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Comparative Thermal Performance Evaluation of Solar Box Cookers Insulated with Kapok Fiber and Sodom Apple Fiber Materials

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ABSTRACT
Reliance on biomass fuels in developing countries has led to environmental degradation and health challenges, highlighting the need for affordable clean cooking alternatives. This study compares the thermal performance of solar box cookers insulated with Kapok fiber and Sodom apple (Calotropis procera) fiber. Two identical cookers were tested using Bureau of Indian Standards (BIS IS 13429:2000) procedures under no-load and water-heating conditions. Performance was evaluated using absorber temperature profiles, first figure of merit (F_1), and second figure of merit (F_2). Both systems showed nearly identical performance, with peak absorber temperatures of 145.7 °C (Kapok) and 146.6 °C (Sodom apple fiber). F_1 values (0.123–0.124 m²K/W) confirmed Grade A performance, while F_2 values (0.056–0.057) indicated similar heat transfer efficiency. Statistical analysis ($p > 0.05$) showed no significant differences between the cookers. Results confirm that Sodom apple fiber performs comparably to Kapok fiber and all locally sourced insulating materials represents a viable, low-cost, and sustainable insulation material for solar box cookers.

Keywords: Solar cooker; Kapok fiber; Calotropis procera; thermal insulation; renewable energy; experimental analysis; energy efficiency

INTRODUCTION

In Nigeria and many developing countries, access to conventional cooking fuels such as kerosene, liquefied petroleum gas (LPG), and electricity remains constrained by high costs and unreliable supply. Consequently, a significant proportion of households rely on biomass fuels, particularly firewood, leading to deforestation, environmental degradation, and adverse socio-economic and health impacts (International Energy Agency [IEA], 2022; World Bank, 2021). The transition to sustainable cooking technologies is therefore critical to achieving energy security and environmental sustainability.

Solar cooking technology offers a clean, renewable, and environmentally benign alternative, particularly in regions with high solar insolation such as northern Nigeria, where solar radiation levels can reach approximately 7 kWh/m²/day with extended sunshine duration (Muhammad *et al.*, 2015). Among the available solar cooking technologies, the box-type solar cooker remains the most practical for household use due to its simplicity, safety, affordability, and ease of operation (Mahavar *et al.*, 2012; Abdulrahim *et al.*, 2020). However, its widespread adoption is still limited by relatively low thermal efficiency and longer cooking times compared to conventional systems (Olatunde, 2025; Palatkar and Katekar, 2025).

Recent advancements in solar cooker research have focused on improving thermal performance through design modifications, heat transfer enhancement, and integration of advanced materials (Palatkar and Katekar, 2025; Ibrahim, 2026). For instance, the incorporation of finned cooking pots has been shown to significantly improve convective heat transfer, resulting in increased cooking power and thermal efficiency of up to 40.55% (Goyal, 2023). Similarly, hybrid and optimized solar cooker configurations have demonstrated improved heat retention and reduced cooking time through enhanced thermal management strategies (Ibrahim, 2026). Furthermore, recent experimental investigations have explored the use of alternative natural insulating materials, such as agricultural waste (e.g., sawdust, groundnut shells, and feathers), highlighting the critical role of insulation in minimizing heat losses and improving overall system performance (Ishaq, 2023; Raut *et al.*, 2023).

In addition, state-of-the-art reviews emphasize that thermal performance parameters such as the first and second figures of merit (F_1 and F_2), cooking power, and exergy efficiency remain the standard metrics for evaluating solar cooker performance, with recent high-performance designs achieving significantly improved values through integrated thermal storage and optimized absorber configurations (Palatkar and Katekar, 2025). Despite these advancements, the effectiveness of solar box cookers continues to depend largely on the thermophysical properties of insulation materials, particularly thermal conductivity, density, and heat retention capacity (Ba *et al.*, 2025; Bravo-Moncayo *et al.*, 2024).

Natural fibers have emerged as promising insulation materials due to their low thermal conductivity, biodegradability, and local availability (Ba *et al.*, 2025; Raut *et al.*, 2023). Kapok fiber, for instance, is well known for its hollow microstructure and excellent insulating capability, which significantly reduces conductive heat losses (Zerga and Tahir, 2022; Kannan *et al.*, 2025). Conversely, Sodom apple fiber (*Calotropis procera*), an underutilized bio-resource, has recently attracted attention due to its fibrous morphology, air-trapping characteristics, and moderate thermal resistance, suggesting its potential suitability for thermal insulation applications (Sathish *et al.*, 2021).

Despite the growing interest in natural fiber insulation for solar thermal applications, limited comparative studies have evaluated the thermal performance of solar box cookers insulated with locally available natural fibers such as kapok fiber and Sodom apple fiber under the same operating conditions. This knowledge gap limits the identification of suitable, low-cost, and sustainable insulation materials for improving solar cooker performance in developing countries. Therefore, the aim of this study is to comparatively evaluate the thermal performance of solar box cookers insulated with kapok fiber and Sodom apple fiber materials using standard performance indicators, including the first and second figures of merit (F_1 and F_2), cooking power, thermal efficiency, and heat retention characteristics, in order to determine the more effective insulation material for enhancing solar cooking performance.

MATERIALS AND METHODS

Insulation materials

The selection of insulation materials was based on their thermophysical characteristics, particularly thermal conductivity, porosity, and density**,** which strongly influence heat retention in solar cookers (Raut *et al.,* 2023). Kapok fiber has been widely reported as an excellent natural insulator due to its hollow microstructure and extremely low thermal conductivity. In this study, Kapok fiber is considered with a thermal conductivity value as low as 0.007 W/m·K, as reported by Musa et al. (2023), which significantly enhances its ability to reduce conductive heat losses. This value is consistent with previously reported ranges for Kapok insulation materials (Zerga and Tahir, 2022; Kannan *et al.,* 2025). Figure 1 shows Seed Pod and fruity of Kapok Silk cotton tree.

Figure 1: Seed Pod and fruity of Kapok Silk cotton tree

In contrast, Sodom apple fiber (*Calotropis procera*) is an underutilized lignocellulosic material that exhibits moderate thermal resistance, fibrous morphology, and air entrapment capability**,** contributing to reduced heat transfer and improved insulation performance (Sathish *et al.,* 2021). Although it's thermal conductivity is higher than that of Kapok fiber, its availability and structural properties make it a promising alternative for low-cost thermal insulation applications (Raut *et al.,* 2023). Sodom Apple fruit harvested and fibre extracted is shown in Plate 1.

Plate 1: Sodom Apple fruit harvested and fibre extracted

Design and Fabrication of Solar Box Cookers

Two identical solar box cookers, designated as Cooker A (Kapok fiber insulation) and Cooker B (Sodom apple fiber insulation), as depicted in plate 2, were designed and fabricated for comparative performance evaluation. The design adopted a double-walled hot box configuration, which is widely recognized for minimizing conductive and convective heat losses in solar thermal systems (Mahavar *et al.,* 2012; Olatunde, 2025).

The outer casing was constructed from ¾-inch plywood with dimensions of 700 × 700 × 445 mm, while the inner absorber chamber was trapezoidal with dimensions of 400 × 400 × 360 mm, inclined at 21° to optimize solar radiation interception. The annular space between the inner and outer walls served as the insulation layer and was filled with Kapok fiber for Cooker A and Sodom apple fiber (*Calotropis procera***)** for Cooker B. figure 2, shows the Isometric drawing of the solar box cooker.

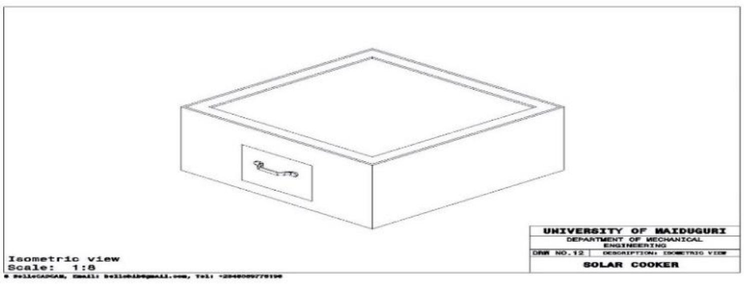

Figure 2: Isometric drawing of the solar box cooker

The absorber tray was fabricated from aluminum sheet and coated with matte black paint to maximize solar absorptivity and minimize reflectivity. To reduce heat losses through radiation and convection, a triple-glazed cover system consisting of three 4 mm thick glass panes with a 25 mm air gap was installed. The trapped air layer acts as an additional insulating barrier, improving thermal retention within the cooker (Sharma *et al.,* 2000; Ibrahim, 2026). A 1.5 mm rubber gasket was placed between the glazing and cooker body to prevent air leakage and maintain internal thermal stability.
Standard cylindrical cooking vessels made of aluminum alloy (18 cm diameter and 10 cm height**)** were used. Each vessel was painted black and fitted with a lid to enhance heat absorption and reduce evaporation losses. Both cookers were identical in all respects except for the insulation material, ensuring a valid comparative experimental framework.

Experimental Procedure and Performance Evaluation
The experimental investigation was conducted at the Centre for Entrepreneurship and Enterprise Development (CEED), University of Maiduguri, Nigeria**.** The cookers were placed in an open field free from shading to ensure maximum solar exposure throughout the experimental period**,** following standard solar cooker testing practices (Mullick *et al.,* 1996; Olatunde, 2025).
Performance evaluation was carried out in accordance with the Bureau of Indian Standards (BIS IS 13429:2000), which provides standardized procedures for assessing solar cooker performance independent of climatic variations (Bureau of Indian Standards [BIS], 2000). The evaluation was based on two key thermal performance indicators:
First Figure of Merit (F_1): representing optical efficiency and heat loss characteristics under no-load (stagnation) conditions
Second Figure of Merit (F_2): representing heat transfer efficiency under load (water heating) conditions
The stagnation test was conducted to determine F_1, while the water heating test was used to determine F_2, consistent with established methodologies in solar cooker performance evaluation (BIS, 2000; Goyal, 2023). The test procedure provides performance characteristics of solar cookers, more or less independent of climatic variables. There are two thermal performance parameters called figures of merit (F1 and F2) associated with testing box-type solar cookers as per BIS. The First Figure of Merit, F1, is determined from a stagnation test under no-load condition while the Second Figure of Merit, F2, is determined from test under full-load condition, taking water as the load. First Figure of meritF_1, (°C m^2/W) or stagnation test is defined as ((BIS) IS 13429: 2000)

$$F_1 = \frac{T_p - T_a}{I_s} \qquad (1)$$

Where Tp, Ta, and is are absorber plate temperature, ambient temperature and solar intensity on a horizontal surface at a time stagnation temperature is reached respectively. Second Figure of merit F_2 or water heating test is defined as ((BIS) IS 13429: 2000);

$$F_2 = \frac{F_1 m_w c_w}{At} \ln\left[\frac{1-\frac{1}{F_1}\left(\frac{T_{w1}-T_a}{I_s}\right)}{1-\frac{1}{F_1}\left(\frac{T_{w2}-T_a}{I_s}\right)}\right] \qquad (2)$$

where F_1 is the First Figure of Merit, M_w is the mass of the water, C_w is the specific heat of water, T_{w1} is the initial temperature of water (≡ 60°C), T_{w2} is the final temperature of water (≡ 90°C), t is the measured time difference in which the water temperature rises from T_{w1} to T_{w2}, T_a is the average ambient temperature over the time period t, H is the average solar radiation intensity incident on the aperture of the cooker, and A is the aperture area of the solar cooker.

Instrumentation and Data Collection
Solar radiation intensity was measured using a digital pyranometer**,** while ambient temperature and wind speed were recorded using a digital thermometer and anemometer, respectively. Absorber plate and water temperatures were measured using thermocouples connected to a digital data logger system**.**
Water volume was measured using a graduated measuring cylinder**,** ensuring consistent loading conditions across both cookers. All measurements were recorded at 10-minute intervals to ensure high temporal resolution and data accuracy (Raut *et al.,* 2023; Ibrahim, 2026). Table 1 shows Instruments used for data collection at 10 minutes interval.

Table 1: Instruments Table

Description	purpose
Digital pyrometer (SPM-1116SD)	Solar radiation intensity (W/m^2)
Measuring cylinder	Water volume (m^3)
Digital aerometer (ABH-4224) Digital	wind speed (m/s) and Ambient Temperature (^{0}C)
thermometer (MTM-3801) and thermocouples	Water temperature and absorber plate temperature (^{0}C)

The experiments were conducted, maintaining compliance with BIS-recommended ranges for solar radiation and ambient temperature to ensure validity, repeatability, and comparability of results**.** Plate 2 depicts the experimental set up.

Plate 2: Experimental Set Up of the Two Similar Solar Box Cookers

RESULTS AND DISCUSSION

Absorber Temperature Performance

Figure 3 shows the variation of absorber temperature for solar box cookers insulated with Kapok fiber (Ceiba pentandra) and Sodom apple (*Calotropis procera*) fiber under identical solar radiation conditions. Experiments were conducted between 10:00 and 14:00 at 20-minute intervals under clear sky conditions.

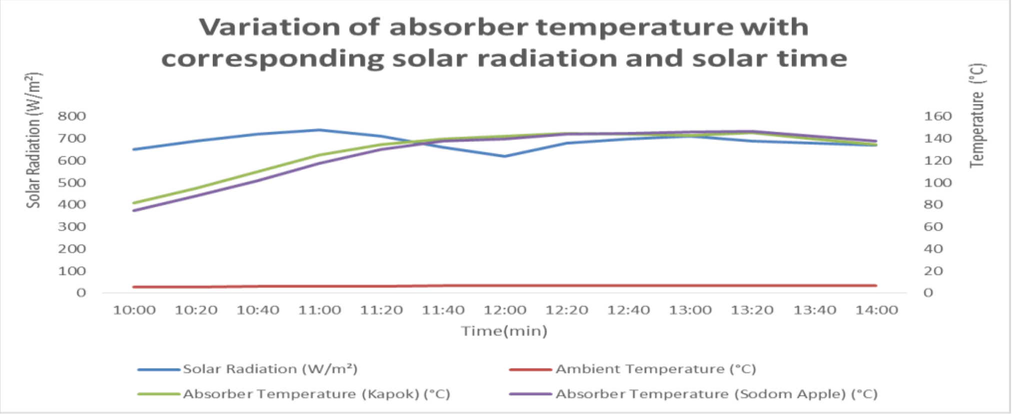

Figure 3: Variation between the Absorber Temperature of solar cooker with kapok wool insulator and the Absorber Temperature of solar cooker with Sodom Apple fiber insulator with corresponding solar radiation/solar time

Initial absorber temperatures were 81.5 °C (Kapok) and 74.8 °C (Sodom apple fiber). Both systems exhibited similar heating trends, with temperatures increasing steadily and reaching peak values at approximately 13:20.

Maximum absorber temperatures were 145.7 °C for the Kapok-insulated cooker and 146.6 °C for the Sodom apple fiber-insulated cooker. The negligible difference confirms comparable thermal retention performance, indicating that both materials effectively minimize heat losses.

This behavior agrees with previous studies which report that absorber temperature dynamics in box-type solar cookers are primarily governed by solar radiation intensity and glazing performance rather than minor differences in insulation materials (Bello *et al.,* 2010; Mohammed *et al.,* 2013).

3.2 First Figure of Merit (F_1)

The first figure of merit (F_1) was computed using standard BIS procedures. The results obtained were found Kapok fiber: 0.123 m²K/W Sodom apple fiber: 0.124 m²K/W using equation (1)

According to the Bureau of Indian Standards (BIS, 2000), a solar cooker is classified as Grade A when $F_1 \geq 0.12$ m²K/W. Both systems therefore meet Grade A requirements, confirming high thermal performance.

The slightly higher value for Sodom apple fiber may be attributed to its fibrous structure, higher air entrapment capability, and improved resistance to conductive heat transfer at the system level.

When compared with earlier studies, the present results show strong agreement:

Bello et al. (2010) reported F_1 values between 0.115–0.128 m²K/W for similar box cookers. , Abdulrahim *et al.,* (2021) obtained $F_1 \approx 0.122$ m²K/W for Kapok-insulated systems under comparable climatic conditions and Mahavar *et al.,* (2012) reported typical values of 0.12–0.13 m²K/W for well-insulated solar box cookers. Therefore, the present study lies within the upper performance range of previously reported systems.

3.3 Water Temperature Performance

Figure 5 shows the variation of water temperature for solar box cookers insulated with Kapok fiber and Sodom apple (*Calotropis procera*) fiber under corresponding solar radiation and ambient conditions. The test was conducted from 10:00 to 12:10 at 10-minute intervals.

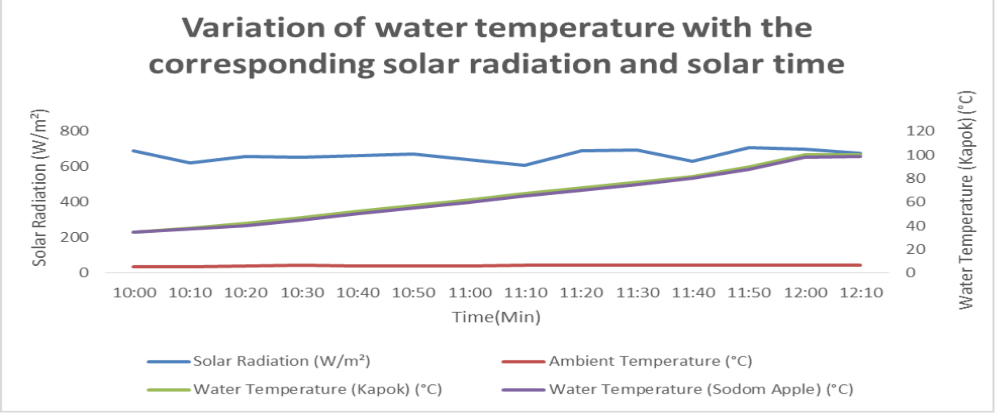

Figure 5: Variation between the Water Temperature of solar cooker with kapok wool insulator and the Water Temperature of solar cooker with Sodom Apple fiber insulator with corresponding solar radiation/solar time of water temperature with the corresponding solar radiation/solar time

Initial water temperatures for both cookers were nearly the same (≈30–32 °C), close to ambient conditions. As solar radiation increased (≈680–710 W/m²), both systems exhibited a steady rise in water temperature.
The Kapok-insulated cooker reached about 100 °C, while the Sodom apple cooker attained a comparable peak of about 98–100 °C. The similar temperature profiles indicate nearly identical heating performance.
The small difference confirms that both insulation materials provide comparable thermal efficiency under load conditions, with performance largely governed by solar intensity and system design rather than insulation differences. This agrees with earlier findings (Bello et al., 2010; Mohammed et al., 2013).
3.4 Second Figure of Merit (F_2)
Under full-load conditions, the second figure of merit (F_2) values were Found to be (Kapok fiber: 0.057 Sodom apple fiber: 0.056) using equation (2)
The close similarity indicates nearly identical heat transfer efficiency from absorber plate to cooking vessel, confirming effective thermal performance under similar operational conditions.
These results are consistent with earlier studies: Mahavar et al. (2012) reported F_2 values of 0.05–0.06 for single-pot box cookers, Mohammed et al. (2013) obtained $F_2 \approx 0.055$ for truncated pyramid solar cookers, Folaranmi (2013) reported values in the range of 0.056–0.058 for double-glazed solar ovens.
The present findings therefore confirm that both systems operate within the standard performance ranges for efficient solar cooking devices.
3.5 Statistical validation of findings using Independent Sample t-Test
To evaluate whether observed differences were statistically significant, an independent sample t-test was conducted at a 95% confidence level ($\alpha = 0.05$).
3.51 Absorber Temperature Comparison, table 2 has shown the statistical comparison absorber temperature Performance observations

Table 2 Statistical Comparison of Absorber Temperature

Parameter	**Kapok**	**Sodom Apple**
Mean (°C)	127.64	124.12
Variance	378.10	422.22
Observations	25	25

T-test results: $t = 0.62$, $df = 48$, $p = 0.536$ and Cohen's $d = 0.176$

Interpretation: The p-value (> 0.05) indicates no statistically significant difference between both systems. The very small effect size confirms negligible practical difference.

3.5.2 Water Heating Performance Comparison, table 3 has shown the statistical comparison water heating performance observations

Table 3: Statistical Comparison of Water Heating Performance

Parameter	**Kapok**	**Sodom Apple**
Mean (°C)	68.80	65.74
Variance	454.30	439.00
Observations	14	14

T-test results: $t = 0.38$, $df = 26$, $p = 0.705$ and Cohen's $d = 0.145$

Interpretation: There is no statistically significant difference in water heating performance. Both systems are functionally equivalent under operational conditions.

CONCLUSION

This study compared the performance of solar box cookers insulated with Kapok fiber and Sodom apple (Calotropis procera) fiber under identical operating conditions using standard thermal performance indicators (F_1 and F_2) and statistical analysis. Results showed very close thermal performance for both systems. Peak absorber temperatures were 145.7 °C (Kapok) and 146.6 °C (Sodom apple fiber), indicating similar heat retention behavior. The F_1 values (0.123–0.124 m²K/W) confirm that both cookers meet the BIS Grade A standard ($F_1 \geq 0.12$ m²K/W), while F_2 values (0.056–0.057) further indicate comparable heat transfer efficiency under load conditions.Independent sample t-test results ($p > 0.05$, $d < 0.2$) confirmed that the differences in thermal performance are statistically and practically insignificant, demonstrating functional equivalence between the two insulation materials at system level.When compared with published studies, the performance indices fall within established ranges for efficient box-type solar cookers, confirming the validity of the results.Overall, both Kapok and Sodom apple fibers are suitable insulation materials for solar box cookers. However, Sodom apple fiber offers additional advantages in terms of local availability, low cost, and sustainability, making it a viable alternative for scalable solar cooking applications in developing regions.

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