer.

Study Area: Maiduguri, Nigeria

This natural fibre (Sodom Apple) which is found in abundance in the study area (Maiduguri North-east of Nigeria) offers several advantages: low cost, low density, biodegradability,

renewability, and environmental friendliness, in addition to being gentle on processing equipment. Integrating such biomass-based insulation in thermal systems contributes to sustainable development and energy efficiency, while also reducing greenhouse gas emissions associated with synthetic materials.



Figure.1 Maiduguri North-eastern Nigeria location of study area laying at $11^{\circ}50'N$ $13^{\circ}09'E$.

Fibre Preparation and Density Optimization

Mature *Calotropis procera* fruits were harvested from Maiduguri ($11^{\circ}50'N$, $13^{\circ}09'E$). Fibres were manually extracted, cleaned, sun-dried to minimize moisture content, and compacted to a bulk density below $32 \text{ kg}\cdot\text{m}^{-3}$.

Optimized packing suppresses K_{conv} and limits radiative transport through fibre scattering. Measured conductivity (Musa et al., 2024):

$$K = 0.066 \frac{W}{m} / k$$



Plate 1: Sodom Apple fruit harvested and fibre extracted

Mature *Calotropis procera* fruits were harvested from Maiduguri ($11^{\circ}50'N$, $13^{\circ}09'E$). Fibres were manually extracted, cleaned, sun-dried to minimize moisture content, and compacted to a bulk density below $32 \text{ kg}\cdot\text{m}^{-3}$.

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Fabrication and Geometry

A double-walled aluminium enclosure was fabricated with a uniform 25 mm insulation cavity.

Component	Length (mm)	Width (mm)	Height (mm)
Outer Box	330	260	280
Inner Box	280	220	240
Insulation Cavity	25	25	25

Uniform fibre packing minimized density gradients, convection pockets, and thermal bridging. Edge sealing reduced infiltration losses.

Figures 2 and 3 illustrate the orthographic design of the fabricated insulated storage box. Figure 2 presents the **outer box**, detailing the overall dimensions and structural features of the aluminium enclosure. Figure 3 depicts the **inner box**, highlighting the cavity reserved for the Sodom Apple fibre insulation and the geometric relationship with the outer shell. These orthographic views provide a clear visualization of the double-walled configuration and enable precise replication of the fabrication process, ensuring uniform fibre packing and consistent thermal performance across experimental trials. The storage box was designed as a double-walled aluminium container with a 25 mm cavity for the Sodom Apple fibre. The fibre was packed uniformly to minimize convective heat losses and ensure consistent insulation (Raja et al., 2023; Olier et al., 2024).

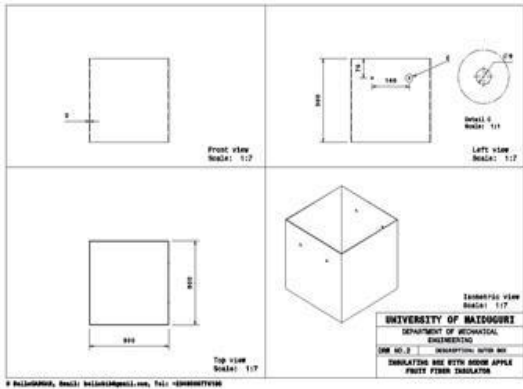


Figure 2: Orthographic view of the outer box

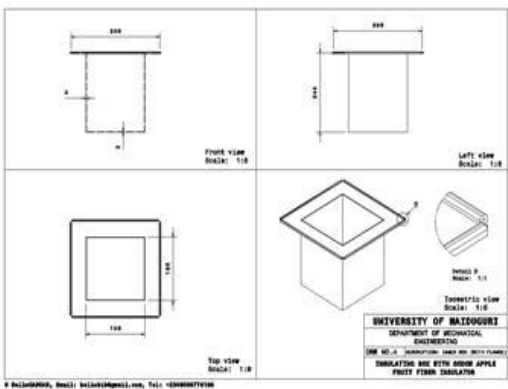


Figure 3: Orthographic view of the inner box

Steady-State Conduction

Heat transfer through the insulation layer follows Fourier’s law:

$$Q = KA \frac{(T_i - T_o)}{L}$$

Thermal resistance:

$$R_{tns} = \frac{L}{K}$$

For L = 0.025 m and k = 0.066 W·m⁻¹·K⁻¹:

$$R_{tns} = 0.379 \frac{\frac{m^2}{K}}{W}$$

Sustainability and Systems Context

Expanded polystyrene (EPS) and polyurethane foams exhibit low thermal conductivity but carry high embodied energy, persistence, and end-of-life environmental burdens. In contrast, *Calotropis procera* fibre offers:

- i. Renewable biomass origin
- ii. Low embodied carbon
- iii. Biodegradability
- iv. Local availability in semi-arid regions

Integration of bio-based insulation into thermal containment systems reduces dependence on petrochemical materials while maintaining functional performance.

From an energy systems perspective, improved passive insulation reduces refrigeration loads, transport energy demand, and lifecycle emissions—supporting decentralized thermal resilience strategies.

Thermal Retention Performance and Functional Equivalence

The thermal containment behavior of the Sodom Apple fibre–insulated enclosure was evaluated over a 300-minute interval and benchmarked against a conventional expanded polystyrene (EPS) reference system. The results are summarized in Table 2.

Table 2. Temperature Retention Comparison

Time (min)	EPS Box (°C)	Sodom Apple Box (°C)
60	84.8	86.4
180	79.2	74.4
300	72.0	61.0

At early time scales (≤60 min), the bio-insulated system exhibited marginally superior retention, likely attributable to suppressed internal convection arising from fibre entanglement and reduced air mobility within the porous matrix. Over extended durations, the EPS enclosure demonstrated lower cumulative heat loss, consistent with its lower intrinsic thermal conductivity and reduced radiative transfer contribution. Table 2 shows the Thermal Retention, indicating the synthetic box performs slightly better, the Sodom Apple box

comfortably stays above the 60°C food safety threshold for up to five hours (Abdulrahim et al., 2020; Musa et al., 2024).

The relative thermal retention efficiency at 300 minutes is:

$$\eta_{rel} = \frac{T_{SA}}{T_{EPS}} \times 100$$

$$\eta_{rel} = \frac{61}{72} \times 100 = 84.7\%$$

Thus, the bio-derived insulation achieves approximately **85% of the thermal performance** of a petrochemical foam benchmark under identical boundary conditions.

This confirms that natural fibre insulation is not only sustainable but also practically viable for temperature-sensitive applications. Similar results have been reported in other studies using biodegradable composites (Babenko et al., 2024; Cárdenas-Oscanoa et al., 2025).

Heat Transfer Interpretation

Under steady-state approximation, conductive heat transfer through the insulation layer is governed by:

$$Q = KA \frac{(T_i - T_o)}{L}$$

The higher long-term retention of EPS is consistent with its lower thermal conductivity relative to the measured $k=0.066 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ for Sodom Apple fibre. However, the performance gap remains modest when evaluated under practical containment durations (<5 hours).

The observed decay behaviour aligns with transient heat transfer theory:

$$\frac{T_{(t)} - T_{\alpha}}{T_0 - T_{\alpha}} = \exp\left(-\frac{t}{\tau}\right)$$

where the time constant τ is influenced by composite resistance and system thermal capacitance. The natural fibre's hollow microstructure and entrapped air pockets contribute to suppression of internal convection and radiative transfer, partially compensating for its higher conductivity relative to EPS.

Importantly, the Sodom Apple fibre system maintained temperatures above the **60 °C food safety threshold** for up to five hours, satisfying practical thermal containment requirements for domestic, educational, and humanitarian applications. This functional parity over operationally relevant time scales is critical when evaluating material substitution viability.

Comparative Context within Sustainable Materials Research

The observed 84.7% relative efficiency lies within the 75–90% performance band reported for other biodegradable insulation systems. Across the literature, bio-derived fibrous insulators

consistently demonstrate competitive thermal performance when optimized for density and moisture control. The present findings reinforce a growing materials paradigm: **complete parity with petrochemical foams is not always required for application viability.**

Instead, achieving sufficient functional performance within sustainability-constrained design space represents a more appropriate optimization objective.

Conclusion

This study demonstrates that *Calotropis procera* (Sodom Apple) fibre is a technically credible and environmentally superior alternative to expanded polystyrene (EPS) for insulated thermal storage. A 25 mm fibre layer in a double-walled aluminium enclosure sustained temperatures above the 60 °C safety threshold for five hours, delivering 84.7% of the retention efficiency of EPS.

While EPS marginally outperforms in long-duration retention, the gap is comparatively small relative to the sustainability gains achieved through a renewable, biodegradable, and low-embodied-carbon material system. The intrinsic hollow fibre morphology and entrapped air structure provide effective resistance to conductive and convective heat transfer within a lightweight architecture.

Collectively, the findings support the integration of lignocellulosic insulation into circular thermal management systems, particularly in biomass-abundant regions. Future work should prioritize conductivity reduction via microstructural optimization, moisture stabilization strategies, hybrid composite development, and full life-cycle assessment to accelerate commercial translation.

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