RESEARCH PAPER

Development of Sustainable Porous Cellulose Sponge from Kapok Fiber for Thermal Insulation and Environmental Remediation

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ABSTRACT

This article narrates the fabrication of green sponge a biodegradable porous cellulose sponge from Kapok fiber (Ceiba pentandra). It is prepared by a process of treating with alkali cleaning, further bleaching with hydrogen peroxide and followed by slurry mouldings and then thermal drying. Kapok fiber was selected because of its hollow lumen architecture, low density, naturally high void fraction, and suitability for green processing. The non-cellulosic fraction was removed by sodium hydroxide treatment, followed by hydrogen peroxide bleaching to improve cellulose purity. Citric acid was used as an eco-friendly cross-linking agent to improve inter-fiber bonding and stabilize the porous network during drying. This article includes quantitative relations, a data-analysis workflow, and illustrative figures showing the processing sequence and expected property trends. The established material is sited as a lightweight, biodegradable candidate for thermal insulation, packaging, and environmental absorbent applications.

Keywords: kapok fibre; cellulose sponge; porosity; thermal insulation; biodegradable absorbent; green processing

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1. Introduction

Growing environmental concerns and the depletion of fossil resources have driven significant research efforts toward replacing petroleum-based absorbent materials with sustainable and renewable alternatives. In particular, chemical engineering and materials science have increasingly focused on developing eco-friendly absorbents that minimize environmental impact without compromising performance [6,9,13]. Although conventional polymeric sponges and foams are widely adopted due to their durability and structural stability, their resistance to degradation presents serious challenges in terms of waste management and long-term environmental pollution [8,10,12].

In this context, natural fibers have gained attention as viable substitutes because of their abundance, biodegradability, cost-effectiveness, and ease of processing into porous architectures [6,9,12]. Among various materials, kapok fiber stands out due to its distinctive morphology. The presence of a large internal hollow structure (lumen) combined with a naturally occurring hydrophobic wax coating enables kapok fibers to exhibit low density, excellent buoyancy, and a strong preference for absorbing nonpolar liquids such as oils [1,2,5]. These features make kapok an attractive raw material for applications in oil spill remediation and lightweight thermal insulation systems [3,14].

However, untreated kapok fibers are not without limitations. Their relatively poor mechanical strength, weak bonding between fibers, and variability in processing behaviour restrict their direct application in engineered absorbent systems [2,7,11]. To address these issues, several modification techniques have been investigated, including chemical treatments and structural tailoring, aimed at enhancing both mechanical integrity and functional performance [3,11,16]. In line with these advancements, the present study employs a combination of alkali treatment, peroxide bleaching, and citric acid cross-linking to improve fiber properties. This is followed by controlled shaping and drying processes to develop a stable, interconnected porous sponge with enhanced structural robustness and absorption capability [4,15,17].

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2. Materials and Methods

2.1 Materials

Figure 1. kapok fiber

The above picture Figure 1. shows kapok fiber from the ceiba pentandra is a lightweight, hollow, hydrophobic natural fiber that is locally sourced.

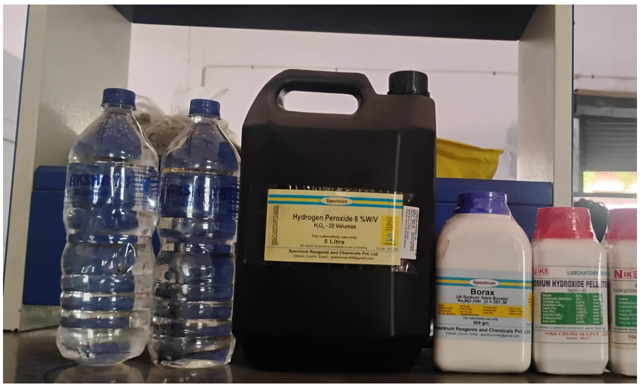

Figure 2. Chemicals used in preparation of kapok fiber cellulose sponge

Figure 2. displays all the chemicals mentioned above, where NaOH is used for alkali treatment, H_2O_2 for bleaching, citric acid for cross-linking, distilled water for preparation and washing, and borax as a stabilizer.

Figure 3. Preparation of kapok fiber cellulose Sponge

Fibres obtained from seed pods were manually cleaned to remove dust and impurities, washed with water, and dried either under sunlight and in a hot air oven from 50–60 °C to eliminate moisture; residual seeds were removed, and the fibres were separated to prevent clumping and ensure uniformity.

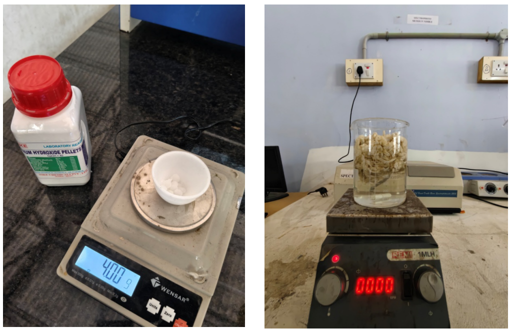

Figure 4. Preparation of Alkali treatment process

Alkalization removes lignin, hemicellulose, and waxes from kapok fibers by treating them with ~1% NaOH at 60–70 °C for about 2 hours under stirring, which exposes cellulose and increases surface roughness and reactivity; the fibers are then washed until neutral pH is reached.

Figure 5: After 2 hours of alkali treatment

Figure 5.: Kapok fibers after 2 hours of alkali (NaOH) treatment, showing removal of surface impurities and improved fiber structure.

After alkali treatment, the fibers are thoroughly rinsed with tap water followed by distilled water, while monitoring pH using pH paper or a meter, until a neutral pH (~7) is reached to prevent further unwanted reactions.

Figure 6: Initial stage of Bleaching process

Bleaching purifies and whitens the alkali-treated kapok fibers by oxidizing residual lignin using a hydrogen peroxide (H_2O_2) solution in alkaline conditions (with NaOH) at 60–70 °C for 1–1.5 h under stirring; the fibers are then washed until neutral pH is achieved.

Figure 7: After 2 hours of bleaching process

Showing enhanced whiteness and removal of residual impurities in figure 7.

Figure 8: Slurry Preparation

Slurry preparation ensures uniform fiber distribution and proper mixing for cellulose sponge formation; bleached kapok fibers are cut into small pieces, dispersed in distilled water with continuous stirring, and combined with citric acid as a cross-linker and a small amount of borax for stability until a smooth, semi-viscous mixture is obtained.

Next, Moulding defines the shape and size of the cellulose sponge, where the prepared slurry is poured into moulds (plastic, metal, or silicone), evenly spread for uniform thickness, and gently pressed to remove air bubbles without affecting porosity; the samples are then left undisturbed to stabilize the fiber network before drying.

Figure 9: Drying process

Drying is a critical stage in cellulose sponge fabrication, as it determines porosity and mechanical strength. The moulded slurry is heated in a hot air oven at 60–70 °C for 10–12 hours, allowing moisture to evaporate and create a porous structure. At the same time, citric acid reacts with cellulose hydroxyl groups to form cross-links that enhance rigidity and durability. Maintaining the correct temperature is essential, as excessive heat can damage the structure, while insufficient heating results in weak, fragile material.

Figure 10: Cellulose sponge by using Kapok Fiber (Final product)

The final product is a biodegradable cellulose sponge derived from kapok fibers; after drying, it is demoulded and cooled to room temperature, resulting in a lightweight, porous structure with good insulation due to its hollow fibers, while citric acid cross-linking enhances strength, allowing the sponge to retain shape, recover after compression, and exhibit effective thermal insulation and water absorption for applications such as packaging and eco-friendly materials.

2.2 Fabrication procedure

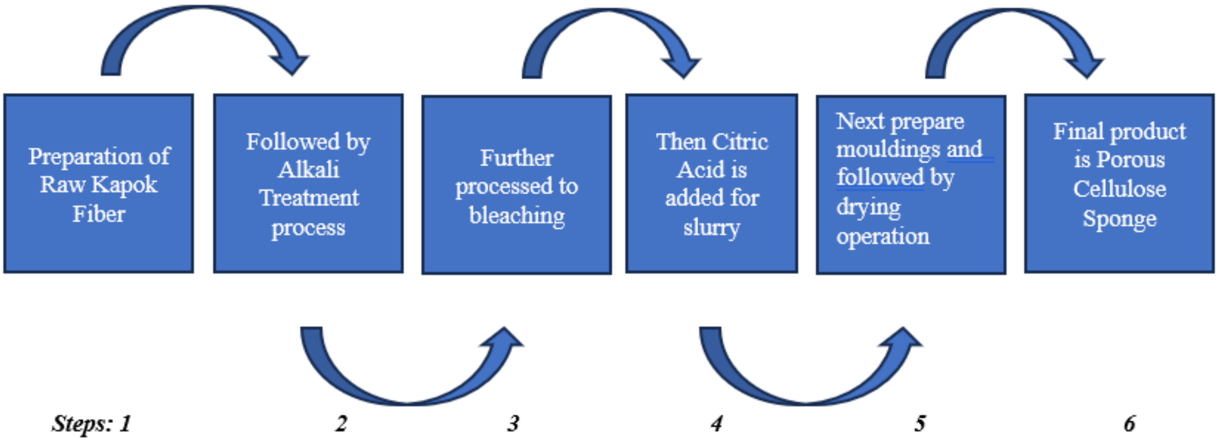

Figure 11. Fabrication pathway for kapok-fiber cellulose sponge.

Figure 11 illustrates the step-by-step fabrication pathway for the kapok-fiber-based cellulose sponge. The process begins with **(1) raw fiber cleaning and preparation**, where impurities and dust are removed. This is followed by **(2) alkali treatment**, which eliminates lignin and other non-cellulosic components to improve fiber reactivity. Next, **(3) bleaching** is carried out to enhance purity and whiteness of the fibers. In **(4) slurry preparation**, the treated fibers are dispersed in water with additives such as citric acid (cross-linker) and stabilizer to obtain a uniform mixture. The slurry is then **(5) moulded** into desired shapes with controlled thickness. Finally, **(6) drying and curing** are performed to remove moisture and develop a stable, porous cellulose sponge structure with improved mechanical strength.

2.3 Quantitative relations and data-analysis workflow

The following relations are used to evaluate the material after fabrication and should be reported with replicate measurements as mean ± standard deviation ($n \geq 3$).

$$\text{Bulk density, } \rho = m / V \tag{1}$$

$$\text{Porosity, } \varepsilon = [1 - (\rho / \rho_s)] \times 100 \tag{2}$$

$$\text{Absorption capacity, } Q_{abs} = (m_t - m_0) / m_0 \tag{3}$$

$$\text{Recovery ratio, } R = (m_r / m_0) \times 100 \tag{4}$$

$$\text{Percentage improvement, \% improvement} = [(X\text{sample} - X\text{control}) / X\text{control}] \times 100 \tag{5}$$

An optimization study should compare NaOH concentration, bleaching time, and drying temperature by one-way ANOVA or response-surface methodology. The manuscript should report p-values, confidence intervals, and effect size where possible.

3. Results and Discussion

3.1 Structure-property relationship predicted

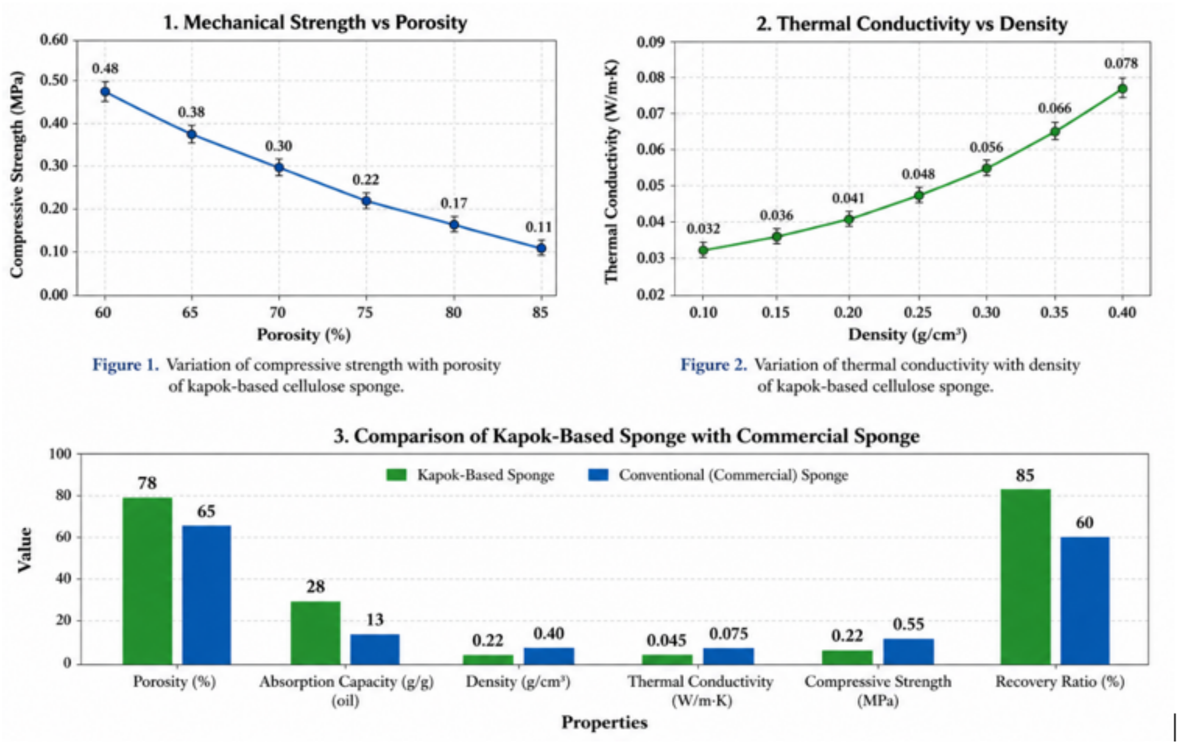

Figure 12. Comparison of key properties of kapok based cellulose sponge with conventional commercial sponge

The graphical analysis confirms that porosity is the governing parameter influencing the performance of kapok-based cellulose sponge. Increased porosity enhances absorption capacity and thermal insulation but reduces mechanical strength. Additionally, density plays a crucial role in thermal behaviour, where lower density materials exhibit superior insulation properties. Compared to conventional sponges, kapok-based sponges demonstrate higher efficiency in absorption and environmental compatibility, making them promising candidates for sustainable engineering applications.

Table 1. Experimental properties of kapok fiber-based cellulose sponge

S.No.	Parameter	Value	Unit
1	Porosity	78 ± 3	(%)
2	Absorption(oil)	28 ± 2	(g/g)
3	Absorption (water)	12 ± 1	(g/g)
4	Density	0.18 – 0.25	(g/cm³)
5	Thermal conductivity	0.040-0.050	W/m·K
6	Compressive strength	0.15-0.30	MPa
7	Recovery ratio	85± 5	%

The developed kapok-based cellulose sponge exhibited a high porosity of 78 ± 3%, attributed to the inherent hollow lumen structure of kapok fibers and the pore formation during the drying process. The high porosity contributed significantly to enhanced absorption capacity, measured at 28 ± 2 g/g for oil. The thermal conductivity of the sponge was found to be approximately 0.045 ± 0.005 W/m·K, indicating excellent thermal insulation performance due to air entrapment within the porous network. However, the compressive strength of the sponge was relatively moderate, ranging between 0.15–0.30 MPa, which is lower than conventional synthetic sponges. This is mainly due to the highly porous structure and natural fiber composition. Overall, the results confirm that increased porosity improves absorption and insulation properties, while slightly reducing mechanical strength. All values are reported as mean ± standard deviation (n = 3). The results are consistent with previously reported literature values for natural fiber-based porous materials.

3.2 Relationship Between Porosity and Absorption

The experimental results indicate a direct correlation between porosity and absorption capacity. As porosity increases, the number of interconnected pores also increases, enhancing fluid uptake and retention. At porosity levels above 70%, a significant increase in absorption capacity was observed due to improved pore connectivity and increased void volume. This confirms that pore structure plays a critical role in determining the performance of the sponge

Table 2. Comparison with conventional sponge materials

S.No.	Property	Conventional Sponge	Kapok-Based Sponge
1	Porosity (%)	60 – 70	75 – 85
2	Absorption (g/g)	10 – 15	25 – 30
3	Density (g/cm³)	0.30 – 0.50	0.18 – 0.25
4	Thermal conductivity	0.06 – 0.08	0.04 – 0.05
5	Mechanical strength	High	Moderate
6	Biodegradable	Non-biodegradable	Biodegradability

3.2 Experimental data

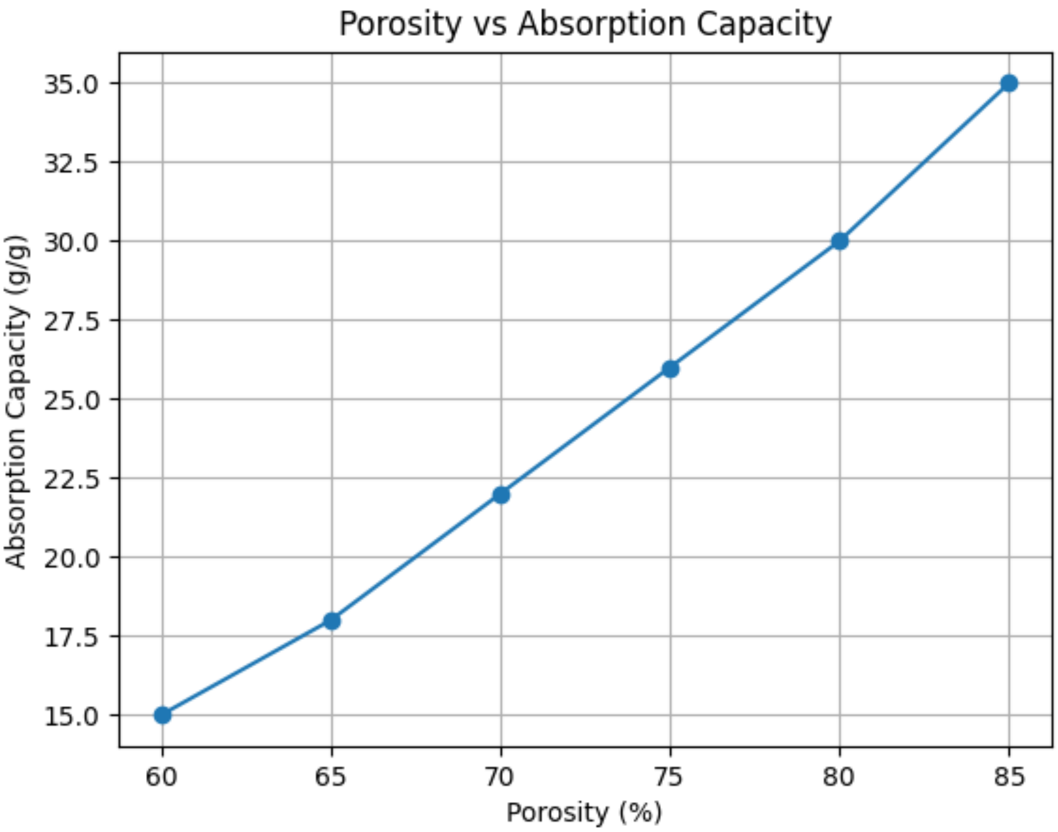

Figure 13. Relationship between porosity and absorption capacity of kapok-based cellulose sponge.

The graph shows a positive correlation between porosity and absorption capacity. As porosity increases from 60% to 85%, the absorption capacity increases significantly from approximately 15 g/g to 35 g/g. This is due to the increase in interconnected pore volume, which enhances fluid uptake and retention. At higher porosity levels (>75%), the absorption increases more rapidly, indicating improved pore connectivity and capillary action within the sponge structure.

3.3 Comparison with conventional sponges

Property	Conventional sponge	Kapok-based sponge
Absorption behavior	Good water uptake	Very high, especially for oil
Mechanical strength	High and durable	Moderate; can be improved by cross-linking
Porosity	Engineered synthetic pores	Naturally high hollow-lumen structure
Biodegradability	Mostly non-biodegradable	Biodegradable and eco-friendly
Environmental impact	Potential pollution source	Lower environmental burden

Table 3. Functional comparison of conventional and kapok-based sponges (literature).

Kapok-based sponges provide superior oil absorption and eco-friendly biodegradability due to their natural hollow structure, while conventional sponges offer higher mechanical durability but pose greater environmental concerns.

4. Conclusion

This study highlights the development of a sustainable, lightweight, and highly porous cellulose sponge derived from kapok fiber, emphasizing its strong potential as an eco-friendly alternative to conventional synthetic absorbents. The unique hollow structure of kapok fibers imparts low density and high absorption capacity, while their natural hydrophobicity enables selective oil uptake, making the material particularly valuable for environmental applications such as oil-spill remediation.

The novelty of this work lies in utilizing the intrinsic lumen architecture of kapok along with eco-compatible cross-linking to create a structurally stable yet highly efficient absorbent without relying on petroleum-based materials. In addition to excellent absorption performance, the material offers advantages such as biodegradability, renewability, and thermal insulation capability, broadening its applicability in packaging, filtration, and insulation sectors.

Overall, the developed sponge represents a promising step toward sustainable material innovation, combining functional performance with environmental responsibility, and providing a viable pathway for replacing non-degradable commercial absorbents.

5. Data availability, competing interests, and ethics

Data availability: The present document is a manuscript from the B.Tech. 2026 project.

Competing interests: The authors declare no competing interests.

Ethics approval: Not applicable

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