



# A review on *Luffa* fibres and their polymer composites

Comfort Abidemi Adeyanju<sup>1</sup> , Samuel Ogunniyi<sup>1</sup> , Joshua O. Ighalo<sup>1,2,\*</sup> ,  
Adewale George Adeniyi<sup>1,\*</sup> , and Sulyman A. Abdulkareem<sup>1</sup>

<sup>1</sup>Department of Chemical Engineering, University of Ilorin, P. M. B. 1515, Ilorin, Nigeria

<sup>2</sup>Department of Chemical Engineering, Nnamdi Azikiwe University, P. M. B. 5025, Awka, Nigeria

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## ABSTRACT

*Luffa spp.* is readily available and widely grown in Asia and Africa and is a rich source of natural fibres for composite development. This paper reviews research findings on *Luffa* fibres and their composites. The progress of research, novel findings that affect the paradigm of the research area, recent trends, knowledge gaps and future perspectives are evaluated. It was found that the average chemical composition of *Luffa* fibres ranges from 57–74% cellulose, 14–30% of hemicellulose, 1–22% of lignin and 0–12.8% of the other components. *Luffa* fibres were usually extracted by drying. Furthermore, the most common modification technique was found to be by alkali mercerisation. About 53% of the research studies made use of epoxy resins for their base polymer making it the most popular polymer type for *Luffa* fibre reinforced composites. The composites are fabricated usually by manual mixing and hand layup and the most common curing technique was found to be compression moulding (about 63% of the research studies). The mechanical, thermal, crystalline and other properties of the composites are also considered in this review. Further interesting areas suggested for future work include investigation of the effect of drying, more trials with *L. acutangula* and utilisation of multi-resin ternary systems. It is concluded that *Luffa* is a promising material for composite development and based on its favourable properties is likely to continue playing an important role for the years to come.

## Introduction

In the era of modern engineering materials, degradability is an important property to be considered in the selecting materials to use [1]. Recently,

researchers have focused on tackling global warming with biodegradable composites [2]. Natural fibre composites are advantageous due to some of their physical, chemical and mechanical properties and unique lightweight [3, 4]. *Luffa spp.* fibres are ones of

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Address correspondence to E-mail: oshea.ighalo@yahoo.com; adeniyi.ag@unilorin.edu.ng

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the most popular natural fibres in composites development.

Based on the scientific classification, *Luffa* belongs to the Order—*Cucurbitales* and Family—*Cucurbitaceae* [5, 6]. It is a sub-tropical herbal plant that requires warm temperature [7]. Seeds from the pod are usually black in colour and have an oblong shape with a bitter taste [5]. The flower is usually yellowish in colour and primes in August–September [8]. The fruit is brownish in colour when mature and dries to develop a sponge-like structures that have a fibrous vascular system [9] and [10]. The fruits produced are cylindrical in shape and smooth [6]. *Luffa* is generally recognised as sponge gourd, vegetable sponge, loofa, dish-cloth gourd or bath sponge. The genus *Luffa* comprises species 5–7 on average but only *Luffa cylindrica* and *Luffa acutangula* are widely used domestically [11]. *Luffa c.* is readily available and widely grown in Asia and Africa where it has been observed to have medicinal benefits [12]. Based on its phytochemical analysis, the fruit and the leaf contain triterpenoid saponins and the seed has some polypeptides [6]. *Luffa* is a rich source of natural fibres (shown in Fig. 1a, b) for composite developments.

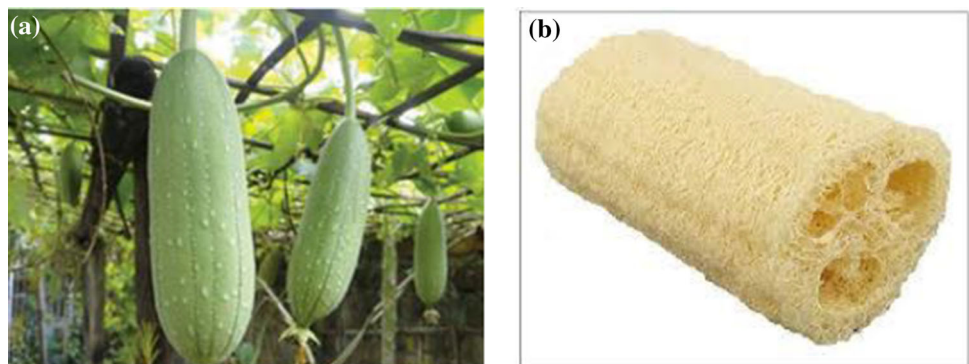
In industry, natural fibre reinforced composite materials are currently in focus [15–17]. Natural fibre reinforced polymer-composites possess extraordinarily high strength to weight ratio, high impact and corrosion resistance, are non-conductive and exhibit low maintenance requirements [18]. The use of natural fibres to reinforce polymers has become more and more attractive due to their low density, renewability and availability [12, 19]. Polymer-based fibre reinforced composite materials are applied in the areas of roof making, home appliances, automotive [20], architectural design, etc. [21]. and others [22–24]. The fibres can be treated by both physical

and chemical means, to increase their adhesion to polymeric matrices when used in composites [25]. Because of the poor compatibility between the fibres and the polymer matrix, surface treatment should be applied to natural fibres to increase their bonding at the fibre-polymer interface [26].

The hydroxyl and carboxyl group relates with the water molecules through hydrogen bonding due to the presence of the cellulose and hemicellulose; the utmost constituents of natural fibres. This relation results in instability and reduction in the mechanical performance because of the presence of moisture in its wet state [12]. The effect of moisture is a crucial research centre-point for natural fibres. There is a hefty reduction in the mechanical performance operation when fully saturated [27]. During the wet state of the plant (Fig. 1a), the fruit is covered with green husk on the outside [28]. The wet leaves could be used as vegetables. The fruits can be used in the Asia continent as curry. In the dry state of the plant, the green husk starts to parched when the maturing time-frame of the fibres inside the husk is completed (Fig. 1b). At maturity the fruit becomes more fibrous [13].

Synthetic fibres usually have higher tensile strength than natural fibres, but their tensile modulus is of equal order of magnitude [29]. However, the natural fibres show higher value of specific modulus compared to the synthetic fibres [30]. Some mechanical properties of the natural fibres are inferior to the synthetic ones which is a great hindrance to their applications. Therefore, blending nano-fillers with natural fibres in a polymer matrix can lead to high-performance materials with good strength of biodegradability [31]. For a polymeric matrix material to be effectively used during the reinforcing phase, the surface of the filler needs to be modified to reduce its intrinsic hydrophilic nature and advance its

**Figure 1** *Luffa Cylindrica* plant [13] (a) and fibre [14] (b).



dispersion in a polymer which is usually hydrophobic [32]. However, the use of both fibre surface treatment (coupling agents) and modification of the polymer matrix resin (maleated poly-olefins) caught the attention of researchers because those factors are efficient in modifying the bonding between the components [33].

Over the years, researchers have investigated the properties of *Luffa* fibres and their composites. These were focused on the production process, treatment method, mechanical, thermal, structural, chemical and morphological properties of the fibres as well as the composites. There is no comprehensive review on *Luffa* fibres and their composites. Hence, there is a need to bridge this gap in knowledge and summarize the findings in this research area. This paper reviews the research findings on *Luffa* fibres and their composites. This was done to evaluate the progress of research, identify novel findings that have affected the paradigm of the research area, discuss recent trends and knowledge gaps and propose future perspectives.

### **Luffa fibre composition**

The extent to which *Luffa* fibres will perform when used in a composite is dependent on their chemical composition. Like other biomass, the major component of *Luffa* fibres is cellulose, hemicellulose and lignin [34]. Cellulose is the desired component in the fibres used for reinforcement of polymer composites. High levels of hemicellulose and lignin usually lead to poor mechanical properties of the fibres and their composites. *Luffa* fibres come from different species, such as *L. acutangula*, *L. cylindrica*, *L. aegyptiaca*, *L. sepium*, *L. operculata* etc. Of all these species, *Luffa c.* is the most popularly studied and applied. Table 1 shows that raw *Luffa* fibres are primarily made up of cellulose, hemicellulose and lignin, although they also contains some other components. From the table, it is seen that the average chemical composition of *Luffa* fibres ranges 57–74% of cellulose, 14–30% of hemicellulose, 1–22% of lignin and 0–12.8% of the other components. There were huge differences in the lignin contents of the *Luffa spp.* studied because the contents and compositions of the species differs naturally at different levels of plant growth which could be influenced by environment factors occurring at different cellular levels because they are cell specific.

The other components include ash and extractives. The cellulose content is similar to that of flax fibre (62–72%) [35], hemp fibre (67–75%) [36] and sisal fibre (65–4%) [37, 38]. However, it is comparatively higher than that of sugarcane fibre (32–55%) [39, 40], kenaf fibre (31–57%) [35] and oil palm fibres 44% [36]. This suggests that *Luffa* fibres are as good as most other fibres for utilisation in reinforced composites especially in terms of the compositional qualities. Differences in lignin content might be due to the intrinsic nature of the fibres. Furthermore, differences might also be due to fibre extraction and processing technique before characterising.

### **Luffa fibre physical properties**

The physical properties of the fibres play an important role in the mechanical performance of the final composites. The physical properties of *Luffa spp.* are summarised in Table 2. The values reported for the physical properties are usually for the dried state. It is unconventional to report wet fibre properties especially in view of composite development. These include tensile strength, tensile modulus, elongation at break, the fibre diameter and density. The values from different studies are slightly different as variations occur from one species to the other due to the nature of the plant, source of the fibre, cultivation region, plant duration, location, nature of the soil, climate conditions and treatment method. A wide range of fibre densities from as low as 0.353 g/cm<sup>3</sup> [49] to as high as 2.2 g/cm<sup>3</sup> [17] was reported. Denser fibres tend to exert more mechanical toughness. For the tensile properties, tensile strength was mostly between 10 and 50 MPa though as low as 0.49 MPa [9] and as high as 385 MPa [7, 47] have been observed. The elongation at break is a representation of the percentage elongation of the fibre before it breaks. The elongations have been observed to range from 0.48% [28] to 20% [50] for *L. cylindrica* and as high as 54.1 MPa [51] for *L. acutangula*. The range of these values is generally acceptable for potential reinforcements in polymer composites.

**Table 1** Composition of *Luffa* spp

	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Others (%)	Refs
	63.0	14.4	1.6	21	[7]
	65.5	17.5	15.2	3.8	[41]
	62.34	–	14.04	0.37	[9]
	59.1	19.9	8.2	12.8	[42]
	57.51	29.47	20.45	–	[43]
	57.03	29.87	19.67	–	[44]
	73.92	–	–	–	[45]
	73.92	–	21.85	–	[46]
	73.92	–	21.85	–	[8]
	67.0	–	8.1	7.2	[47]
	63.0	19.4	11.2	3.1	[48]

**Table 2** Physical properties of *Luffa* spp. fibres

Fibre	Density (g/cm <sup>3</sup> )	Tensile strength (MPa)	Tensile modulus (GPa)	Elongation at break (%)	Diameter (μm)	Refs
<i>L. cylindrica</i>	0.719–0.721	0.41–0.69	5.495–4.548	12.30–18.80	–	[9]
<i>L. acutangular</i>	0.82–0.92	12.40–13.56	23.14–73.29	54.1	–	[51]
<i>L. aegyptiaca</i>	2.2	3	0.004	7	–	[25]
<i>L. cylindrica</i>	–	9–20	0.0015–0.0140	–	–	[52]
<i>L. cylindrica</i>	1.15–1.50	9.13–17.97	0.446–1.331	–	–	[53]
<i>L. cylindrica</i>	0.8–0.9	1.7–20.5	0.9–1.8	1.1–2.2	–	[28]
<i>L. cylindrica</i>	1.1	–	1–12	–	–	[54]
<i>L. cylindrica</i>	1.1–1.5	178.20–192.70	4.263–5.184	1.86–3.12	–	[14]
<i>L. cylindrica</i>	–	20–33	0.4–0.5	2	–	[55]
<i>L. cylindrica</i>	0.82–0.92	68.1 ± 24	2.4 ± 0.215	4.5 ± 2.7	0.055	[41]
<i>L. cylindrica</i>	–	17.628	0.076	3.681	–	[56]
<i>L. cylindrica</i>	0.82–0.92	4.875–8.029	1.287–1.697	5.04	–	[57]
<i>L. cylindrica</i>	–	7.65	0.021	–	–	[58]
<i>L. cylindrica</i>	0.92 ± 0.05	16–19	3.4	0.48	631	[59]
<i>L. cylindrica</i>	0.84–0.92	50.25	–	4–7	220	[60]
<i>L. cylindrica</i>	1.33	15.9 ± 1.3	–	4.3	–	[33]
<i>L. cylindrica</i>	1.06	18.7	0.042	–	–	[61]
<i>L. cylindrica</i>	1.14	20–25	0.070	–	–	[62]
<i>L. cylindrica</i>	0.56	20–40	–	–	226	[63]
<i>L. cylindrica</i>	1.38	31	0.072	–	200	[64]
<i>L. cylindrica</i>	0.92 ± 0.05	385 ± 10.52	12 ± 1.02	2.65 ± 0.05	631	[47]
<i>L. cylindrica</i>	–	385 ± 10.52	12.2 ± 1.02	2.65 ± 0.05	–	[7]
<i>L. cylindrica</i>	1.26	17.4	0.354	20	–	[50]
<i>L. cylindrica</i>	1.2 ± 0.1	202.3	4.5	2.5 ± 0.2	150 ± 20	[65]
<i>L. cylindrica</i>	0.353	11.1	1.332	–	–	[49]
<i>L. cylindrica</i>	0.91	9.4	12–13	2–3	20–270	[66]
<i>L. cylindrica</i>	0.56	17	0.750	–	270 ± 20	[67]
<i>L. cylindrica</i>	–	385	12.2	3	10–20	[68]
<i>L. cylindrica</i>	0.82–0.92	6.7	–	11	–	[69]

## Extraction and treatment of *Luffa* fibres

In this section, the methods of extraction and treatment of *Luffa* fibres or composite development are discussed. Table 3 gives a summary of the extraction and modification of *Luffa* spp. The conventional techniques used for the extraction of natural fibres rely on decortication and water retting [18, 70]. However, it is observed that *Luffa* fibres are not extracted in this way. When dried, *Luffa* fibres usually become easy to separate from the other parts of the pod. Extraction is therefore done by sun-drying or by natural air drying [13, 33, 62, 64, 71]. When dried, the hard-outer layer is cut off to remove the seed from the pod. The sap colour can then be removed by soaking in water [72]. Drying of the *Luffa* c. plant is the most common method of extracting fibres from the plant [1, 27, 69] although some researchers purchased the fibres directly from a particular source [48, 73], others did not give the specifics of the fibres used in their research [74].

Fibres are chemically modified because their hydrophilic nature makes them adhere poorly to polymer matrix [75]. Thus, they are chemically treated to improve their mechanical properties and structural responses. Mercerisation with NaOH is the most popular fibre treatment technique as seen from the table. Untreated fibres have their surface covered with pectin, lignin and other impurities which are removed by treatment with NaOH, while increasing the surface roughness of the fibre [72]. This treatment also reduces the fibre diameter and increases interfacial bonding between the *Luffa* fibres and the polymer matrix. Other modifications used are benzylation (using benzoyl chloride), acetylation (using acetic acid), and oxidation (using potassium permanganate or hydrogen peroxide). The concentration of the solution, temperature and the duration at which the treatment is carried out influences the strength of the treated fibres [69]. Most of the treatments were carried out at room temperature for 15 min to 6 h; however, the temperatures ranging between 80 and 120 °C were also used by some researchers. Also, the treatment time as long as 12, 24 or 48 h were also applied (Table 3). Concentration varied between 1 and 20%, although treatment with acetic acid, or H<sub>2</sub>SO<sub>4</sub> at the concentration as high as 100% and 66%, respectively, were also used. After treatment, the fibres were generally washed with distilled water and dried (either in an oven or

naturally in sun) to remove moisture contents before they were used for the composites.

## *Luffa* composite preparation techniques

In this section, different preparation strategies and polymers utilised in the development of *Luffa* reinforced polymer composites are discussed. As shown in Fig. 2, epoxy resin is the most common polymer used for preparing *Luffa* composites. About 53% of the research studies made use of epoxides for their polymer matrix. This is due to exceptional mechanical properties, high adhesion to many substrates, and good heat and chemical resistance of epoxy polymers. They are used across a wide range of fields as fibre reinforced materials, general-purpose adhesives, high-performance coatings, and encapsulating materials [91]. The use of polyester resins [46, 59, 92] is about 16%, polypropylene [3, 89] and polyethylene [93, 94] is 7%, vinyl ester [47, 60] is 6% while other polymers, including polyurethane [25], resorcinol/formaldehyde resins [82], polylactic acid [90], polycaprolactone [32], starch [95], and polybutylene succinate-co-lactate copolymer [50] contribute about 12% to the *Luffa* fibre composites.

Composites have been fabricated by conventional methods called hand lay-up. This method has been widely explored to fabricate composites, because of its flexibility, cost-effectiveness and simplicity. It is economically suitable for developing countries and less financially supported colleges and universities [96]. From Fig. 3, manual mixing and hand lay-up [12, 13, 62] is seen as the most popular method of mixing and lay-up. Another method commonly used is mechanically mixing. This can be done using different mechanically designed devices like torque rheometer at 60 rpm for 10 min at an elevated temperature of 190 °C [55], intermeshing twin-screw extruder [73], micro compounding equipment [30]. Magnetic stirring was also used [47].

Compression moulding is a high-pressure, high-volume moulding process which is recommended for thermoplastic polymers. It is very advantageous in that it is relatively inexpensive, takes short cycle time, is good for high volume production, and delivers good dimensional accuracy, uniform density and improved impact strength of the final product [18]. Hot compression moulding usually was done at an elevated temperature such as 70 °C [59], 80 °C

**Table 3** Chemical Treatment of *Luffa spp.* fibres

Chemical Reagent	Temp (°C)	Concentration	Time (hrs)	Refs
NaOH	80	6 M	24.00	[64]
NaOH	Room	2% w/v	1.00	[71]
NaOH	80	5% w/v	2.00	[62]
NaOH	Room	5% w/v	4.00	[13]
NaOH	Room	2% w/v	2.00	[33]
NaOH, H <sub>2</sub> O <sub>2</sub>	85	5% w/v	1.00	[43, 76]
NaOH, CH <sub>3</sub> COOH	40	10% w/v, 20vol%	0.50	[43, 76]
NaOH, CO(NH <sub>2</sub> ) <sub>2</sub>	80	18% w/v, 1.6% w/v	0.50	[43, 76]
NaOH, H <sub>2</sub> O <sub>2</sub>	85	5% w/v	1.00	[44]
NaOH, CH <sub>3</sub> COOH	40	10% w/v, 20vol%	0.50	[44]
NaOH, CO(NH <sub>2</sub> ) <sub>2</sub>	80	18% w/v, 1.6% w/v	0.5	[44]
NaOH	80	2–10% w/v	6.00–24.00	[69]
NaOH	Boiling	0.1 M	0.30	[55]
NaOH	Boiling	0.1 M	0.30	[77]
NaOH	60	5 M	4.00	[66]
NaOH	80–120	4–12% w/v	1.00–3.00	[78]
NaOH, H <sub>2</sub> O <sub>2</sub>	100–120	2–10% w/v, 5–15vol%	1.00–3.00	[78]
NaOH	100	4% w/v	2.00	[26]
NaOH, H <sub>2</sub> O <sub>2</sub>	100	4% w/v, 10vol%	2.00	[26]
NaOH	25	1 N, 10% w/v	2.00	[1]
NaOH	Room	20% w/v	12.00–24.00	[27]
NaOH	25	5% w/v	48.00	[72]
NaOH	25	1 N	1.00	[45]
Ca(OH) <sub>2</sub>	25	1 N	1.00	[45]
Tri-chloro-vinyl silane	25	0.3vol%	1.00	[45]
NaOH	25	1 mol/L	1.00	[46]
HCOOH	20	99vol%	0.70	[79]
CH <sub>3</sub> COOH	40	100vol%	0.70	[79]
NaOH	25	2% w/v	1.00	[80]
NaOH	25	5% w/v	2.00	[53]
NaOH	25	5% w/v	–	[81]
NaOH	Room	1% w/v	1.00	[50]
NaOH	25	8% w/v	24.00	[12]
NaOH	25	5% w/v	48.00	[25]
Benzoyl chloride, NaOH	110	15 mL, 40% w/v	48.00	[25]
NaOH	Room	5% w/v	4.00	[67]
Benzoyl chloride	Room	–	0.25	[67]
KMnO <sub>4</sub>	Room	0.05% w/v	0.30	[67]
NaOH	25	1–7% w/v	2,4,6	[63]
NaOH	25	2% w/v	0.50	[61]
Acetone	37	–	6.00	[73]
Acetone, HCOOH	37	1 wt%	6.00	[73]
Acetone, CH <sub>3</sub> COOH	37	1 wt%	6.00	[73]
CH <sub>3</sub> CN:(CH <sub>3</sub> CO) <sub>2</sub> CO	37	3 wt%	6.00	[73]
NaOH, H <sub>2</sub> O <sub>2</sub>	37	1 M	6.00	[73]
NaOH, H <sub>2</sub> O <sub>2</sub> , CH <sub>3</sub> CN:(CH <sub>3</sub> CO) <sub>2</sub> CO	37	1 M, 3 wt%	6.00	[73]
CaCl <sub>2</sub> , Na <sub>2</sub> HPO <sub>4</sub>	Room	2 mol/L	12.00	[82]
CaCl <sub>2</sub> , Na <sub>2</sub> CO <sub>3</sub>	Room	2 mol/L	12.00	[82]
CaCl <sub>2</sub>	Room	3 mol/L	12.00	[82]
NaOH	80	5% w/v	1.00	[30, 83–86]
NaClO	80	2% w/v	2.00	[30, 83–86]

Table 3 continued

Chemical Reagent	Temp (°C)	Concentration	Time (hrs)	Refs
H <sub>2</sub> SO <sub>4</sub>	45	60vol%	2.00	[30, 83–86]
NaOH	Room	5% w/v	0.5–2.5	[87]
NaOH	25	2% w/v	1.50	[88]
NaOH	25	1 N	2.00	[31]
NaOH	25	0.1 N	1.00	[74]
NaOH	25	10% w/v	–	[89]
NaOH	50	5% w/v	2.00	[14]
ClO <sub>2</sub> , Furfuryl alcohol	100	1.88 mmol, 11.35 g	2.00	[14]
NaOH	25	5% w/v	2.00	[65]
NaOH	25	2% w/v	1.00	[7]
NaOH	80	4% w/v	2.00	[41]
NaClO <sub>2</sub>	80	1.7 wt%	2.00	[41]
NaOH	Room	2% w/v	2.00	[47]
PDMA	55	0.25 g	24	[47]
NaOH	25	2% w/w	0.17–1.50	[48]
Methacrylamide	25	1–3% w/v	1, 2, 3	[48]
NaOH	80	5% w/v	1.00	[90]
NaClO	80	2% w/v	2.00	[90]
NaOH	Room	2–10% w/v	24.00	[58]

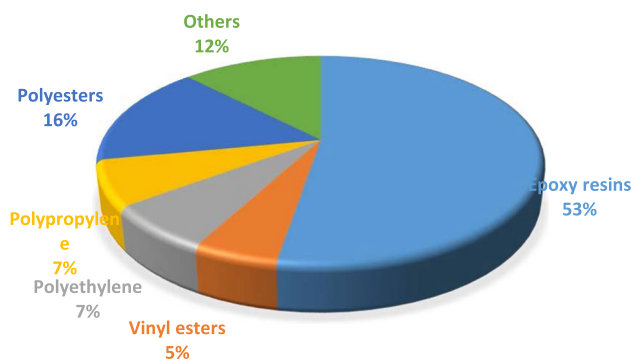


Figure 2 Polymer used for preparing Luffa fibre reinforced composites.

[66, 97], 100 °C [14] and as high as 190 °C [55]. Koruk and Genc [20] used a hot hydraulic press. On the other hand, cold compression moulding was commonly done at room temperature [72, 92, 96]. About 62% of the research studies used this method. Open moulding also known as laminate method or casting process is a general technique used for making thermoset and other composites products. The resin and reinforcement material are placed on an open mould surface and the composite is then allowed to cure at room temperature. Although this process is

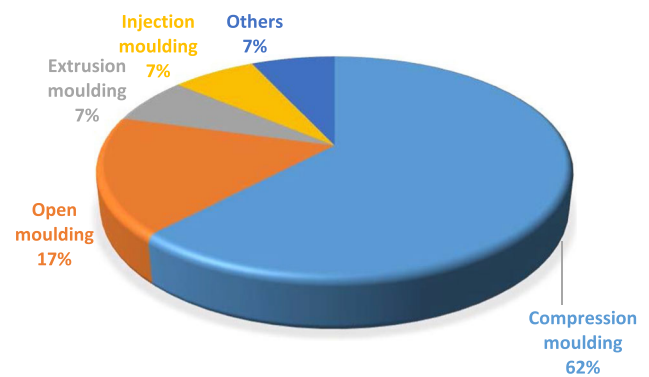


Figure 3 Processes used for preparing Luffa fibre reinforced composites.

very advantageous for large scale production and for complex materials with little equipment investment, it is labour intensive, generates high waste, takes long time to cure and there can be non-uniformities in the products obtained [18]. About 17% of research studies used this method for preparation of the composites [26, 27, 98]. 7% of research studies used extrusion moulding [93, 94] and 7% used injection moulding [50, 89]. Others methods included micro compound-ing moulding [90], resin transfer moulding [99], closed moulding [82] and multimode microwave

technique [1]. The preparation techniques for the *Luffa* composites are summarised in Table 4.

### Mechanical properties of *Luffa* fibre-reinforced composites

This section focuses mainly on the mechanical properties of different *Luffa* fibre-reinforced composites. Mechanical properties are the most studied properties of reinforced polymer composites. For *Luffa* composites, mechanical properties in the domain of impact, tensile and flexural properties have been investigated. Tensile samples were investigated based on the ASTM D638 standard and were tested using a universal testing machine [51, 52, 57, 74, 85, 86]. The impact strength tests were conducted using the Charpy set up parameters according to the ASTM D6110-10 standard. Hardness characteristic of a material is a measure of the material resistance to confined deformation. Rockwell hardness tester was used to analyse the hardness number and to evaluate the hardness of each of the composites using ASTM E92 standard [51]. The water absorption capacity tests of *Luffa* fibre-reinforced composite were carried out following ASTM D-570 standard [52]. Furthermore, samples were also prepared according to ISO 14,125 standard to examine the flexural properties, ultimate tensile strength, Young's modulus and elongation-at-break of the composites, using a Universal Testing Machine. Table 5 shows that the average tensile strength of the *Luffa* fibre-reinforced epoxy composites values vary between 3 and 80 MPa. Highest flexural strength values were observed when *Luffa* fibres were used for reinforcement of epoxy composites. Impact strength of the *Luffa* fibre composite indicates the highest energy required to disrupt the material and it ranges between 22.60 and 68.42 kJ/m<sup>2</sup> and 1.3 to 9 J, respectively. Stiffness of the composite materials (Young's modulus) was higher in polyester materials compared to other composite materials. Flexural modulus which measures the resistance to bending when a perpendicular force is applied to the side of the composite reached the highest value of 4858 MPa [80]. On average, the water absorption of the *Luffa* fibre composite materials varies between 1 and 14%. Moreover, it was reported that tensile and flexural properties decreased as the fibre/polymer ratio increased.

### Thermal and crystalline properties of *Luffa* fibre-reinforced composites

A simple and accurate method for investigating the decomposition pattern and thermal stability of composites is thermogravimetric analysis (TGA) [95]. Chemical constituents of fibres (cellulose, hemicellulose, and lignin) are the determinants of thermal stability of natural fibre reinforced composites [67]. A summary of the thermal properties of *Luffa* reinforced composites is given in Table 6. Ibrahim, Rajkumar [1] used decomposition characteristics to compare conventionally cured and microwave cured samples and their extent of cure. The samples were heated in TA Instruments TGA to 600 °C at a heating rate of 10 °C/min in N<sub>2</sub> atmosphere. It was observed that at 40% filler concentration, the initial and final degradation temperature of *Luffa*-epoxy composites cured at room temperature were 363 and 600 °C, while that of the microwave cured were 388 °C and 600 °C, respectively. The result of TGA and DTGA obtained by Kaewtatip and Thongmee [95] showed that *Luffa* fibres improved the thermal stability of starch reinforced composites. The thermogravimetric curves of composite with 10 wt% and 20 wt% were similar. Weight loss was noticed to have occurred within the temperature range of 100–200 °C which could be due to evaporation of water and glycerol. The maximum temperature of weight loss was 336 °C and 343 °C for the composites with 10 wt% and 20 wt% of *Luffa* fibres, respectively, which could be due to decomposition of starch and cellulose.

Mohanta and Acharya [67] observed that the thermal stability of chemically treated fibres was higher than that of the untreated ones. At about 313 °C, the maximum decomposition occurred for untreated fibres. At 417 °C, the thermal decomposition for both alkali-treated and the untreated fibres was completed. The weight loss of untreated fibres was 9.77 and 97.38% at 100 and 500 °C, respectively. A crystallinity of 0.39 was observed. Siqueira, et al. [32] performed differential scanning calorimetry (DSC) experiment on poly caprolactone-based nanocomposite. In order to minimize oxidative degradation, 6 mg and 10 mg samples were placed in hermetically closed DSC dishes under nitrogen atmosphere. The glass transition temperature (T<sub>g</sub>) was found to be -58.8 °C and 0.56 was the degree of crystallinity determined from DSC thermograms with the heating and cooling cycles carried out from -100 °C to



**Table 4** Preparation techniques used for *Luffa* composites

Polymer	Mixing and lay-up	Curing	Refs
Epoxy resin	Mechanical stirring and hand lay-up	Compression moulding (room temperature, 5 MPa, 24 h)	[71]
Epoxy resin	Manual mixing and hand lay-up	Compression moulding (72 h)	[100]
Epoxy resin	Manual mixing and hand lay-up	Open moulding	[62]
Epoxy resin	Manual mixing and hand lay-up	Compression moulding (room temperature, 72 h)	[13]
Vinylester	Mechanical stirring at 100 rpm	Open moulding (room temperature, 2 h)	[33]
Epoxy resin	Manual stirring and hand lay-up	Compression moulding (room temperature, 24 h)	[69]
Epoxy resin	Manual stirring and hand lay-up	Compression moulding (72 h)	[12]
Polypropylene	Torque rheometer (190 °C, 60 rpm, 10 min)	Compression moulding (190 °C, 100 bar, 10 min)	[55]
Epoxy resin	Mixed using an overhead stirrer	Compression moulding (20 kg/cm <sup>2</sup> , 80 °C, 1 h)	[66]
Polyester	Mechanical stirring and hand lay-up	Compression moulding (room temperature, 24 h)	[92]
Polyethylene	Mechanically mixed	Twin-screw extrusion (300 rpm)	[94]
Polyethylene	Mechanically mixed	Twin-screw extrusion (30 rpm, 24 h, 60 °C)	[2]
Epoxy resin	Mechanically mixed	Compression moulding (5 bars, 80 °C, 5 h)	[54]
Epoxy resin	Mechanically mixed	Compression moulding (500 kPa, 80 °C, 5 h)	[101]
Epoxy resin	Mechanically mixed	Multimode microwave (1200 W)	[1]
Epoxy resin	Manual mixing and hand lay-up	Open moulding (air-cure 24 h)	[27]
Polyethylene	Rheomix mixer 600 instruments (32 rpm, 160 °C, 3 min)	Compression moulding (5 tons, 175 °C, 3 min)	[102]
Epoxy resin	–	Compression moulding (7 MPa, 24 h)	[72]
Starch	Mechanically mixed	Compression moulding (200 kg/cm <sup>2</sup> , 150 °C, 10 min)	[95]
Unsaturated polyester	Manual mixing and hand lay-up	Open moulding	[26]
Unsaturated Polyester	Hand lay-up	Compression moulding (room temperature, 15 MPa, 4 h)	[45]
Unsaturated polyester	Hand lay-up	Compression moulding (30 °C, 5 MPa, 12 h)	[46]
Unsaturated polyester	Mechanically mixed	Compression moulding (17 MPa, 24 h)	[8]
Unsaturated polyester	–	Compression moulding (room temperature, 5 MPa, 24 h)	[21]
Epoxy resin	–	Compressed with hot Hydraulic press	[20]
Epoxy resin	Hand lay-up	Compression moulding (24 h)	[103]
Epoxy resin	Manual mixing and hand lay-up	Open moulding (28 °C, 24 h)	[19]
Epoxy resin	Hand lay-up	Compression moulding (24 h)	[80]
Epoxy resin	Manual mixing and hand lay-up	Open moulding (room temperature, 24 h)	[53]
Epoxy resin	Manual mixing and hand lay-up	Compression moulding (24 h)	[81]
Poly (butylene succinate -co-lactate)	Intermeshing twin -screw extruder (360 rpm, 90–120 °C)	Injection moulding	[50]
Epoxy resin	Manual mixing and hand lay-up	Compression moulding (72 h)	[63, 67, 104, 105]
Polyurethane	Hand lay-up	Compression moulding (60 °C, 1.9 MPa, 6 h)	[25]
Epoxy resin	Hand lay-up	Compression moulding	[104]

Table 4 continued

Polymer	Mixing and lay-up	Curing	Refs
Unsaturated polyester	Mixed with stirrer	Compression moulding (3 h)	[60]
Epoxy resin	Mixed with roller and hand lay-up	Compression moulding (24 h)	[52, 61]
Epoxy resin	Hand lay-up	Compression moulding	[73]
Resorcinol–formaldehyde	Manual mixing	Closed moulding (60 °C, 4 h)	[82, 84–86]
Poly lactic acid	Mechanically mixed with micro-compounding moulding equipment (100 rpm)	Injection moulding	[30, 83]
Unsaturated polyester	Mechanically stirred and hand lay-up	Compression moulding (room temperature, 24 h)	[96]
Epoxy resin	Mechanically mixed and hand lay-up	Compression moulding (room temperature, 5 MPa)	[88]
Epoxy resin	Manually mixed and hand lay-up	Compression moulding (24 h)	[56]
Epoxy resin	Manually mixed and hand lay-up	Compression moulding (24 h)	[31]
Epoxy resin	Manually mixed and hand lay-up	Open moulding	[74]
Polypropylene	Mechanically mixed	Injection moulding	[89]
Epoxy resin	Hand lay-up	Compression moulding (100 °C, 5 MPa, 1 h)	[14]
Epoxy resin	Hand lay-up	Resin transfer moulding (600 kg/cm <sup>2</sup> , 12 h)	[65]
Unsaturated polyester	Hand lay-up	Compression moulding (room temperature, 110 bar, 90 min)	[7]
Vinyl ester	Mechanically stirred (100 rpm)	Compression moulding	[47]
Polycaprolactone	Magnetically stirred	Open moulding (room temperature)	[32]
Epoxy resin	Hand lay-up	Open moulding	[98]
Unsaturated polyester	Hand lay-up	Open moulding	[98]
Epoxy resin	Mechanically mixed	Compression moulding (80 °C, 5 bars, 5 h)	[97]
Polyethylene	Mechanically mixed	Extrusion moulding (15 rpm) and injection moulding (1400 bar)	[93]
Unsaturated polyester	Mechanically mixed	Compression moulding (70 °C, 3.6 MPa, 2 h)	[59]
Polypropylene	Mechanically mixed	Injection moulding	[3]
Poly lactic acid	Mechanically mixed	Micro-compounding moulding equipment (170 °C, 100 rpm, 10 min)	[90]
Polypropylene	Mechanically mixed	Twin-screw extrusion moulding	[57]

100 °C and from 100 °C to –100 °C, respectively, at the rate of 10 °C/ min. It was noticed that addition of cellulose nanocrystals slightly increased T<sub>g</sub> value however upon varying the filler content, no significant modification was observed, which could confirm that the *Luffa c.* nanocrystals restricted the rotational motions of the poly caprolactone polymer chain by establishing hydrogen bonding forces.

## Other properties and applications

Several other properties and applications have been explored for *Luffa* fibre reinforced composites. Genc and Körük [54] studied the sound absorption coefficient of the *Luffa* composite sample, which was measured as a function of frequency using two-microphone impedance tube. They observed that sound absorption coefficient and sound transmission loss of the *Luffa* composite generally increased with increase

**Table 5** Mechanical properties of *Luffa* fibre reinforced composites

Polymer (ternary component)	Fibre-resin ratio (wt% or $V_f^*$ )	Impact strength (kJ/m <sup>2</sup> )	Tensile strength (MPa)	Flexural strength (MPa)	Young's modulus (MPa)	Flexural modulus (MPa)	Water Absorption (%)	Elongation at break (%)	Hardness number (shore $D^*$ )	Refs
Epoxy	–	1.689	24.00	59.00	–	–	5.00	–	–	[74]
Epoxy (Boron Carbide)	10:90	40.10	13.56	–	73.29	–	–	–	91.00	[51]
Polyurethane	–	–	3.00	–	22.00	–	14.00	75.00	–	[25]
Epoxy	40:60	1.289	20.00	140.0	–	–	–	–	–	[52]
Epoxy	25:75	–	17.97	106.7	1331	4858	–	–	–	[80]
Poly lactic acid	2:98	28.10	36.45	48.64	2828	3624	–	–	–	[30]
Epoxy	40:60	1.289	20.00	140.0	–	–	–	–	–	[31]
Epoxy	30:70	1.10	22.64	–	58.66	–	11.21	1.74	13.30	[14]
Resorcinol–formaldehyde	50:50	–	14.88	80.67	680.0	3338	–	–	–	[82]
Polypropylene	15:85	–	19.50	–	750.0	–	2.80	17.00	–	[55]
Epoxy	40:60	1.778	18.20	105.0	–	–	–	–	–	[1]
Polyester	30:70	0.996	–	–	–	–	–	–	–	[106]
Cellulose	–	–	–	68.10	2410	–	–	4.50	–	[41]
Epoxy	–	68.00	57.00	635.0	–	–	–	–	–	[53]
Epoxy	15:85	–	13.56	41.36	72.29	72.25	–	–	83.00*	[56]
Epoxy	13:87	–	16.76	24.83	–	–	–	–	–	[105]
Polypropylene	55:45	31.29	7.089	19.40	1697	2.742	–	8.85	–	[57]
LDPE	20:80	5.644	7.650	17.08	21.08	705.9	–	–	85.33	[58]
Polyester	42.6: 57.4*	0.889	19.40	–	5200	–	–	0.48	–	[59]
Starch	10:90	–	1.240	–	–	–	32.00	17.00	–	[95]
Epoxy	67:33	–	80.00	90.00	–	–	10.36	–	100.2	[27]
Epoxy	20:80	–	24.00	–	–	–	–	–	–	[72]
Polyester	50:50	–	30.03	31.59	–	–	–	–	74.00	[8]
Vinyl ester	30:70	1.156	50.25	29.41	–	–	–	5.50	–	[60]
HDPE	40:60	34.70	20.80	37.70	2082	–	–	–	–	[2]
Polyester	41:59	8.00	31.50	–	–	–	2.25	–	13.30	[92]
Epoxy	50:50	1.156	20.00	70.00	–	–	5.50	–	–	[61]
Polyester	15:85	–	21.20	–	–	–	4.30	–	–	[33]
Epoxy	–	68.42	56.66	58.96	–	–	–	–	–	[19]
Epoxy	10:90	–	14.35	111.3	–	–	5.00	–	–	[62]
Epoxy	19:81	–	–	25.00	–	–	–	–	–	[63]
Polypropylene	20:80	5.333	24.00	10.00	–	–	1.00	–	55.00	[89]
Geopolymer	10:90	–	–	14.20	63.00	883.0	–	–	–	[64]
LDPE	25:75	–	13.10	–	165.9	–	–	11.30	–	[102]
Resorcinol–formaldehyde	20:80	–	29.44	–	1662	4479	–	–	–	[84]
Polyester	–	–	49.70	81.10	2860	2500	–	2.65	–	[7]
Poly (butylene succinate-co-lactate)	30:70	22.60	–	–	354.0	818.0	5.00	39.00	–	[50]
Polyester	50:50	29.32	46.47	57.36	3576	2270	–	5.00	79.00	[45]
Epoxy	25:75	–	4.52	21.57	–	–	–	–	–	[103]
Epoxy	40:60	–	27.50	71.50	800.0	1700	–	–	–	[65]
Polyester	10:90	7.111	37.33	72.00	–	–	2.17	–	12.90	[96]
Epoxy (Polyester)	10:90	1.818	140.7	–	–	–	–	–	77.30	[98]
Epoxy	8:92	2.933	18.30	220.0	14.80	–	4.00	–	–	[66]

**Table 5** continued

Polymer (ternary component)	Fibre-resin ratio (wt% or $V_f^*$ )	Impact strength (kJ/m <sup>2</sup> )	Tensile strength (MPa)	Flexural strength (MPa)	Young's modulus (MPa)	Flexural modulus (MPa)	Water Absorption (%)	Elongation at break (%)	Hardness number (shore $D^*$ )	Refs
Epoxy	13:87	6.667	27.00	55.00	1000	3900	–	–	–	[67]
Polyester	–	–	11.00	–	1100	–	–	3.00	–	[68]
Epoxy	–	–	29.90	72.17	–	–	–	11.00	–	[69]
Epoxy	50:50	27.50	22.50	115.0	–	–	13.00	–	–	[71]

\*Values that were given in terms of volume fraction,  $V_f$

**Table 6** Thermal properties of *Luffa* reinforced composites

Polymer	Amount of filler (wt% or vol%*)	Glass transition temp (°C)	Initial degradation temp (°C)	Final degradation temp (°C)	Crystallinity	Refs
Epoxy	40.00	–	363	600	–	[1]
Thermoplastic starch	10.00	–	100–200	336	–	[95]
Thermoplastic starch	20.00	–	100–200	343	–	[95]
Epoxy	15.00	–	100	417	0.39	[67]
Polyester	50.00	95.23	200	680	–	[45]
Poly (butylenes succinate-co-lactate)	10.00	–	250	385	–	[50]
Polyurethane	10.00	–	250	500	–	[25]
Epoxy	30.00	–	258	700	–	[14]
Polyester	28.00*	–	270	600	–	[7]
Vinyl ester	15.00	–	265	600	–	[47]
Polycaprolactone	12.00	58.80	–	–	0.56	[32]
Polyester	35.20*	–	250	580	–	[59]

\*Values that were given in terms of volume percentage, vol%

of frequency. It was also noted that sound damping is the dominating factor of the vibroacoustic behaviour of *Luffa* composite and structures with higher loss factor could be obtained by optimizing the *Luffa*/epoxy ratio. In their work, Thilagavathi et al. [107] used a desktop computer to determine the sound absorption coefficient from the measured transfer function data. It was discovered that *luffa* fibrous mats did not exhibit good noise reduction coefficient (NRC) if they were used alone, even though the fibrous mats had serrated surface and microporous structure. By increasing the thickness of the mats, the noise reduction coefficient of *Luffa* mats was improved. Jayamani et al. [72] discovered that changing the fibre concentration caused changes in the composite sound absorption coefficient. Dielectric loss factor, electrical conductivity and dielectric constant of pure polymer matrix, and treated and

untreated *Luffa* fibre composite have been studied by Parida et al. [85]. A decrease in dielectric constant and loss factor of all samples was obtained; however, ac conductivity of all the samples increased with the frequency increase.

## Knowledge gap and future perspectives

Based on this review, several areas have been observed to have some gap in knowledge. This section draws the attention of the research community to these interesting problems that could form the foundation for future studies. The genus *Luffa* comprises from 5 to 7 species, but only *Luffa c.* and *Luffa acutangula* are widely used. Generally, much research focus has been on the *L. cylindrica* and very few studies have focused on *L. acutangula*. Though *Luffa* is

usually extracted by drying, the effect of drying parameters, such as temperature and time on the physical and compositional properties of the fibres is unknown. This is an interesting area that can be investigated to determine optimal periods for drying the pods to harness the fibres in their best physical state. Besides the popular epoxies, the only other reported resins for *Luffa* composites are polyesters [46, 59, 92], polypropylene [3, 89], polyethylene [93, 94], vinyl esters [47, 60], polyurethane [25], resorcinol formaldehyde resin [82], polylactic acid [90], poly caprolactone [32], poly butylene succinate-co-lactate [50]. In the future, other novel polymers will likely be applied for *Luffa*-based composites and multi-polymer ternary systems may be employed.

## Conclusions

The average chemical composition of *Luffa* fibres ranges from 57–74% cellulose, 14–30% hemicellulose, 1–22% lignin and 0–12.8% of the other components. The physical properties of the *Luffa* fibres such as tensile strength, tensile modulus, elongation at break, the fibre diameter as well as the density are generally acceptable for their use as potential reinforcements for polymer composites. *Luffa* is usually not extracted by the decortication and water retting but by drying. Furthermore, the most common modification technique is alkali mercerisation. In composite preparation, about 53% of the research studies made use of epoxy resins making them the most popular resins for *Luffa* fibre reinforced composites. The composites are fabricated usually by manual mixing and hand layup. The most common curing technique for *Luffa* fibre reinforced composites is compression moulding. The average tensile strength values of the *Luffa* composites vary between 13 to 36 MPa for most of the composites and highest flexural strength values were observed when *Luffa* fibres were used for reinforcement of epoxy composites. Further interesting areas, suggested for future work, include the investigation of the effect of drying, more trials with *L. acutangula* and the utilisation of multi-resin ternary systems. *Luffa* is a promising material for composite development and based on its favourable properties, it is likely to continue playing an important role in the area of natural fibre reinforced composites for years to come.

## Compliance with ethical standards

**Conflict of interest:** The authors declare that there are no conflicts of interest.

**Human and animal rights** This article does not contain any studies involving human or animal subjects.

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