Jurnal Kejuruteraan 38(2) 2026: 819-844
https://doi.org/10.17576/jkukm-2026-38(2)-28

Compressive Behavior and Energy Absorption of Cylindrical Luffa Biomaterials: A Review

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Received 19 March 2025, Received in revised form 27 October 2025
Accepted 27 November 2025, Available online 30 March 2026

ABSTRACT

The world demand dictates that alternative eco-friendly and sustainable materials are very much coveted that many researchers are drawn to composites materials made of natural fibres and biodegradable materials that are cheap, boast off good mechanical properties and biodegradability. This paper reviews relevant literature which deals with the natural plant known as Luffa cylindrica (LC) or Luffa sponge (LS). An overview is given by numerous research works for commonly used fibre surface treatments for Luffa fibre (LF). Furthermore, this study discusses the compositions and the mechanical properties of Luffa plant, also how water immersion affects compression behavior in addition the remarkable shape memory effects and mechanical recovery features are also common features of Luffa sponge material. A comprehensive understanding behavior of LS as energy absorbing structure under different compression loads that were investigated on it, such as (quasi-static and dynamic load) and the mechanical-properties of the luffa plant. As a result, from an energy-absorbing point of view, the Luffa sponge material is evidenced to display striking stiffness, strength and energy absorption capacities as opposed to the metallic cellular counterparts. In addition, Luffa sponge is an ultra-light cellular material, it also has an environmentally friendly feature, sustainable, renewable, ease of production and low cost.

Keywords: Energy absorption; luffa sponge; lightweight; compression; natural fiber

INTRODUCTION

The world is grappling with the grave issue of environmental pollution, a phenomenon with direct implications for global warming. Consequently, researchers and scholars globally are intensifying efforts to develop green materials as a critical strategy for pollution reduction. This urgency has provided the impetus for developers to create truly effective, sustainable, and essential materials. Furthermore, advancements in science and technology demand the immediate development of specialized engineering materials that are lightweight, high-strength, customized for service needs, yet characterized by low cost and minimal energy consumption (Mohanta 2016).

Modern industries, such as the automotive sector, are rapidly migrating toward natural fiber-based bio-composites. This preference is predicated on their favorable attributes: ecological compatibility, cost-effectiveness, superior light weight, and ubiquitous availability. The fundamental driver for the research, development, and eventual commercialization of bio-composites lies in their capability to serve as sustainable, renewable, and environmentally sound substitutes. Their expanding utilization across a range of applications has thus catalyzed the creation of novel research avenues (Zwawi 2021).

Bio-composites are considered an ideal alternative to traditional synthetic composites because they offer comparable mechanical properties while being inherently environmentally beneficial. In stark contrast, synthetic composites are associated with a high carbon footprint, the emission of harmful byproducts, intensive energy consumption, difficulty in recycling, and overall pollution. Therefore, environmental protection necessitates restricting the use of synthetic composites. This imperative is further strengthened by the growing realization that the sustainability of synthetic composites is undesirable due to the depletion of limited petroleum resources (Al-Oqla & Sapuan 2014; Alhijazi et al. 2020; Bhat et al. 2021; Debnath 2017; M. Jahanzail Kamran et al. 2021; Majeed et al. 2013). As aforementioned, bio-composites have great potential to be used in different applications; the automotive, textile, construction, and packaging industries are the main sectors that use bio-composites. Although research has produced encouraging results, more advancements and research are needed to commercially commercialize bio-composites (Zwawi 2021), (Abdul Khalil et al. 2012).

The automotive industry has been showing increasing interest in natural fiber composites as the need for lightweight and ecologically friendly materials grows. According to, Naik et al. (2021) natural fiber composites can reduce the weight and cost of a car component by 20% and by 30%, respectively. Studies have shown that lightweight automotive parts offer recycling possibilities and lower noise. Furthermore, designing a mixture of lightweight and powerful heavy-duty composite panel can tremendously improve a vehicle's fuel consumption and further lessen carbon dioxide emissions. A schematic diagram of the sustainable features and potential of natural fibre composites in the vehicle sector is highlighted in Figure 1.

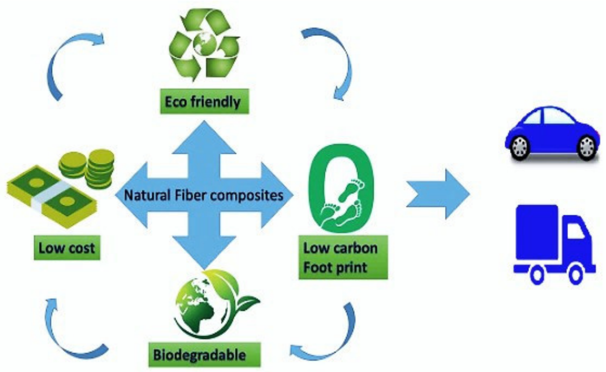

FIGURE 1. Natural fiber composites is sustainable alternative in vehicle sector (Naik et al. 2021)

Compared to the production of synthetic fibre, the energy needed to create bio-composite is far lower. Bio-composites use less energy than synthetic composites during production (Banik et al. 2017). Natural fibres possess qualities or properties comparable to those of the synthetic composites. One of the most crucial types of natural fibres serving as composite materials is the sponge gourd, *Luffa cylindrica*. It has a ligneous netting system containing fibrous cords in multiple directions. This fibrous vascular system consists of fibrils joined by organic resins found in plant tissue. Several researcher describe the use of Luffa fibres in the reinforcement of composite materials and other technological applications (Ghali et al. 2009).

Luffa sponge is a cellular material that is both lightweight and sustainable, with a very high specific energy absorption capacity. As a result, it can be a great option and strong candidate for a filler (J. H. Shen et al. 2012), (Wang et al. 2015). The Luffa sponge's superior specific energy absorption can be attributed to its light base material and microstructures, which promote a higher densification strain. Because of its high strength-to-weight ratio and improved energy absorption capacity at a high strain rate, the Luffa sponge is suitable for both packaging and effective energy dissipation (J. Shen et al. 2013) (Cai et al. 2025).

The paper seeks to analyse the strengths and classification of natural fibres, with particular focus on the luffa plant. the importance of luffa plant and the factors contributing as an energy absorber are also highlighted. Compared to more established natural fibers (like flax or jute), comprehensive scientific literature on the practical mechanical properties and optimal processing methods for large-scale production of LC composites can still be considered limited. In other words, this study aims to enhance the in-depth understanding of the luffa's response to quasi-static and dynamic loading conditions. The outcomes could serve as an initial design guideline for using the luffa plant for energy absorption and its potential use in numerous related applications.

NATURAL FIBER

CLASSIFICATION AND STRUCTURE

Plant fibres are widely used in industry, making them a popular subject of study for academicians. Cheung et al. (2009), & Mohammed et al. (2015) classified natural fibres as either animal or plant fibres. It is common for the latter to be mixed with polymers to form Natural Fibre Reinforced Polymer (NFRP) composites to produce domestic products, where cost and strength are major considerations. Such fibres are also known as renewable sources and can be extracted from nature without harming the environment; they could replace glass fibre in diverse engineering applications (Cheung et al. 2009).

Some researchers (Abdur Rahman et al. 2023; Aditya et al. 2017; Akter et al. 2023; Bharath & Basavarajappa 2016; Bhat et al. 2023; Fogorasi & Barbu 2017; Musa & Onwualu 2024; Sanjay et al. 2015; Sanjay et al. 2018; Schutz et al. 2024; Sharath et al. 2024; Suriani et al. 2021; Yadav & Singh 2022) classify Natural-fibres according to their origin as animal, mineral, and plant. Furthermore, the classification of vegetable or plant fibres as (bast, seed, fruit, leaf, grass, stalk, straw, and wood) fibers (Sathish et al. 2021; Vinod et al. 2020) as summarised in Figure 2.

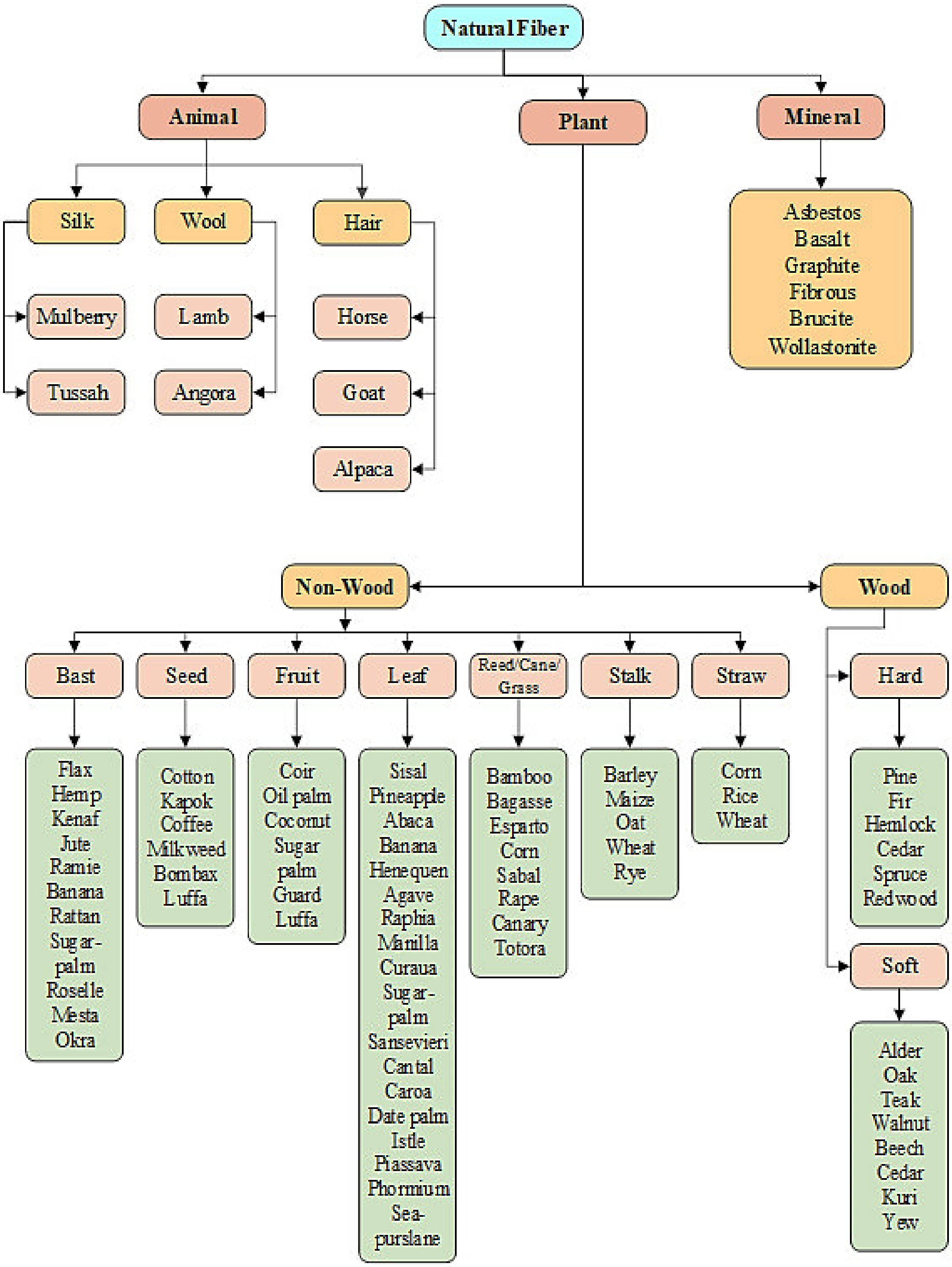

FIGURE 2. A comprehensive classification of Natural fiber

Through the microscopic view, natural fibres have intricate structures. The microfibrils have crystalline and amorphous regions, in which the former conditions the fibre strength, while the latter is relatively soft and illustrates irregular molecular chains (shown in Figure 3). The reliance of the natural fibre's internal structure rests upon the plants' age and origin, along with the state of the climate (Cheung et al. 2009), (Ho et al. 2012).

The framework of the fibre structure contains the main component which is the cellulose content of the natural fibre, which is also accountable for the strength/stiffness of composite and structural stability (Pickering et al. 2016), (Dharmalingam et al. 2020). In other words, cellulose is also answerable to the plant fibre's strength and mechanical properties.

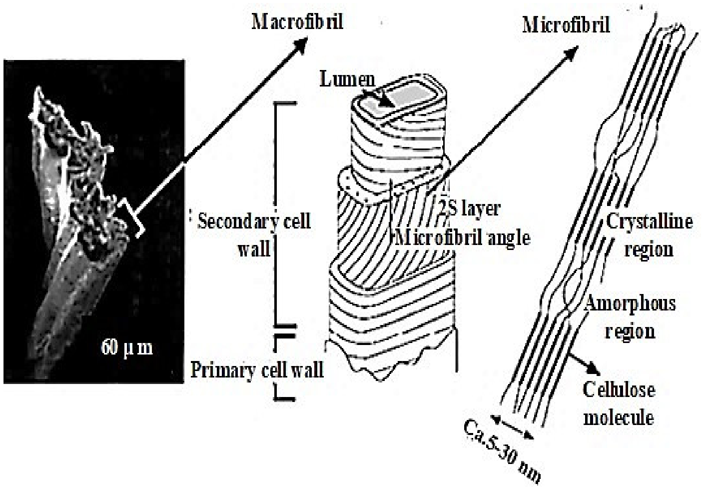

FIGURE 3. SEM of Natural fibre and it's schematic of macro-structure and micro-structure (Cheung et al. 2009)

APPLICATION OF NATURAL FIBRES IN VEHICLE STRUCTURE

Since sustainability is a primary concern, professionals like scientists, engineers, and researchers are perpetually pursuing new biodegradable materials and sustainable alternatives to be of use in various industries (Nayak et al. 2020; Pandey et al. 2018; Prasad et al. 2016; Ramesh et al. 2022; Syduzzaman et al. 2020; Trung et al. 2023; Yuvaraj et al. 2023). Synthetic fibres are not favourable to the environment as they do not degrade easily. Too much use of synthetic fibres can bring about severe catastrophes, and as far as environmental sustainability is concerned, it is now a global concern that can have far-reaching consequences (Haque et al. 2023).

Several benefits of natural fibres over synthetic fibres have been well reported and acknowledged (Mohanty et al. 2000; Peças et al. 2018). Natural fibres thus, stand out as an attractive industrial option as they can deal with multifarious socio-economic and environmental challenges. Plant fibre will soon take the rein as a sustainable and renewable resource in the field of composites, that can take the place of synthetic fibres in several applications (Akter et al. 2023). Natural fibres composites are ideal for vehicle panels (side and front panels) in the automotive business as they are minor structural components according various researchers as summaries in table (1). When Natural fibre composites substitute for the traditional glass fibre composites and aluminum in these components, the vehicle's cost and weight could be lessened to a certain extent (Lau et al. 2018; Peças et al. 2018).

TABLE 1. Vehicle applications and components of natural plant

Type of Natural plant	Applications and components	References
Hemp, jute, kenaf, sisal, coir, abaca	Vehicle application/instrument panel, arm rest, dashboard, door panel cover	Symington et al. (2009), Murugu Nachippan et al. (2021)
Banana fiber	Automotive application/wrapping paper	Puglia et al. (2005), Ramdhonee and Jeetah (2017)
Pineapple	Automobile application/interior part	Kim et al. (2011)
Flax fiber	Automotive/ hood or bonnet, seat, door panel	Kumar et al. (2018), Peças et al. (2018)
Sisal/kenaf	Vehicle application/door panel	Sreenivas et al. (2020)

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Jute	Automobile/frontal bonnet	Alves et al. (2010)
Caryota	Vehicle application/interior components	Vijayakumar and Palanikumar (2020)
Areca fiber	Automotive/dashboard panel	Nayak et al. (2018)
Leucas plant	Automotive/brake pad	Vijay et al. (2020)
Cotton	Automotive application/trunk panel, insulation materials	Witayakran et al. (2017)
Coconut fiber	Automobile application/interior parts	Palani Kumar et al. (2020)
Calotropis	Interior parts in vehicle/sport equipment	Peças et al. (2018)
Demostachya fiber	Vehicle application/interior components	Sai Krishnan et al. (2021)
Coir	Automotive application/seat mattress and cover	Holbery and Houston (2006)
Abaca	Automobile application /floor and body panel	Barba et al. (2020)

The rise in the use of composite materials is attributed to their reasonable costs, the absence of organic solvents in surface treatments, and their competitive strength-to-weight ratio (John & Thomas 2008), (Furtado et al. 2014). It is also undeniable that there is a contribution made by the materials to lower fossil fuel consumption and greenhouse gases (GHG) emissions of vehicles through the materials' use lesser energy in their incineration, in compliance with Environmental Directives (Alves et al. 2011). A significant drawback is the lengthy preparation time required. For instance, jute fibers are harvested only once per year and need about 20 to 30 days for immersing in water, drying, and yarning (Furtado et al. 2014). From mentioned above, natural fibers need many steps, treatments, procedures, and adhesives or matrixes, before they are ready for use, except for the luffa plant, which can be used directly in some industries due it cylindrical structure.

LUFFA PLANT

LUFFA MICRO-POROUS MATERIAL

Luffa cylindrical (LC) or loofah, also goes by the names of gourd, bath sponge, vegetable sponge (Srinivasan et al. 2014), and petola (in Malaysia) (Jamaluddin et al. 2020). It is a subtropical plant commonly found in some Asian countries especially China, and Japan, as well as in South America. (Mohanta & Acharya 2018), and in Kuching-Malaysia (Jamaluddin et al. 2020), belonging to the Cucurbitaceae family (Ferreira et al. 2022; Gurjar et al. 2024; Jiang et al. 2023; Karim et al. 2024; Siqueira et al. 2010). The plant can be as long as 10 m. The Luffa plant bears fruit, with its cylindrical shape(Srinivasan et al. 2014), the luffa's length is15 cm to more than 100 cm with a diameter of 4 cm to more than 8 cm (Carmona & Colorado L 2020). When ripe It will be in yellow color and dark-brown when dried (Carmona & Colorado L 2020), (Ferreira et al. 2022). There are four parts in the sponge (Xie et al. 2020), namely the outer-layer, the middle-layer, the inner-layer and the core-layer, labelled O, M, I and C, respectively, as seen in Figure 4.

The structural composition and mechanical behavior of the luffa sponge are characterized by a complex network of three-dimensional energy-absorbing elements, including tubular, fibrous, and cellular structures. Critically, the sponge features a central core of thicker fibers that provides robust support to the outer fibrous wall. This internal architecture significantly enhances the material's overall structural stability, particularly when subjected to axial compressive forces. As a result of these inherent qualities, the luffa sponge's impact resistance is exceptional among natural plant materials, establishing it as an ideal, eco-friendly energy absorber with a structure inherently optimized by nature.

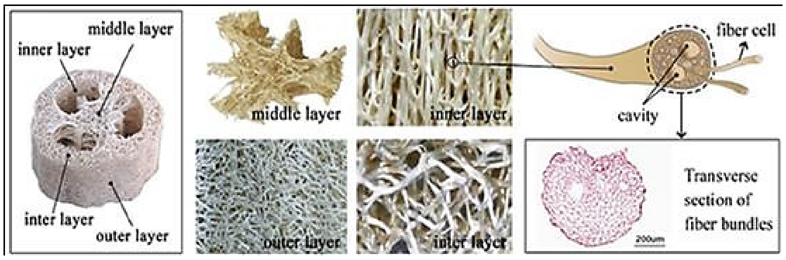

FIGURE 4. Luffa sponge structure (Y. Chen et al. 2018)

Bio-cellular materials exhibit superb mechanical properties at low density (Fan et al. 2014), (Wang et al. 2015), (Anbukarasi & Kalaiselvam 2015). The luffa sponge is one these Bio-cellular materials, where they contain a complex, interconnecting pore structure (J. Shen et al. 2012; J. Shen et al. 2013), (Chen et al. 2014; Shen et al. 2014). luffa sponge is a foam-like biological material, the Investigation of biological systems may enable engineers and scientists to reveal novel develop biological materials with desired engineered properties (An et al. 2015).

Owing to the fact that it is a cellular material, the Luffa sponge has macro-pores and micro-pores, making it extremely light. Its strength is significantly boosted by the rigid inner surface layer surrounding the macro-pores (An & Fan 2016). There are some factors on which the luffa plant depends on its chemical composition, such as plant type, soil, climatic conditions, weather conditions, etc. (Shen et al. 2014), (de Souza et al. 2022), (Sasan Narkesabad et al. 2023). Being a fibre-connecting porous natural material, the Luffa fibres' major chemical components are cellulose, hemi-cellulose, and lignin (Chen et al. 2014). As depicted in Figure 5 and table (2) display the different percentages of luffa components.

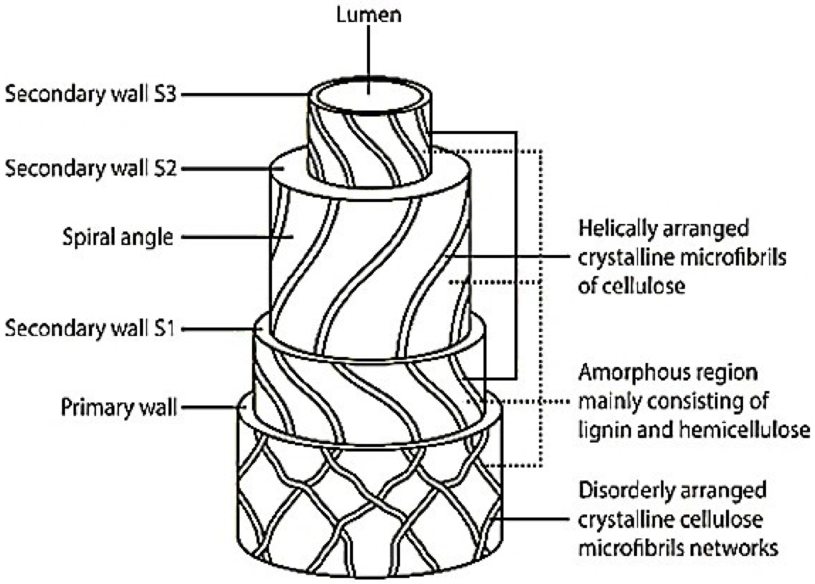

FIGURE 5. The main chemical components of the natural fibre (Zwawi 2021)

TABLE 2. Composition of Luffa plant

Lignin (%)	Hemicellulose (%)	Cellulose (%)	Others (%)	References
10–23	8–22	55–70	-	Li et al. (2007), Pathak et al. (2018)
11.2	20	62	Ashes 0.40	Pereira et al. (2015)
11.7	-	63	-	Dharmalingam et al. (2020)
11.2	20	62	Ash 0.4, extracts 3.1	Labeeba et al. (2019)
11.69	20.88	63	Ash 0.4	Shamsudin et al. (2022), P. Sabarinathan (2016), Saw et al. (2013)
1.6	14.4	63	21	Seki et al. (2012), Haque et al. (2023), Mohanta and Acharya (2018)
15.2	17.5	65.5	3.8	(de Souza et al. 2022; Siqueira et al. 2010), Liu et al. (2016)
11.2	19.4	63	3.1	Tanobe et al. (2005)

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Lignin (%)	Hemicellulose (%)	Cellulose (%)	Others (%)	References
8.1	-	67	7.2	Siqueira and Botaro (2013)
14.04	-	62.34	0.37	Akgül et al. (2013)
21.85	-	73.92	-	Kalusuraman et al. (2016)
19.67	29.87	57.03	-	Chen. Zhang. Zhang. et al. (2019)
8.2	19.9	59.1	12.8	d'Almeida et al. (2006)
-	-	73.92	-	Kalusuraman et al. (2020)
12.03	19	65.69	Moisture 9.74	Wetaka et al. (2016)
13.4	26.6	60	-	Oun et al. (2021), Hong et al. (2020), Taimur Al et al. (2018)
14.7	15.8	37.7	Ash 10.4	Nyong et al. (2021)
10-23	8-22	55-90	Ash 0.4 extracts 3.2	Koruk and Genc (2019), Yuxia Chen et al. (2018), Siqueira et al. (2010), Sharath et al. (2024), Ashok et al. (2020), Hong et al. (2020), Abdel-Fattah (2019)
11.2	20	62	-	Sivakandhan et al. (2020)
21.85	-	73.92	Ash 4.74 Wax 0.48	Kalusuraman et al. (2019)
19.67	29.87	57.03	-	Y. Chen et al. (2018)
8.2-16.36	16.5-22	59.1-65.5	-	Ghali et al. (2009), Carmona and Colorado L (2020)
1–22	14–30	57–74	0–12.8	Adeyanju et al. (2020)
10–23	8–22	55–70	Extracts 3.2	M. J. Kamran et al. (2021)
10	30	60	Ash 1.04	Saeed and Iqbal (2013), Mazali and Alves (2005)
10-23	8-22	55-70	Ash 0.4 extractive 3.2	Saw (2017)
11.2	20	62	-	Arvind Kumar (2021)
10	30	60	-	Kharrati et al. (2022), Abd-Al Ftah et al. (2022), Parida et al. (2015), Srinivasan et al. (2014), Oboh and Aluyor (2009), Rahman et al. (2021)
25.18	28.54	54.26	Ash 8.81 Wax 0.26	Cheng et al. (2020)
10.6–11.2	19.4–22	60-63	-	Daniel-Mkpume et al. (2019), Macuja et al. (2015)
11.2	19.4	63	Ash 0.4 extractive 3.2	NagarajaGanesh and Muralikannan (2016)
11.2	20	62	Ash 0.4 extractive 3.1	Niharika Mohanta and Acharya (2015)
11.7	20.9	63	Ash 0.4	Jamaluddin et al. (2020)
15.20	17.5	65.50	Ash 0.70	Sasan Narkesabad et al. (2023)

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Lignin (%)	Hemicellulose (%)	Cellulose (%)	Others (%)	References
10.14	-	81.69	Ash 1.18 Wax 0.22	Sahayaraj A et al. (2023)
10-15	15-20	60-65	-	Wang et al. (2018)
16.91	14.62	68.29	-	Guo et al. (2019)
10.6	22	60	-	Laidani et al. (2012)
10-22	9-22	55-90	-	Nath et al. (2021)
16.36	16.50	59.42	-	Taimur Al et al. (2018)

MECHANICAL PROPERTIES OF LUFFA SPONGE AND LUFFA FIBER

The mechanical properties of the Luffa sponge column and luffa fiber are very much interrelated to the amount of density rather than other features as geometric one, that show similarities to other cellular materials (J. Shen et al. 2012). The Luffa sponge columns density in Kg/m^3 can calculate using Equation (1) and (2) according to Chen, et al. (Chen et al. 2017):

$$v = \frac{(S_1 + S_2) \times 2}{H} \tag{1}$$

$$\rho = \frac{m}{v} \tag{2}$$

m = mass in Kg, v = volume of luffa column in m^3, H= the high of luffa column. S1 and S2 = areas of the top and bottom cross-sections of the luffa cylindrica (excluding the pores), respectively.

And according to Chen, et al. (Y. Chen et al. 2018), Zhang et al. (Zhang et al. 2019) via using Equation (3):

$$\rho = \frac{2m}{(s_1 + s_2) \times H} \tag{3}$$

For Young's modulus Equation (4) Shen, et al. (J. Shen et al. 2012) found the experiential formula is:

$$E = 1.48 \times 10^6\, {\rho_0}^{1.16} \tag{4}$$

Li et al.(Li et al. 2006) defined the efficiency of energy dissipation (E_d) for luffa column is as via using Equation (5).

$$E_d(\varepsilon_a) = \frac{\int_0^{\varepsilon_d} \sigma(\varepsilon) d\varepsilon}{\sigma_a}, \quad 0 \le \varepsilon_a \le 1 \tag{5}$$

ε_a = strain (particular), σ_a = the stress at ε_a

Regarding, the plateau-stress σ_{p1} Equation (6) is measured as (J. Shen et al. 2013) (J. Shen et al. 2012):

$$\sigma_{p1} = \frac{\int_0^{\varepsilon_d} \sigma(\varepsilon) d_\varepsilon}{\varepsilon_d} \tag{6}$$

σ_{pl} = The plateau stress, ε_d = The densification strain.

The compressive strength is presented in Equation (7) according to Chen, et al. (Chen. Zhang. Guo. et al. 2019):

$$\delta_0 = 3A(\rho_0)^B \tag{7}$$

While according to the empirical formula by Shen, et al. (J. Shen et al. 2012). The compressive strength is given in the following Equation (8):

$$\frac{\sigma_0}{\sigma_{yf}} = A\left(\frac{\rho_0}{\rho_f}\right)^B \tag{8}$$

Also, in Equation (9) compressive strength according to Shen, et al. (J. H. Shen et al. 2013) it can be calculated as:

$$\frac{\sigma_o}{\sigma_f} = 0.37(1 + 0.24\varepsilon^{0.1})\left(\frac{\rho_o}{\rho_f}\right)^{0.28} \tag{9}$$

The content of cellulose in luffa sponge is similar to cellulose content in flax (Siakeng et al. 2018), sisal (Gupta & Singh 2018), and hemp (Cheung et al. 2009). But it is relatively higher than content of sugarcane (Karp et al. 2013), oil palm (Cheung et al. 2009), and kenaf (Siakeng et al. 2018). This indicates that luffa fiber is similar to or better in terms of the structural characteristics compared to other fibres (Adeyanju et al. 2020). Differences in the content of lignin may be due to the essential nature of the plant fiber. Moreover, the differences may also be due to the technique of fiber extraction, type of treatments and processing before characterization. The differences in the cellulose content and lignin lead to the differences in the natural fibre's mechanical properties as highlighted in Table 3.

TABLE 3. Mechanical and Physical properties of luffa fiber and some other of natural fibers

Types of natural fiber	Mechanical and Physical properties				Ref.
	Tensile strength (MPa)	Young's modulus (GPa)	Elongation (%)	Density (g/cm^3)	
Luffa	202.3	4.5	2.5	0.92-1.2	M. Jahanzail Kamran et al. (2021), Saw et al. (2013)
Hemp	550	70	1.6	1.5	Karthi et al. (2020), Gholampour and Ozbakkaloglu (2019)
Sisal	511–635	9.4–22	2.0–2.5	1.3	John and Anandjiwala (2007)
Kenaf	930	53	1.6	1.1	John and Anandjiwala (2007)
Flax	1.339	27.6–38	3.2	1.5	Fuqua et al. (2012)
Jute	300-700	2.5–26.5	2	1.5	Singh et al. (2018), Gholampour and Ozbakkaloglu (2019)
Rami	147-938	44-128	2-3.8	1.5	Isaac and Ezekwem (2021)
Abaca	400-760	12	3-10	1.5	Pathak et al. (2018)
Coconut	500	2.5	20	1.15	Isaac and Ezekwem (2021)
Bamboo	140-800	11-33	1.4	0.6-14	Isaac and Ezekwem (2021)
Silk	500-1300	5.22	15.4	1.32	Ahmad et al. (2014)
Banana	444-600	12	5.9	1.35	Ahmad et al. (2014), Khan et al. (2018)
Arenga engleri	102.34	1.735	15.76	0.9502	Cheng et al. (2020), Chen et al. (2017)
Coir	131-175	4-6	3.70-44.70	1.15-1.3	Bourmaud et al. (2018), Cheng et al. (2020)

LUFFA PLANT BEHAVIOR

BEHAVIOR OF LUFFA FIBER AFTER TREATMENTS PROCEDURE

Natural fibers need many steps, procedures and treatments before they are ready for use, except for the luffa plant, which can be used directly in some industries, but if used with composite must do the treatment. The most treatments that used with natural fibers are include the sodium hydroxide, silanes, permanganate and isocyanates.

SURFACE TREATMENT BY SODIUM HYDROXIDE

Sodium-hydroxide (NaOH) treatment is one of the most popularly used fibre surface treatments. The hydrogen bonding is disrupted by sodium hydroxide treatment, which increases surface roughness. Additionally, depolymerization of cellulose brought on by sodium hydroxide surface treatment exposes short-length crystallites (Mohammed et al. 2015). A number of treatment methods can be adopted to make the adhesion stronger (M. Jahanzail Kamran et al. 2021) (Yuxia Chen et al. 2018). In the past, numerous researchers have demonstrated a variety of methods to enhance the properties utilizing sodium hydroxide surface treatment. Researchers have adapted various concentration values, immersion periods, temperatures, and catalysts or coupling agents (Wetaka et al. 2016) (Kamran et al. 2022).

Some researchers have conducted studies using various concentrations, immersion periods, and immersion temperatures, which has resulted in the development of numerous sodium hydroxide surface treatment methods (M. Jahanzail Kamran et al. 2021) (Bekele et al. 2023) (Kharrati et al. 2022). Additionally, compared to untreated luffa fibre, sodium hydroxide surface-treated luffa fibre has always demonstrated improved mechanical performance. Laib et.al (Laib et al. 2020) found from the analyses that Luffa fibres with treated hydroxide surface have higher flexural strength than those with untreated fibres. With regard to composite materials made of natural fibers and polymers, it was found that by using sodium-hydroxide, the surface treatment improves the natural fibre-polymer adhesion. It should be added that the chemical reaction between the fibre and sodium-hydroxide is given in the Equation 10 (Li et al. 2007), (Gupta et al. 2015).

$$\text{fibre - OH} + \text{NaOH} \rightarrow \text{fibre - O - Na} + H_2O \qquad (10)$$

Chen et al. (Chen. Zhang. Zhang. et al. 2019) examined the impacts of three alkali-based softening treatments on the highly densed Luffa fibre bundles' properties. The observation shows that the treatment lowered the compressive strength and plateau stress of the fibres significantly. Even so, the treatment using 10% NaOH/20% CH_3COOH was regarded as the best.

SURFACE TREATMENT BY SILANE

Silane is known to be a strong coupling agent. The surface of natural fibres is treated with silane to highlight a decrease in cellulose hydroxyl groups in the fibre matrix (Mohammed et al. 2015). Covalent bonds are created on the fibre's surface caused by the reaction between silanol, taking place when moisture is present, and reacting with the hydroxyl groups (Gupta et al. 2015; Huda et al. 2007).

For the silane surface treatment, various silane coupling agents are available; they have rather striking effects on the fibre as the result, and provide varying mechanical properties. For the fact that it is convenient to use and it is generally accessible, 3-aminopropyltrimethoxy silane is known as one of the most widely utilized silane coupling agents. It is also worth adding that with respect to the mechanical properties, the silane surface-treated fibre composites showed a better performance than the untreated fibre composites. (Kamran et al. 2022), (M. Jahanzail Kamran et al. 2021), (Sasan Narkesabad et al. 2023).

Silane treatments further strengthened the mechanical properties of the Luffa fibre, i.e. the flexural properties of the Luffa fibre composites, compared to the untreated Luffa fibre composite, folllowing the improved interfacial bonding (Laib et al. 2020). Next, the chemical reaction between the Silan and fibre is shown in the Equation (11) (Akter et al. 2023).

$$\mathrm{CH_2Chi\ (OH)_3 + Fibre - OH} \rightarrow \mathrm{CH_2CHi\ (OH)_2O - Fiber - H_2O} \tag{11}$$

SURFACE TREATMENT BY PERMANGANATE

Typically, the potassium permanganate ($KMnO_4$) in an acetone solution is used to permanganate-treat natural fibres. The copolymerization process begins with this treatment producing highly reactive permanganate (Mn3+) ions that react with the hydroxyl of the cellulose- a procedure that improves chemical interlocking at the interface and offers greater matrix adherence (Li et al. 2018). The greater thermal stability of the fibre is caused by the formation of cellulose-manganate. To add, it interacts with the components of lignin (hydrophilic -OH) and dissociates from the fibre cell wall. It reduces the fibre's hydrophilic properties. More $KMnO_4$ (more than 1%), causes excessive delignification within the cellulose structure and deterioration of fibre characteristics (Mohanta 2016), (Abisha et al. 2023). Mohanta and Acharya (Mohanta & Acharya 2016) looked into the effect of the fibre surface treatment on various properties of Luffa fibre treated with potassium permanganate at room temperature. Through observation, the chemically treated Luffa cylindrica-reinforced epoxy composites had remarkably improved the mechanical-properties of the composite. To add, the chemical reaction between the Silan and permanganate is depicted in the Equation (12).

$$\mathrm{Cellulose\ (fibre) - H + KMnO_4} \rightarrow \mathrm{Cellulose\ (fibre) -H-O- Mn\ (= O)_2OK^+} \tag{12}$$

SURFACE TREATMENT BY ACETYLATION

The introduction of acetyl functional groups is the essence of the acetylation treatment. As the acetylation surface treatment adds acetyl functional groups into the fibre's microstructure, this makes the fibre more hydrophobic, further esterifying the cellulose fibre (Li et al. 2007).

There are numerous approaches to attained natural fibres an acetylated surface treatment. It is possible to utilize various combinations of catalyst, temperature, immersion time, and concentration. Whatever the method, the ultimate goal is to increase the fiber's hydrophobicity. (M. Jahanzail Kamran et al. 2021) (Thamarai Selvi et al. 2022).

Comparing treated and untreated luffa fibre-composites, those with an acetylation surface exhibit improved mechanical characteristics (Oladele et al. 2020). Stronger adhesion between the polymer and the fibre may be the cause of this. This is due to the surface treatment's substitution of acetyl functional groups for hydroxyl functional groups. Higher values of concentration lead to the deterioration of the fibre surface, which results in poor mechanical properties (Kamran et al. 2022), (Shaari et al. 2021). Additionally, the chemically reaction between the Acetyl and fibre is then given in the Equation 13.

$$\mathrm{fibre - OH + CH_2 == CH - COONa} \rightarrow \mathrm{fibre\text{-}O\text{-}CH_2\text{-}CH_2\text{-}COOH} \tag{13}$$

BEHAVIOR OF LUFFA SPONGE UNDER COMPRESSIVE LOADING

The Luffa sponge behavior refers to the mechanical characteristics under compression loading conditions. Luffa sponge is a naturally occurring product with a fibrous structure. It frequently takes a cylindrical shape, making it ideal for applications that required cylindrical shapes. In general, it is crucial to develop and optimize the use of luffa sponge in multiple engineering applications by comprehending its cylindrical behaviour.

Under axial quasi-static loading, Shen, et al. (J. Shen et al. 2012), performed the first scientific examination of the Luffa sponge's varying properties with the intention to adopting it as a replacement for sustainable engineering materials in various applications. A number of compression tests have been run. The stress-strain curves exhibit nearly constant plateau stress over strains, perfect for applications that need energy absorption. The stiffness, strength, and energy absorption of the Luffa sponge material are exceptional and equivalent to those of several metallic cellular materials in the same density range. The strength of the Luffa sponge is superior to most other cellular materials now in use. Figure.6 provides an important illustration of the fact that the average plateau stress of the Luffa sponge is much higher than that of the Ni-P micro-structure.

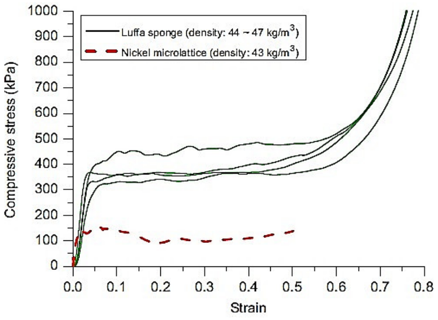

FIGURE 6. Load-displacement curve of luffa-Nickel microlattice (J. Shen et al. 2012)

Shen et al. (2014), ran a test on the ability of the Luffa to absorb energy after having it compressed several times after the Luffa kept its original shape when immersed in water and dried. Multiple experiments were conducted for the Luffa sponge columns, where the test methods used were axial compression tests for the Luffa column Figure 7. The axial compressive tests at the strain rate ranging from 10^{-3} s^{-1} (quasi-static) were conducted using the INSTRON machine test. The Luffa sponge columns exhibited a regular pattern after every compression.

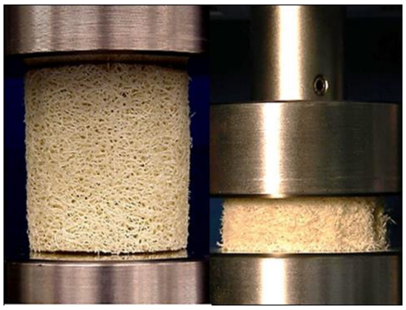

FIGURE 7. Luffa sponge under axial compression loading (Shen et al. 2014)

Y. Chen et al. (2018), studied two types of luffa sponge column high-density (HD) and low-density (LD), under quasi-static loading (compressed by 40% and 60%.). The results of the luffa sponge with high density showed that the compressive strength was remarkably greater than that of the luffa sponge with low density (LD) reaching ten times that of the low-density as in Figure 8. After compression, a high-density luffa sponge shows good stability in dimensions.

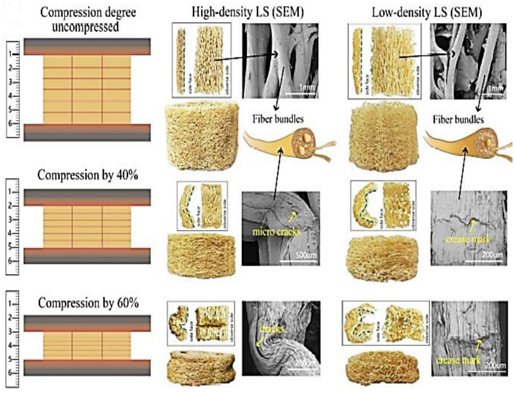

FIGURE 8. Luffa sponge with high-density and low-density under quasi-static loading (Y. Chen et al. 2018)

According to Chen. Zhang. Guo. et al. (2019), a two variety-density of luffa cylinderica as a filling material were investigated. The speed of unloading and reloading were 3 mm min^{-1} in repetitive loading test as shown in Figure 9. The results highlighted that the compressive strength and plateau stress of LCs of high and low densities have a significant relation to their density. However, the compressive strength of the former was approximately 3 times that of the latter. The plateau stress of high-density LCs is almost 10 times more than the low-density LCs. Higher plateau stress offers higher energy absorption, indicating that the energy absorption capacity of high-density LCs is higher than that of low-density LCs. Moreover, the plateau stress of both the two types of LCs increases with their density.

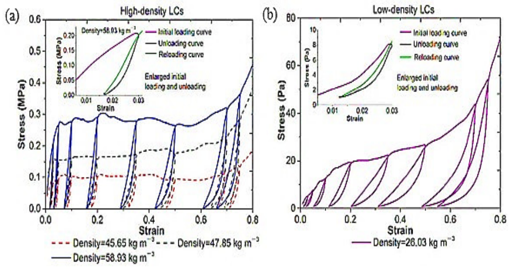

FIGURE 9. Loading, unloading and reloading (a) Luffa sponge LCs with high density (b) Luffa sponge LCs with low density (Chen. Zhang. Guo. et al. 2019)

In a recent study conducted via Yin et al. (2019), Luffa sponges with nickel-plated were discovered to exhibit more bending-dominated behaviour. These bio-inherited materials' ability to absorb energy can be more powerful than many artificial engineering materials with regard to the toughness qualities. This ability to absorb energy is displayed in an Ashby chart and compared with other light cellular synthetic materials, this can be seen in Figure 10 (Ashby et al. 2000). The bio-inherited materials can be compared to CFRP honeycombs, and stainless-steel lattice while outperforming aluminium foam. To be specific the Ni/Ag foams are made in the same way through the electrochemical deposition on polymer foams. However, unlike nickel-plated Luffa sponges, the energy absorption is significantly lower. The Ashby chart's density contrast can aid the material selection for a particular density range. Luffa sponges' stable deformation and effective energy absorption capabilities can have a link with their structural makeup.

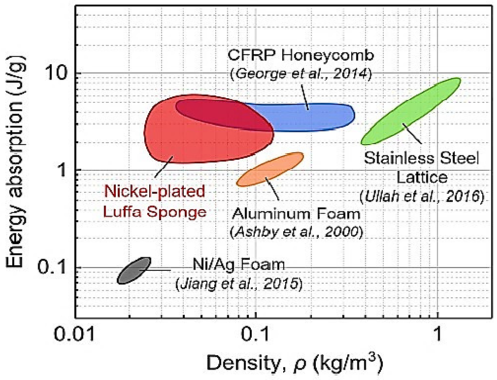

FIGURE 10. The energy absorption and density chart of luffa sponge and some cellular synthetic materials (Yin et al. 2019)

Goudarzi et al. (2022), introduced a novel composite panel made of luffa fibres, magnetite nanoparticles, and chitosan adhesin as a natural composite with agreeable resistance to compression and penetrating forces as illustrated in Figure 11. Luffa samples functioned as a natural mat from the luffa plant, and chitosan as adhesin was produced from shrimp shells as a natural resin. The quasi-static punch test was used to determine the maximum needed load for penetrating the manufactured Luffa-chitosan composite panels. The results of the punch tests revealed that the maximum penetration load of the related composite panel increased by at least 500 N for every additional three layers of Luffa-chitosan. With considerations given to the lightweight, high strength, and capacity to absorb energy during compression, using natural composite panels made of Luffa-chitosan in bulletproof vests and armour is an idea deemed creative and clever.

FIGURE 11. Explains (a) Chitosan gel (b) Luffa layers impregnated with chitosan (c) Two covered rigid plates (d) Placing the impregnated Luffa-chitosan between two platens applying quasi-static load on the impregnated layers (f) Processing the panel in an oven (g) Panel of Luffa-chitosan (h) Panel of glass-chitosan (Goudarzi et al. 2022).

Under axial dynamic loading as illustrated in Figure 12, J. Shen et al. (2013), paid attention to the compressive experiments on the Luffa sponge material performed at various strain rates over a wide density range. The compressive strength, plateau stress, and specific energy absorption of the Luffa sponge material tend to be rate-dependent when the dynamic data are drawn in comparison to those of the quasi-static trials. The dynamic augmentation for compressive strength was also highlighted as being more pronounced than that for plateau stress. Comparatively speaking, the Luffa sponge can absorb more energy than other cellular materials with comparable plateau stress under different strain rates.

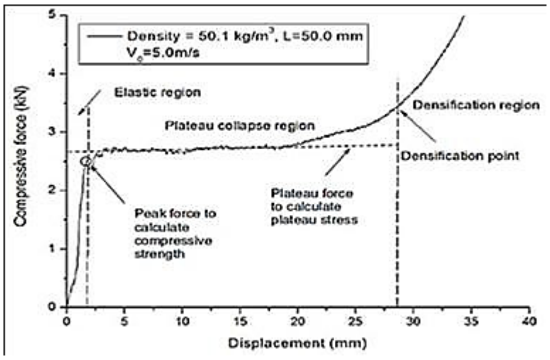

FIGURE 12. Force-displacement curve for luffa column under dynamic condition (J. Shen et al. 2013)

A numerical investigation of the luffa sponge was carried out according to Wang et al. (2015), ABAQUS/Explicit aided the investigation of the Luffa sponge columns. Finite element analysis (FEA) and theoretical models helped to explore numerically and analytically, respectively the behaviour of Luffa under uniaxial compression. The experimental data validated the FEA models. Using the verified FEA models as in Figure 13, the impacts of Luffa density, tube thickness to diameter ratio, and cross-sectional topology of Luffa core were studied parametrically. It was discovered that the optimal density of the Luffa sponge had a strong relation to the optimal density of the Luffa used as filler for the Luffa-filled tubes, growing with the increase of the thickness-to-diameter ratio of the tube.

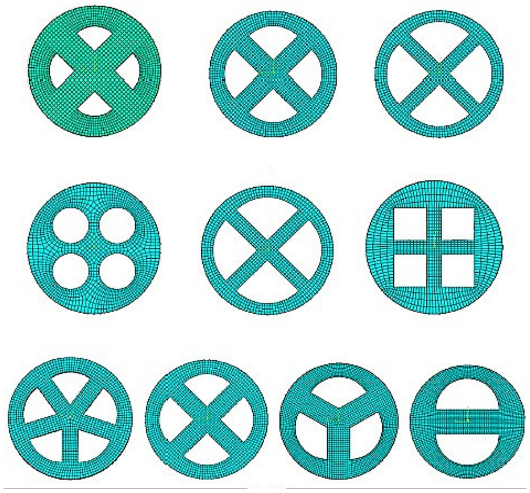

FIGURE 13. Core cross-section topologies for luffa-filled tubes vary in size, shape, and number of cores (Wang et al. 2015)

Researchers An et al. (2015) compressed luffa sponge cylinders laterally. As the result, the cellular foam is condensed within the cylindrical shell, but the pore structure itself remained, as depicted in Figure 14. The more increased the compressed area in time, the heavier the stress load on the fibres. The compression of the pores comes next and plastic hinges formed in the shell. The inner surface layer offered very little to these plastic hinges as it displayed a reduced bending motion. The contractions among fibres give the anti-crushing stability to elude lateral compression.

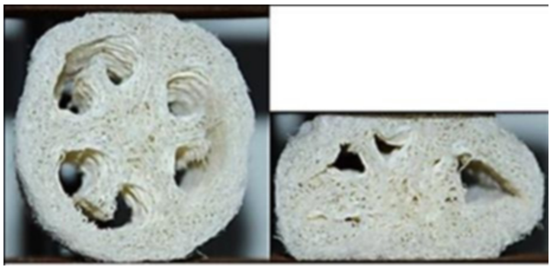

FIGURE 14. Luffa sponge under lateral loading (An et al. 2015)

Some researchers Cai et al. (2025) developed low-cost, high-performance impact-resistant material using natural luffa sponge column as reinforcement for composites. Impact-resistant materials are crucial for applications where materials must absorb and dissipate energy effectively. The impact performance of the luffa sponge stands out within the realm of natural plants, making it an ideal, naturally topology-optimized green energy-absorbing material. Figure 15 illustrate, the Luffa sponge, occupies a very interesting position in in the upper region, indicating it possesses a remarkably high specific strength. It outperforms many other well-known natural materials in this regard, including Jute, Coir, Wool, and Banana. Its specific strength is shown to be in the same range as high-performance fibers like Sisal and even surpasses some ranges of Flax and Sugarcane. Furthermore, this study effectively demonstrates the unique mechanical advantage of the Luffa sponge as a lightweight engineering material. While many natural fibers are valued for their stiffness, the Luffa sponge's standout characteristic is its exceptional strength-to-weight ratio.

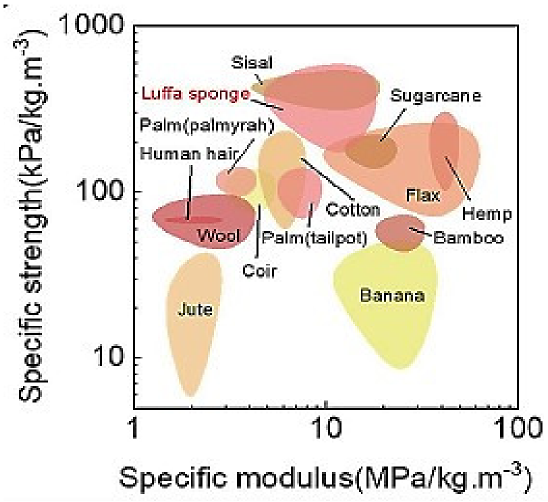

FIGURE 15. Specific strength with respect to the specific modulus of natural materials (Cai et al. 2025)

BEHAVIOR OF LUFFA SPONGE AFTER WATER IMMERSING-DRYING PROCEDURE

Stemming from the hydrophilic nature of the Luffa sponge and how it is able to absorb moisture, and to make sure that the Luffa is able to crush after the exposure to water or after immersion in water prior to drying for a period of time, some researchers (Shen et al. 2014) (An et al. 2015), probed into the effect of immersing the Luffa sponge in water and then drying it at room temperature. It is found that the Luffa sponge was able to absorb energy during crushing even after immersion in water and the subsequent drying. The longitudinally crushed Luffa sponge column that is crushed longitudinally can almost fully return to its original shape after being immersed in water- as highlighted in Figure 16. There is a large degree of recovery of the mechanical properties of the Luffa sponge after the following drying process.

To note, although they point to a swelling effect in water, different types of wood, palms, and fruits do not all show the same type of shape memory behaviour. The shape memory effect SME of the Luffa sponge is influenced by the cellulose, hemicellulose, and lignin composite patterns found in the material, and also by different mechanical properties of the Luffa sponge when they are wet and dried. The current literature fails to justify in full, these two elements, thus more research is vital (Shen et al. 2014).

The stress-strain curves of the subsequent compression cycles for the dried specimen are akin to the initial compression, except for the hardening behaviour at the strain level near to the maximum compressive strain of the initial loading cycle. Crushed cylinders can regain their load-bearing ability in part, and fully regain their geometric shape when submerged in water (An et al. 2015).

The remarkable shape memory effects and mechanical recovery features which could be exploited or bio-mimicked for water-responsive smart materials that are subject to large deformations, are also common features of Luffa sponge material (Shen et al. 2014).

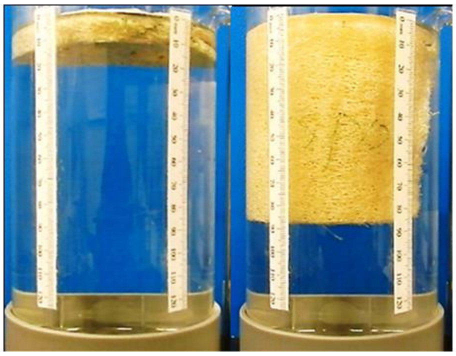

FIGURE 16. The shape memory phenomena in luffa cylindarica (Shen et al. 2014)

LUFFA CYLINDRICAL AS ENERGY ABSORBING STRUCTURE

Natural hierarchical materials are a perfect subject for porous structures studies especially bio-cellular luffa column. Where they boast off great porosity, and have the capability to maintain a constant stress deformation plateau during crushing. Porous materials are often used in applications to improve the energy absorption and lower the overall weight. Depending on how they are designed, these structures can be utilised as strong, lightweight components (Siddique et al. 2022).

The presence of the cells inside LC expands, causing the cells elongation and the subsequent development of a fibrous structure (Yin et al. 2019). As aforementioned, due to LC's fibrous and spongy nature, it has great mechanical properties (Saw 2017).

The Luffa sponge is deemed flawless for applications that require energy absorption owing to its varying exceptional characteristics, and which can be juxtaposed with those found in various foam materials with density ranges that are also comparable (J. H. Shen et al. 2012), (J. Shen et al. 2013), (Wang et al. 2015), (Sharath et al. 2024), (Mohanta & Acharya 2018).

Several ways have been adopted to mechanically analyses Luffa sponge specimens, with the compression examined over small block-shaped samples being indicative of good energy absorption results stemming from varying configurations or tests on individual fibres. This is to obtain readings on different aspects (Carmona & Colorado L 2020). The Luffa's columnar samples' dynamic mechanical properties are also investigated further. A finding reveals that there are obvious strain rate effects on the compressive strength, plateau stress and specific absorption energy of Luffa sponge (Xie et al. 2020). Additionally, by investigate the amount of moisture, the Luffa sponge's mechanical characteristics are also controlled. (J. Shen et al. 2012).

There are three stages of Luffa's unialzial crushing curve, as stated by An, et al.(An et al. 2015) elastic deformation, stable crushing deformation plateau, and densification Figure 17. They summed up that energy absorption capacities of Luffa sponges are better than those of polymer and aluminum foams (J. Shen et al. 2012). Compared to lattice materials (Fan et al. 2014), Luffa sponge materials display better specific energy absorptions.

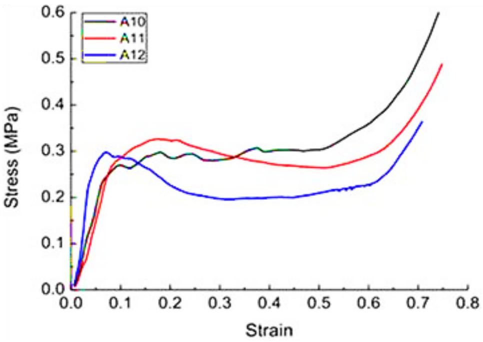

FIGURE 17. Stress-strain curve of luffa under quasi-static loading (An et al. 2015)

The recent experimental study (M. M. Fareed 2025) investigated the potential of using luffa cellular material as an efficient core filler for light-weight, thin-walled circular aluminum tubes to enhance their crush-response and energy-absorption capabilities under axial quasi-static loading. The research compared the crush behavior of luffa-filled tubes with that of empty tubes, analyzing force-displacement curves and deformation modes. A separate compression test was also performed on luffa sponges of varying densities to understand the filler's intrinsic properties. Luffa-filled circular tubes significantly outperform empty tubes, showing an increase in energy absorption capacity of over 42% and specific energy absorption (SEA) of over 31%. This superiority demonstrates that luffa-filled tubes are highly suitable as impact energy absorbers due to their enhanced ability to sustain axial loads. The load capacity of the filled tubes increases with the density of the luffa filler, which is attributed to the beneficial interaction effect between the aluminum tube and the luffa material as depicted in Figure 18.

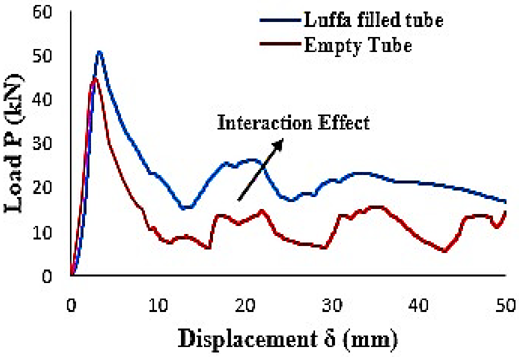

FIGURE 18. Load-displacement curve for empty tube and luffa-filled tube (M. M. Fareed 2025)

Another recent study, under the uniaxial compressive tests as illustrated in Figure 19. Cai et al. (2025) investigated the development and characterization of luffa sponge-reinforced cementitious composites (LSRCC) as a sustainable and high-performance impact-resistant material. The primary objective of this study was to develop low-cost, high-performance impact-resistant materials using natural luffa sponge as reinforcement for cementitious composites. It aimed to be the first to investigate the effect of temperature on the impact performance of LSRCC across a wide range, specifically from –196°C to 200°C. The study also sought to address the brittleness of traditional materials at low temperatures and pioneer a sustainable, ultra-low-temperature impact-resistant material.

The paper systematically investigated bio-inspired impact-resistant cementitious composite materials based on luffa sponge, proposing the incorporation of its natural three-dimensional fiber system into the cement matrix to enhance toughness. Uniaxial compressive tests revealed a strong synergistic effect between the cement matrix and luffa sponge, leading to improved stiffness, strength, and a transition from brittle to ductile failure modes. The luffa sponge effectively mitigates the inherent brittleness of cement paste as shown in Figure 19.

LSRCC specimens demonstrated excellent impact resistance at ambient temperature due to the reinforcing effect of the luffa sponge. Under repeated impact loads, the material maintained structural integrity, transitioned from brittle to ductile failure, and showed significant energy dissipation. Where the energy dissipation per impact increased, and the plateau stage in force-displacement curves broadened, indicating suitability for multiple impact loads. LSRCC exhibited excellent adaptability to extreme thermal conditions, Thermal decomposition of luffa fibers at 200°C and water crystallization at –196°C led to higher energy dissipation during repeated impacts at these temperatures.

The study successfully demonstrated that luffa sponge-reinforced cementitious composites (LSRCC) are a promising low-cost, high-performance impact-resistant material. This bio-inspired approach offers a sustainable solution for developing advanced materials with improved performance and environmental benefits.

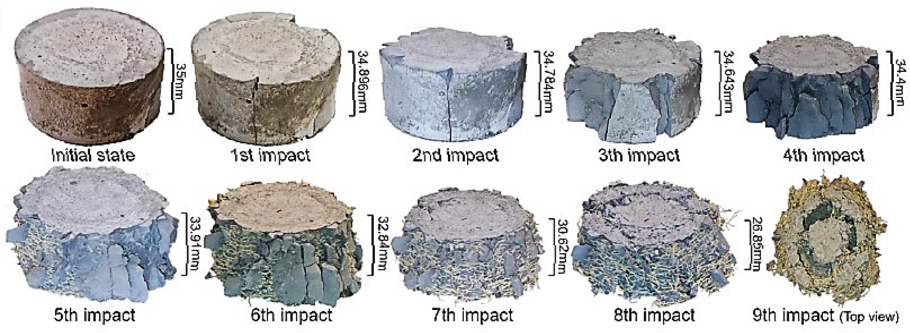

FIGURE 19. Initial and residual states of LSRCC after repeated impacts (Cai et al. 2025)

LUFFA FIBRES IN VEHICLE APPLICATIONS

The automotive industry has been a key adopter of Natural Fiber Reinforced Polymers (NFRPs), driven by the dual pressures of enhancing fuel efficiency through weight reduction and meeting stringent environmental regulations. The key advantage here, beyond weight savings of 10-30% over glass fiber counterparts, is their behavior in a crash. Luffa fibers, like other natural fibers, offer a significant density advantage over glass fibers, leading to a higher specific strength and stiffness (strength-to-weight and stiffness-to-weight ratios). They are also less abrasive to processing equipment, have a lower environmental footprint, and are more cost-effective. In essence, the choice between using luffa as a fiber or a sponge depends entirely on the intended application. For creating strong, lightweight composite materials, the individual fibers are key. For applications that leverage its unique cellular structure for energy and sound absorption, the intact sponge is the superior choice. This versatility makes Luffa cylindrica an exceptionally promising resource in the pursuit of sustainable engineering materials.

it's crucial to distinguish between the applications of Luffa cylindrica based on its form: as individual luffa fibers for reinforcing composites, and as the intact luffa sponge, which is a cellular solid. Each form offers a unique set of properties that makes it suitable for different high-performance applications

The current trajectory of research suggests that Luffa fiber composites are most immediately suited for non-structural and semi-structural automotive components, where low weight, acoustic properties, low cost, and sustainability are highly valued. Continued advancements in fiber treatment and hybridization techniques will be critical to extending luffa-based materials into more demanding applications within the rapidly evolving automotive sector (Natrayan & Kaliappan 2023).

As a forementioned, the material of luffa fiber exhibits remarkable hardness, also demonstrates great strength and energy absorption capacity. This is unlike some commonly used synthetic cellular materials. The component of Luffa has high cellulose so it is lightweight and has a structural fibrous hierarchy. The using of luffa fiber in some engineering industry such as Automotive is in composite material form as example polymer and epoxy reinforced matrix material. Table 4 summaries some of automotive applications by using luffa fiber composites.

TABLE 4. luffa fiber composites in automotive applications

Luffa composite	Application in Automotive	References
Carbon–luffa epoxy hybrid composites	Various automotive applications	Natrayan and Kaliappan (2023)
Luffa–Pineapple with e-glass fiber	Leaf Spring in Automotive	Sethuraman et al. (2018)
Luffa Fiber–Reinforce Epoxy Resin	Interior and Exterior Parts of Automobiles	Daniel-Mkpume et al. (2019)
Luffa/polyester composites	Interior part/door lining	Tanobe et al. (2014)
Luffa and snake grass with epoxy resin and hardener	Automotive Industries	Suriyaprakash et al. (2023)
Palm Kernel and Luffa	Car Bumper	Alimako Bitrus et al. (2021)
Luffa–Reinforce Epoxy Resin	Automotive Industries	Saw et al. (2013)
Luffa fiber–Reinforce Epoxy	Automobile Components /Brake Pads	Kalusuraman et al. (2020)

CONCLUSION

The availability of various types of natural fibres is well acknowledged. It is in the foreseeable future that fibre will soon become one of the composite field's sustainable and renewable resources that can replace synthetic fibres in various applications. This paper throws some light on Luffa cylindrica (LC). Its dedication to LC's research work in the past has been impressive. Natural fibers, particularly luffa plant, offer a multitude of benefits due to their sustainability, biodegradability, and unique properties. Their advantages, including lightweight, strength, excellent absorbency, thermal insulation, and biodegradability, make them valuable materials for various applications. Understanding the factors affecting luffa plant growth and its importance as an energy absorber further highlights its potential in sustainable engineering and design.

This paper discussed results of other relevant researches were presented the properties of the luffa column, its components, the types of commonly surface treatments used, the different loads that were investigated on it, such as (quasi-static and dynamic load) and the mechanical-properties of the luffa plant. Additionally, the way of behaving of luffa crushed after immersion in water and then drying then performed the compression test again was discussed. Above all, numerous studies have demonstrated that luffa plant somehow show desirable impact behavior in comparable with other natural fibers. Accordingly, this paper summaries significant scientific findings on the utilization of luffa plant in energy absorption applications as a conclusion below:

1. The Luffa sponge has shown a great potential as an energy-absorbing device in structural applications, and is ideal for energy absorption and impact resistance compared to metallic cellular counterparts.
2. Luffa is a hydrophilic plant and it has a shape-memory behaviour after being immersed in water, and after drying it can be exposed to loading and energy is absorbed again.
3. Having compared both the mechanical and physical properties of Luffa fibre and some other natural fibres, Luffa fibre is similar to, or better than, other fibres in terms of the structural characteristics.
4. The main chemical components of the luffa fibers are cellulose, hemicellulose and lignin and others.
5. Surface of luffa fibres treated with sodium hydroxide-treated have always demonstrated improved mechanical performance.
6. The economic viability of LC fiber stems largely from its cost-effectiveness as a natural, renewable resource, making it an attractive “green” alternative

In the context of vehicle applications, Luffa cylindrica is not merely a single material but a versatile platform. Luffa fibers offer a pathway to producing lightweight, cost-effective, and sustainable interior components with good mechanical properties and noise, vibration, and harshness (NVH) benefits. Concurrently, the luffa sponge serves as a natural, high-performance model for next-generation energy absorption and acoustic insulation systems. The ongoing research into hybridization, surface modification, and bio-mimetic design ensures that luffa will play an increasingly significant role in the development of more sustainable and efficient vehicles.

In conclusion, the research underscores that the luffa plant is more than just a source of sustainable fibers; it is a natural marvel with a built-in architecture for energy management. Its collective advantages such lightweight, strength, excellent absorbency, thermal insulation, biodegradability, and especially its proven performance in energy absorption solidify its position as a valuable and renewable raw material for next-generation sustainable engineering. Continued research into the factors affecting its growth, optimization of its treatment, and integration into advanced composites will be crucial for fully realizing the transformative potential of Luffa cylindrica in creating a more sustainable world.

CHALLENGES, LIMITATION AND FUTURE RECOMMENDATIONS OF USING LUFFA

Different types of natural fibres are known to be potential raw materials for bioproducts, but it is important to choose fibres that are the most available and cheap, does not require a long time to form, and the percentage of cellulose is high to ensure excellent mechanical properties before attempting to employ it in some industries, It needs to give a lasting solution to the challenges that have to do with the current materials being used and will help to achieve more innovations and increase development, particularly in the automotive industry. The restriction of the natural lignocellulosic fibre composites has been linked with the hydrophilic nature of the fibres, which lowers the dry strength of materials and makes them prone to interfacial strength loss in moisture or aqueous environments.

LC fiber presents a compelling economic case for sustainable, low-cost raw material but requires continued research and development, particularly in fiber treatment and large-scale, consistent production methods, to overcome its performance limitations and fully challenge the dominance of synthetic fibers in structural fields.

As a limitation of using luffa fiber composites, LFC is a lignocellulosic fiber, making it hydrophilic (water-absorbing). This can lead to poor interfacial bonding with hydrophobic polymer matrices, dimensional instability, and performance degradation lower mechanical properties, moisture-induced swelling over time, requiring extra, surface treatments such as alkali/chemical treatments to mitigate. In contrast, using luffa sponge column as a filler no need to do surface treatments.

Future studies on Luffa sponge cylindrica (LSC) and luffa fiber composites (LFC) are recommended to focus on using LSC as the energy absorption structure as there is a scarcity of research conducted in this area. Moreover, if LFC are to be used in more industries especially aerospace, automotive and other application. more research should be considered and conducted, as demonstrated in this paper. Therefore, based on the literature, the future recommendation using luffa column as filler for energy absorption structure in vehicle such as for car in crash box, A-pillar, B-pillar, etc. and in train as a filler inside some type of the attenuator that have cylindrical tube, and inside the (frame or structure car body) in Racing cars.

Finally, more research that consider polymer and epoxy matrices should be in place to make composites include luffa sponge. Thus, it is perhaps easier to mitigate environmental pollution within the use of natural fibres like Luffa column (LC), where, through the green sustainability composites and the combination of these fibres, a sound and timely solution can be offered and undertaken.

ACKNOWLEDGEMENT

This research is supported by the Ministry of Higher Education (MOHE) and Universiti Teknologi Malaysia under Grant Vote No. RJ130000.7824.5F643 and R.J130000.7724.4J755. Sincere gratitude and recognition also go to Universiti Teknologi Malaysia (UTM) and UNITEN University for the continuous support in completing this research.

DECLARATION OF COMPETING INTEREST

None.

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