

DETERMINATION OF THE PHYSICAL AND THERMAL CHARACTERISTICS OF SODOM APPLE (CALATROPIS PROCERA) FRUIT FIBRES HARVESTED IN MAIDUGURI, BORNO STATE, NIGERIA

Musa, H.* , Abdulrahim, A.T., Ngala, G.M. and Hammajam, A.A.

Department of Mechanical Engineering, University of Maiduguri, P.M.B. 1069 Maiduguri, Nigeria

*Corresponding email: harunadabujii@gmail.com

ABSTRACT

This study addresses the environmental concerns associated with the widespread use of synthetic fibers, emphasizing their non-biodegradability, contribution to microplastic pollution, and energy-intensive manufacturing processes. The research focuses on evaluating the physio-thermal properties of Calotropis procera fiber harvested in Maiduguri, Borno State, Nigeria. Key objectives include determining the density, moisture content, and water absorption of Sodom Apple (Calotropis procera) fibers, investigating their morphology, assessing thermal conductivity, heat transfer coefficient, and specific heat capacity, as well as conducting thermo-gravimetric analyses. The fibers were meticulously collected, cleaned, sorted, and subjected to standard testing methods namely scanning electromicroscopy, density test, moisture content test, moisture absorption tests, thermal conductivity test and Thermogravimetric. The collected Sodom Apple fibers exhibit a single-cell structure with a fine, hollow, and smooth composition, resembling fibers like kapok or cotton. The specific gravity of 0.1124 and density of 0.1099 g/l indicate a lightweight nature, while exceptional moisture absorption at 66.144%, along with a moisture content of 11.04%, suggests potential suitability for insulation purposes. Thermal analysis reveals a low thermal conductivity of 0.066 W/mK, a heat transfer coefficient of 1.6814 W/m²K, and a specific heat capacity of 0.0156 J/kg°C. Thermal Gravimetric Analysis depicts distinct weight loss stages, further supporting the fiber's promising characteristics for sustainable applications. These findings collectively suggest the fiber's lightweight nature, outstanding moisture absorption, and potential suitability for insulation purposes. The structural and thermal characteristics bear resemblance to fibers like kapok or cotton, signifying comparable attributes.

Keywords: Sodom Apple, Fibre, Insulation, Thermal.

1 INTRODUCTION

Thermal insulation materials play a crucial role in minimizing heat transfer. While synthetic materials dominate the market due to their desirable physical properties, such as low thermal conductivity and moisture protection, they come with high costs and environmental hazards [1]. Synthetic insulating materials like calcium silicate, mineral fiber, fiberglass, polyurethane, polystyrene, perlite, and rock wool are popular due to their low thermal conductivity, but concerns regarding cost, health, and environmental impact warrant exploration of alternative thermal insulators. Natural fibers from agricultural crops like hemp, kenaf, or flax are gaining favor due to their eco-friendly, renewable, and biodegradable characteristics, offering superior insulation properties [2]. After decades of focusing on high-tech artificial fibers, there is renewed interest in natural fibers such as kenaf, flax, jute, hemp, and sisal [3]. The advantages of using natural reinforcements in composite materials include biodegradability, lower specific weight resulting in higher specific strength and stiffness than glass, renewable resources requiring little energy for

production, and eco-friendly processing with low costs [4]. Synthetic fibers, being non-renewable and non-biodegradable, pose disposal challenges and contribute to environmental pollution. In contrast, natural fibers are abundant, renewable, and cost-effective, making them viable substitutes in various applications [5]. The refurbishment of existing structures has led to a significant volume of discarded insulation materials, prompting the search for biodegradable, sustainable, and environmentally friendly options [6]. Sodom Apple (*Calotropis procera*), a xerophytic shrub found in tropical regions, offers natural fibers with good strength and fineness, making it a potential source of eco-friendly insulation [7]. However, its rapid spread as a weed raises environmental concerns, and its abundance in Borno state, Nigeria, presents an untapped resource. Researchers have investigated the properties of Sodom Apple fibers due to their resilience against mechanical and thermo-physical stresses [8]. Thermal insulation materials are pivotal in minimizing heat transfer, with synthetic options dominating the market due to their favorable physical attributes like low thermal conductivity and moisture resistance. However, the high costs and environmental risks associated with synthetic materials, as highlighted by [1] prompt a need for exploring alternative thermal insulators. Natural fibers derived from agricultural crops, such as hemp, kenaf, and flax, are gaining traction due to their eco-friendly, renewable, and biodegradable qualities, offering superior insulation properties [2]. In a shift away from decades of emphasis on high-tech artificial fibers, there is a renewed interest in natural fibers like kenaf, flax, jute, hemp, and sisal, as noted by [3]. The advantages of incorporating natural reinforcements in composite materials are numerous, including biodegradability, lower specific weight leading to higher specific strength and stiffness than glass, reliance on renewable resources with minimal energy requirements for production, and eco-friendly processing with low costs [4]. Synthetic fibers, being non-renewable and non-biodegradable, pose challenges in disposal and contribute to environmental pollution. In contrast, natural fibers are abundant, renewable, and cost-effective, making them viable substitutes in various applications [5]. Natural fibers like cotton, wool, hemp, jute, and coir have proven themselves as effective insulators over time, offering outstanding thermal properties along with eco-friendly characteristics. The increasing concerns about the environmental impact, sustainability, and health risks associated with synthetic fibers have driven a shift towards sustainable alternatives [9]. This study aims to explore the physio-thermal properties of *Calotropis procera* fibers harvested in Maiduguri, Borno State, Nigeria. Objectives include determining density, moisture content, water absorption, morphology, thermal conductivity, heat transfer coefficient, specific heat capacity, and conducting thermo-gravimetric analyses of Sodom Apple fibers. Plates 1 and 2 depict Sodom Apple fruit and the fruit fiber.



Plate 1. Sodom Apple fruit



Plate 2. Sodom Apple fruit fibre

2 LITERATURE REVIEW

[10] emphasizes the growing competitiveness of nature-based thermal insulation products, such as straw bales, fiberboard, and cellulose insulation, driven by advancements in manufacturing technology, durability, reliability, and adherence to standards. New products using renewable raw materials, particularly agricultural or industrial by-products like hemp fiber, flax fiber, cotton, and seagrass, have emerged. Research and development efforts aim to harness agricultural waste, including palm fiber, cornstalks, and sunflower stalks, to create innovative thermal insulating products. [11] Present experimental results indicating that thermal conductivity of new boards using cornstarch as a binder is comparable to Rockwool

mineral fiber. The organic nature of cornstarch makes it a promising and safer alternative. [12] argue that, from a sustainability perspective, natural organic fiber-based thermal insulating materials offer a better alternative to synthetic counterparts, despite challenges such as high-water absorption and poor fire response. [1], conducted a study characterizing local date palm fibers, demonstrating their good thermal conductivity compared to other natural and synthetic insulating materials. This suggests the potential for the development of efficient and safe thermal insulating materials using date palm wood. [13] focused on the thermal performance of Natural Pumice-Based Bricks, showcasing their advantages in lighter weight, tensile strength, and superior thermal insulation characteristics. [14] Investigated six different thermal insulators made from various materials, with the insulator made from used water cotton filter proving to be the most efficient. [15] Explored the apparent thermal conductivity for biodegradable coconut and sugarcane fiber, indicating their suitability for building thermal insulation. [16] studied the variation of thermal properties of selected wood materials, showcasing low thermal conductivity comparable to industrial insulators. [17] Investigated the physical and chemical properties of kapok and balsa fibers, highlighting their composition and characteristics. [18] Researched the thermal conductivity of experimental wall constructions made from renewable insulating materials, showing competitive potential for these materials in the building materials market. [2] Characterized thermal insulation materials developed with crop wastes and natural binders, finding comparable thermal conductivity to wood fiber boards. [19] Studied natural fiber insulation in rural Southern Chile, with sheep's wool providing the best insulation values. [20] compared the thermal conductivity of various natural fibers, with banana fiber showing the lowest value. [21] presented thermal analysis and acoustic characteristics of Apple of Sodom fibers, demonstrating their stability and potential for sound absorption. [22] explored composites of *Calotropis gigantea* fruit fiber-polyester composites, suggesting the potential of natural fiber-reinforced plastics in replacing synthetic fiber composites. [23], experimented with the mechanical and machining properties of *Calotropis gigantea* fruit fiber-reinforced plastic, highlighting improvements in tensile strength, modulus, flexural strength, modulus, and impact energy. These studies collectively underscore the diverse and promising landscape of natural and renewable materials for thermal insulation, showcasing their potential to compete with and, in some cases, outperform synthetic alternatives. Table 1 Indicates the range of thermal conductivity for nature based thermal Insulation materials.

Table 1. Thermal conductivity of nature-based thermal insulation materials [10]

Material	Thermal conductivity (W/mK)
Rediscovered materials	
Cork	0.037-0.060
Wood wool	0.070-0.090
Fiberboard	0.040-0.090
Particleboard	0.055-0.100
Reeds	0.042-0.060
Straw bales	0.038-0.072
Flax	0.037-0.045
Hemp	0.039-0.050
Recently introduced materials	
Cellulose insulation	0.045-0.055
Cotton	0.040-0.050
Sheep wool	0.035-0.040
Coconut fiber	0.040-0.050
Seagrass	0.040-0.045
Materials in experimental stage	
Cornstalk block	0.045-0.055
Corn cob board	0.096
Bamboo fibers	0.080-0.340
Palm fibers	0.041
Kenaf fibers	0.039
Sunflower stalks	0.064-0.085

3 MATERIALS AND METHODS

3.1 Material Selection

Choosing suitable natural fibers based on its flexibility, availability for the intended application. *calotropis procera* fruit fibre was chosen. Preparation: Cleaning and treating the fibers to remove impurities. Characterization: Testing the physio-thermal properties of the *calotropis procera* fruit fibre ensure it meets the required standards and specifications. These methods involve a combination of scientific knowledge, material engineering, and processing techniques to assess a new natural thermal insulation material with improved properties for various applications. Five test samples were prepared and the average value was reported. The *calotropis procera* fruit fibre was obtained from matured pods of the *calotropis procera* tree and the fibre is extract from the pods by hand and partly dried. Complete drying was done by spreading the fibre on sheets in room for about three days until the fibre becomes lustrous in appearance and a fair amount of dust and dirt separates out from the fibre using manual method as perfumed by [31]

3.2 Fiber surface morphology

The surface morphology of Sodom Apple (*calotropis procure*) fruit fibre was examined using a scanning electron microscope (SEM; SUPRA Zeiss, Oberkochen, Germany), Plate 3 shows SEM machine. The fiber sample was coated with a thin gold layer to make its surfaces conductive and to avoid electron charge gathering. The SEM studies was conduct by scanning the samples with a high-energy electron beam at an accelerating voltage of 10 kV in a vacuum chamber.



Plate 3. EM machine SEM; SUPRA Zeiss, Oberkochen, Germany)

3.3 Sample Density

The density of the Sodom Apple fiber sample was determined using water displacement method. Density was calculated from the ratio of the mass to the volume of water displaced by the sample. The weight of the sample was taken before placing it into the water and the increment in the volume of water is automatically the volume of the sample.

$$\rho = \frac{M}{V} \quad (1)$$

where ρ = Density, M = Mass of sample (g) and V = Volume of water displaced(cm^3).

3.4 Water absorption

Water absorption of the Sodom Apple fiber as a function of immersion time was determined following ASTM D570. Test specimen (11 cm^3) was immersed in distilled water at room temperature for 24 hours and was removed and dried off excess water using towel. The percentage increase in weight during the immersion was calculated by the following equation:

$$\text{water absorption (\%)} = \left[\frac{(w-w_0)}{w_0} \right] \times 100\% \quad (2)$$

Where w is wet final weight and w_0 is dried initial weight in gram.

3.5 Determination of Moisture Content

To determine of a moisture content of the sample at displayed adsorption water activity and temperature, 10g of the material from the cell was weighed into sample baskets and placed in a BIOBASE infrared moisture analyzer sets at 105°C. The analyzer will digitally display the moisture content of sample in percentage wet basis. The moisture content obtain is term the equilibrium moisture content (EMC) of the sample at the corresponding water activity. Plate 4 show BIOBASE infrared moisture analyzer with a sample loaded.



Plate 4. BIOBASE infrared moisture analyzer loaded with sample

3.6 Thermal Conductivity test

The thermal conductivity of the composite samples was measured by using TecQuipment (TQ) TD 1002 in accordance with ASTM E1530 standards as shown in Plate 5. Therefore, thermal conductivity of a sample was determined from the rising temperature using the equation 3.

$$\lambda = \frac{Q \times x}{A(T_2 - T_1)} \quad (3)$$

where; λ ; Thermal conductivity of sample [W/mK], Q; generated heat per unit length of sample/time [W/m²], X; Thickness of sample [m], A; Area [m²], T₁ and T₂; Temperature [K].



Plate 5. TecQuipment (TQ) TD 1002 thermal conductivity experiment carried out

3.7 Heat Transfer Coefficient U (W/m²•K)

The general expression of the heat transfer coefficient is given as:

$$U = \frac{q}{A(\Delta T)} \quad (4)$$

Where; Q: heat flux, W/m²; U: heat transfer coefficient, W/(m²•K), ΔT : difference in temperature between the solid surface and surrounding fluid area.

3.8 Specific Heat Capacity, Cp (J/kg*°C)

Specific heat capacity (Cp) is expressed as:

$$Cp = \frac{Q}{m(\Delta T)} \quad (5)$$

Where; Unit of Cp is J/kg*°C, m is the Mass (kg), Q is change in energy (J), and ΔT is Temperature change (°C).

3.9 Thermo gravimetric Analysis

The most commonly employed method used to determine the thermal stability of the fiber is Thermo gravimetric analysis as shown in Plate 6, where, a mass loss of a weighed quantity of the fibre is perform Thermal gravimetric analysis will was conducted using TGA Q500 machine. Samples weighing approximately 10mg was subjected to pyrolysis in nitrogen environment to a maximum temperature of 600 °C at a heating rate of 10 °C/min. The weight loss was recorded in response to increasing temperature, with final residue yield on set of degradation temperature and number of degradation steps report.



Plate 6. Thermal gravimetric TGA Q500 machine

4 RESULTS AND DISCUSSION

4.1 Fiber surface morphology

Plate 7 Show SEM micrographs of *calotropis procera* fibre.

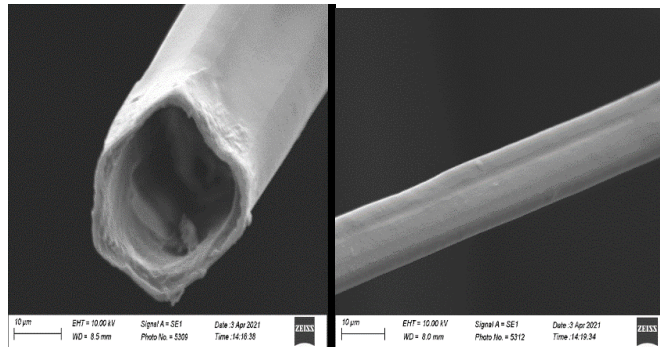


Plate 7. SEM micrographs of *calotropis procera* fibre

Surface morphology of raw Sodom Apple (*calotropis procera*) fibre show that there is more uniformity and homogeneity in the raw fibre, (SEM micrographs shown in Figure1). Sodom Apple (*calotropis procera*) fibre being a single cell is fine fibre, but without convolutions. It is evident that the fibres are hollow in nature, lack of convolution or irregularities in the fiber's structure may contribute to enhanced insulation capabilities, contribute to better fluid flow properties, potentially making it valuable in

filtration applications or as a reinforcement in composites used in fluid handling systems. The hollow nature can trap air within its structure, providing better thermal resistance, making it suitable for insulation purposes in various industries like construction or packaging. Being fine and hollow can contribute to the fiber's lightweight nature, making it advantageous for applications where weight is a concern, the Sodom Apple (*calotropis procera*) fibres have a very smooth surface morphology. The smooth texture could offer a refined surface finish, making it suitable for applications requiring a polished appearance. This smooth and lustrous effect on the fiber surface is observed as a result of the wax content in the fibers, which is similar to the result of [24, 25] The SEM images of Sodom Apple (*calotropis procera*) fibres One of the main characteristic features of Sodom Apple (*calotropis procera*) fruit fibre is its porous structure, which reduces thermal conductivity and helps obtain natural conditioning effects, confirm that it can be used as a reinforcement of novel composite materials for light-weight applications as reported by [26]. Understanding and leveraging the unique characteristics of this natural fiber without convolution, with its hollow and smooth nature, can lead to innovative and specialized applications across various industries. However, further research and development would be necessary to fully explore and optimize its potential in different fields.

4.2 Density, Specific Gravity, Water Absorption, Thermal Conductivity, Moisture Content and Heat Transfer Coefficient of Sodom Apple Fiber Sample

Table.1; show the value of the density, specific gravity, water absorption, thermal conductivity, moisture content and heat transfer coefficient of the studied fibers dried at 105 °C for 24 hours was evaluated using the equation Five Samples with a mass (**w**) 1.211g [27].

Table 1; value of the density, specific gravity, water absorption, thermal conductivity, moisture content and heat transfer coefficient

S/No	Parameters	Unit	Result
1	Density	g/cm ³	0.1099
2	Specific Gravity	-	0.1124
3	Water Absorption	%	66.144
4	Moisture Contents	%	11.03
5	Thermal Conductivity	w/mk	0.067
6	Specific Heat Capacity	cp (j/kg°C)	0.0156
7	Heat Transfer Coefficient U	(W/m ² •K)	1.6814

Density is one of the most important factors determining the properties of the natural fibre. The measured density along with the corresponding specific gravity and water absorption are presented in Table 2. Density of 0.1099 g/cm³, suggest a relatively open structure of the fibre. The open structure of the fibre could allow for greater airflow, which would help to prevent moisture buildup and improve the thermal insulation ability of the fibre, this correspond to the report of [25] which stated ‘Natural fibers have much lower density than synthetic fiber composites which makes them more engrossed with automotive manufactures’. Glass fiber has a higher density of 2.4 g/cm³ than natural fiber, which has a density of 1.2–1.6 g/cm³. As a result, it can be used to make light-weight composites [26]. Water absorption is another important property to consider when evaluating natural fibre for use as insulators, 66.144% this means it can absorb much moisture from the surrounding, this make it a better choice for application where moisture resistance is critical. The samples presented indicated moisture absorption behavior that can be related to hydrophilic nature of this type of fibre and the reactivity of its chemical components consisting essentially of cellulose and hemicelluloses as observed by [1]. These morphological behaviours at high fibre content translate to high water absorption percentage values as the incompatibility between the fiber components creates unoccupied interphases or empty pores to allow the penetration of water into the composites. [29]. The high absorption of water negatively affects the properties of the thermal insulation material by increasing thermal conductivity and density. The moisture content of 11% is within the range of the typical natural fibres like cotton, wheat straw fibre. Having a higher moisture contents may have a negative effect

on the thermal conductivity of the fibre, because moisture conducts heat more effectively than dry materials however, it is important to consider others factors as well, such as density of the fibre. Evidently, an increase in moisture content increased the time for the fibre material to reach EMC. According to [30] findings, moisture content of 20%, is sufficiently dry enough for installing a vapour barrier and drywall. The low thermal conductivity of the natural fibre suggest that it is an excellent material for insulating application. This low thermal conductivity of *calotropis procera* fibre 0.067 W/m.K. indicates that *calotropis procera* fibre can resist the flow of it, making it an effective barrier to heat transfer. The heat transfer coefficient of 1.5614w/m²*k suggests that *calotropis procera* fibre is capable of effectively transferring heat away from the source, making it a good choice for application where rapid heat dissipation is needed. The heat capacity of 0.0156 J/kg*C indicates that *calotropis procera* fibre has the ability to store a moderate amount of heat, making it suitable for use in variety of application. In summary, *calotropis procera* fibre has a combination of properties that make it an effective thermal insulator. These values are comparable to those found for other fibres (Cotton, kenaf, cattail fiber) [1, 10, 31].

4.3 Thermo gravimetric Analysis

Thermo gravimetric Analysis curves of Sodom Apple (*calotropis procera*) fruit fibres show three steps Figure 1. Thermogravimetric analyses curve of Sodom Apple (*calotropis procera*) fruit fibre. degradation in the ranges of around 100°C, between 270 to 420°C and 420-580°C due to decomposition of lignin, hemicellulose, and cellulose respectively. The initial stage, observed at 35°C, signifies an early phase where typically minimal weight loss occurs, around 1%. This minor weight loss might be attributed to the evaporation of surface moisture or volatile compounds presents in the fibre, which are easily driven off a lower temperature. The second stages occurring at 271°C with a weight loss of 3%, indicates a more significant decomposition process. This phase could involve the breakdown of complex compounds present in the Sodom Apple (*calotropis procera*) fibre, such as hemicellulose or cellulose, resulting in release of gases or degradation products. This stage often reflects the degradation of more heat stable components within the Sodom Apple (*calotropis procera*) fibre structure. The most substantial weight loss occurs during the third stage at 579.°C accounting for approximately 73% of the material's original weight. This signifies a crucial phase where the major decomposition of the Sodom Apple (*calotropis procera*) fibre takes place. At this temperature range, the breakdown of lignin, cellulose and other complex organic polymers composing the Sodom Apple (*calotropis procera*) fibre occurs, leading to significant mass loss. Overall, these TGA results highlight the thermal stability and decomposition behaviour of the Sodom Apple (*calotropis procera*) fibre across different temperature ranges, these degradation stages is crucial in determining the thermal performance and application suitability of the Sodom Apple (*calotropis procera*) fibre in various industries such as textiles, composite materials or thermal insulation where material's resistance to heat and stability under different temperature condition are critical factors. The result is similar to the findings of [32, 33, 34, 35].

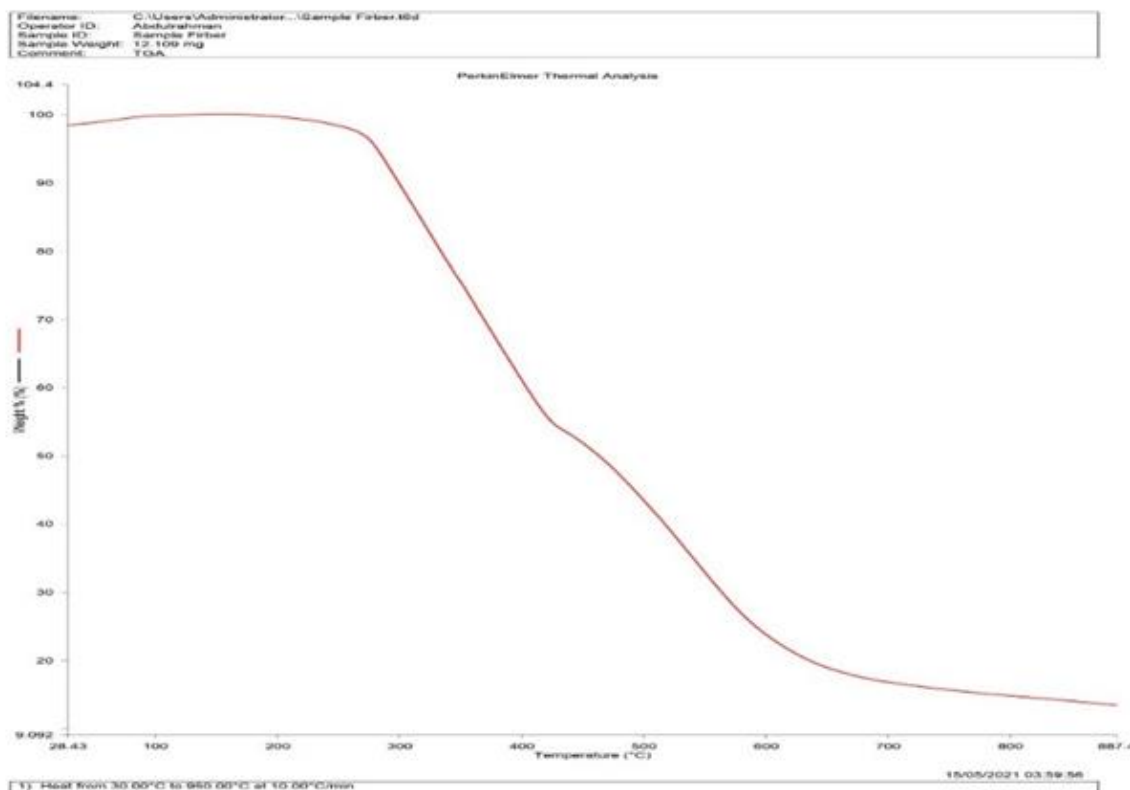


Figure 1. show thermogravimetric analyses curve of Sodom Apple (*calotropis procera*) fruit fiber

5 CONCLUSIONS

Study of the physical and thermal characteristics of Sodom apple (*calotropis procera*) fruit fibres harvested in Maiduguri, Borno state, Nigeria was successfully achieved and from the results of the study, the following conclusions have been drawn. A specific gravity of 0.1124, density of 0.1099g/l, moisture absorption of 66.144%, moisture content of 11.04%. Morphology; a single cell fiber, fine, hollow, smooth structure without convolution. Thermal conductivity of 0.066 W/mk, heat transfer coefficient of 1.6814 W/m²k, specific heat capacity of 0.0156 J/Kg/C. TGA curve indicating first stage at 35.09°C with 1.44% weight loss, 2nd stage at 271°C Celsius with 3.09% weight loss and a 3rd stage at 579°C with 73% weight loss.

REFERENCES

1. Oushabi, A., Sair, S., Abboud, Y., Tanane, O. and EL Bouari. A. (2015). Natural thermal-insulation materials composed of renewable resources: characterization of local date palm fibers (LDPF). *Journal of Materials and Environmental Science*, vol. 6, no. 12, pp. 3395-3402.
2. Khatoon, A., Iqbal, N., Asif, M., Masooma, H., Cheema, N., Saeed, M. and Bashir, A. (2018). Comparative Analysis of Fiber Morphogenesis Genes of *Calotropis procera* and *Gossypium hirsutum*. *International Journal of Agriculture and Biology*, pp. 288-296.
3. Avinash, R.P. and Ramanand, N.J. (2014). Surface Morphology & Mechanical properties of some unique Natural Fiber Reinforced Polymer Composites- A Review, *Journal of Materials and Environmental Science*, vol. 6, no. 4, pp. 902-917.
4. Azizatul, K., Muhammad, R.R., Sasa, S.M., Ismadi, Y.A., Ratih, D., Muhammad, A.R.L., Asri, P.W.N., Apri, H.I., Ahmad, F., Mochamad, A., Euis, S., Nasmi, H.S., Bayu, R.P., Widya, F.,

- Deded, S.N., Sanjay, M.R. and Suchart, S. (2021). A Comprehensive Review on Natural Fibers: *Technological and Socio-Economical Aspects, Polymers*, vol. 13, no. 4280, pp. 1-27.
5. Baqer, A.A. and Hayder, N.M. (2020). Investigating New Thermal Insulators Based on Cheap Natural Organic and Waste Materials: *Part 1, IOP Conference Series: Materials Science and Engineering*, vol. 671, pp. 1-2.
 6. Chama, A.S. and Babu, D.G.A. (2013). mechanical and machining properties of calatropis gigantea fruit fibre reinforced plastic. *International Journal of Engineering Research and Technology*, vol. 2, issue 6, pp. 1524-1530.
 7. Claude-Alain, R. (2015). Measuring thermal Characteristics of Building Insulation Materials, Building Energy Efficiency Project. *Training Manual*, pp. 1-93
 8. Bozsaky, D. (2019). Nature-Based Thermal Insulation Materials from Renewable Resources – A State-Of-The-Art Review. *Slovak Journal of Civil Engineering*, vol. 27, no. 1, pp. 52-59.
 9. Dilli, B.G., Sivaji, B.K. and Nanda, K.P. (2014). Tensile and Wear Behavior of Calotropis Gigentea Fruit Fiber Reinforced Polyester Composites. *12th Global Congress on Manufacturing and Management, Procedia Engineering*, vol. 97, pp. 531-535.
 10. Edmunds, V., Staņislavs, P., Ilmars, P., Juris, S. and Uldis, G. (2019). Thermal Conductivity of Experimental Wall Constructions of Renewable Insulating Materials. *Research for Rural Development*, vol. 1, pp. 175-180.
 11. George, A., Sanjay, M.R., Srisuk, R., Parameswaranpillai, J. and Siengchin, S.A. 2020. Comprehensive Review on Chemical Properties and Applications of Biopolymers and Their Composites. *Int. J. Biol. Macromol.*, vol. 154, pp. 329-338.
 12. Niresh, A.N., Karthik, T. and Tan, W.H. (2019). Physical, Chemical, Morphological and Thermal Characterisation of Natural Fibers for Sound Absorption. *Tekstil Ve Konfeksiyon*, vol. 29, no. 3, pp. 219-227.
 13. Jiří, Z., Jitka, H., Jiří, B., Zdeněk, K. and Albinas, G. (2013). 11th International Conference on Modern Building Materials, Structures and Techniques, MBMST, Development of Thermal Insulating Materials on Natural Base for Thermal Insulation Systems. *Procedia Engineering*, vol. 57, pp. 1288-1294.
 14. Jorge, S.S.N., Henrique, F.M.D., Ricardo, A.A.A. and Mariana, D.B. (2021). A Review on the Thermal Characterisation of Natural and Hybrid Fiber Composites. *Polymers*, vol. 13, no. 4425, pp. 1-27. <https://doi.org/10.3390/polym13244425>.
 15. Manohar, K. (2016). A Comparison of Banana Fiber Insulation with Biodegradable Fibrous Thermal Insulation. *American Journal of Engineering Research*, vol. 5, issue-8, pp-249-255.
 16. Manohar, K., Dale, R., Gurmohan, K. and Subhas, H. (2014). Biodegradable Fibrous Thermal Insulation, *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, vol. 28, no. 1, pp. 45-47.
 17. Palumbo, M., Navarro, A., Avellaneda, J. and Lacasta, A.M. (2014). Characterization of thermal insulation materials developed with crop wastes and natural binders, Sustainable construction materials, natural fibres insulations, crop wastes, hygrothermal behavior, pp. 1-10.
 18. Miguel, G. and Marco, Z. (2013). Study High Performance Thermal Properties of Natural Pumice-Based Bricks. *British Journal of Applied Science and Technology*, vol. 3, no. 4, pp. 1022-1034.
 19. Mohamed, E.A. and Abdullah, A. (2019). thermal and Acoustic Characteristics of Promised Hybrid Insulation Wasted Materials - Made of Apple of Sodom and Palm Tree Surface Fibers as New

- Insulation Materials for Buildings. *Proceedings of the International Conference on Industrial Engineering and Operations Management Riyadh, Saudi Arabia*, pp. 88-84.
20. Ali, M.E. and Zeitoun, O.M. (2012). Discovering and Manufacturing a New Natural Insulating Material Extracted from a Plant Growing Up in Saudi Arabia. *Journal of engineered fibers and fabrics*, vol. 7, issue 4, pp. 88-94.
 21. Mohau, J.P., Julia, P.M., Mapoloko, M.P., Mfso, M. and Zikhona, T.N. (2023). Chemical, thermal and morphological properties of polybutylene succinate-waste pineapple leaf fibres composites. *Heliyon*, vol. 9, pp. 107 -207.
 22. Mohit, M. and Rajiv, C. (2019). Experimental Investigation on the Thermal Behavior of Untreated and Alkali-Treated Pineapple Leaf and Coconut Husk Fibers. *International Journal of Applied Science and Engineering*, vol. 7, no. 1, pp. 1-16.
 23. [Misra](#), M. and [Drzal](#), L.T. (2002). Sustainable Bio-Composite from Renewable resources: Opportunities and Challenges in the Green Materials World, *Journal of polymers and environment*, vol. 32, no. 8, pp. 1105-1115.
 24. Nadlene, R., Sapuan, S.M., Jawaid, M., Ishak, M.R. and Yusriah, L. (2015). Material Characterization of Roselle Fibre (*Hibiscus sabdariffa* L.) as Potential Reinforcement Material for Polymer Composites. *Fibers and Textiles in Eastern Europe*, vol. 6, pp. 23-30. <https://doi.org/10.5604/123036661167413>.
 25. Nourelhouda, E., Samir, D., Mansour, R., Fares, M.L.R. and Rafik, H. (2022). Characterization and analysis of novel natural cellulosic fiber extracted from *Strelitzia reginae* plant. *Journal of Composite Materials*, vol. 56, no. 1, pp. 99-114.
 26. Oluyamo, S.S., Aramide, T.M., Adekoya, M.A. and Famutimi, O.F. (2017). Variation of Bulk and Particle Thermal Properties of Some Selected Wood Materials for Solar Device Applications. *IOSR Journal of Applied Physics*, vol. 9, issue 3, pp. 14-17.
 27. [Peijs](#), T. (2000). Natural Fiber Based Composites. *Advanced Performance Materials*, vol. 15, [issue 4](#), pp. 281-285. <https://doi.org/10.1080/10667857.2000.11752892>.
 28. Dhivar, P.S. and Patil, A.R. (2017). Thermal Insulation Using Agricultural By-Product: A Review. *Journal of Mechanical and Civil Engineering*, pp. 53-61.
 29. Lopez, P.H., Rouilly, A., Raynaud, C. and Vandebosch, V. (2016). The properties of cellulose insulation applied via the wet spray process, pp. 43-51. <http://dx.doi.org/10.1016/j.buildenv.2016.07.017>.
 30. Raghavendra, S., Kestur, G.S. and Balachandra, S.P. (2017). Evaluation of Structural, Tensile and Thermal Characterization of Banana fibers. *Journal of Natural fibers*, vol. 14, no. 4, pp. 485-497. <https://doi.org/10.1080.2016.121277>.
 31. Raghu, M.J. and Govardhan, G. (2020). Effect of Water Absorption on Mechanical Properties of *Calotropis Procera* Fiber Reinforced Polymer Composites. *Journal of Applied Agricultural Science and Technology*, vol. 4, no. 1, pp. 3-11.
 32. Rashid, B., Leman, Z.; Jawaid, M.; Ghazali, M.J.; Ishak, M.R. 2017. Influence of Treatments on the Mechanical and Thermal Properties of Sugar Palm Fibre Reinforced Phenolic Composites. *Bio-Resources*, vol. 12, no. 16, pp. 1447-1462.
 33. Ravi, K.U. (2014). Ethnomedicinal, pharmaceutical and pesticidal uses of *Calotropis procera* (Aiton) (Family: Asclepiadaceae). *International Journal of Green Pharmacy*, pp. 135-146.
 34. Purnawati, R., Febrianto, F., Wistara, N.J., Nikmatin, S., Hidayat, W., Hwan, L.S. and Hun, K.N. (2018). Physical and Chemical Properties of Kapok (*Ceiba pentandra*) and Balsa (*Ochroma*

- pyramidale*) Fibres. *Journal of the Korean Wood Science and Technology*, vol. 46, no. 4, pp. 393-401. <https://doi.org/10.5658/WOOD.2018.46.4.393>.
35. Sergeo, N.M., Felipe, P.D.L., Aiton, S.F. and Denis, C.O. (2009). Natural Fiber Polymer Matrix composites: cheaper, tougher and environmentally friendly, *Polymer matrix composites*, vol. 16, pp. 17-22.
 36. Verma, S. (2016). *Calotropis Procera* (Asclepiadaceae): A Review. *IJSRST*, vol. 2, issue 6, pp. 487-490.
 37. Teixeira, L.A., Junior, L.V.D. and Luz, S.M. (2020). Chemical Treatment of Curaua Fibres And Its Effect on The Mechanical Performance of Fibre/Polyester Composites. *Plastic and Rubber Composite*, vol. 50, pp. 189-199.
 38. Petit-Breuilh, X., Whitman, C.J., Lagos, C., Armijo, P.G., Schiappacasse, P.N.L. (2013). Natural Fibre Insulation in Rural Southern Chile, PLEA2013 - 29th Conference, Sustainable Architecture for a Renewable Future, Munich, Germany.
 39. Chan, J.M., Day, P., Feely, J., Thompson, R., Little, K.M. and Norris, C.H. (2015). Acacia mearnsii industry overview. *Current status, key research and development issues*, vol. 77, pp. 19-30.