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Review Article

Preparation, Characteristics, and Application of Biopolymer Materials Reinforced with Lignocellulosic Fibres

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Various environmental concerns motivate scientists and researchers to look out for unique new materials in science and technology. In order to address the demand for polymeric materials with partial biodegradability, the usage of lignocellulosic fibre in the polymer matrix has risen. Lignocellulosic fibres are a cheap, easily renewable resource that is readily available in all regions. Cellulosic plant fibres also have a plethora of possibilities for use in polymer reinforcement because of their properties. Many researchers put their effort into developing a natural polymer with better mechanical properties and thermal stability using nanotechnology and the use of natural polymers to make its composites with lignocellulosic fibres. This study provides a review of the biodegradable composite market, processing methods, matrix-reinforcement phases, morphology, and characteristic improvements. In addition, it provides a concise summary of the findings of significant research on natural fibre polymer composites (NFRCs) that have been published. Indeed, a noticeably brief discussion is provided on the significant issues faced during composite extraction as well as the challenges encountered during the machining. Recent developments in the study of lignocellulosic fibre composites or NFRCs have demonstrated their enormous potential as structural elements in vehicles, aerospace structures, buildings, ballistics, soundproofing, and other structures.

1. Introduction

In the recent era, researchers are showing attention towards the growth of strong ecologically and technologically balanced materials, such as natural fibre polymer composites (NFRCs). The existence of organic materials, such as cellulosic fibres reinforced in a connective tissue, inspired the researchers for development of NFRCs with unique characteristics. These novel fibres act as a substitute for synthetic fibre in many industrial applications, such as aerospace, sports, automobiles, and construction. Synthetic fibres are not biodegradable, are hazardous to health and the environment, consume more energy, and have a high production cost. Natural fibres are gaining popularity over synthetic fibres in polymer matrix due to their superior properties, such as light weight, low cost, processing flexibility, recyclable, biodegradable, renewable, eco-friendly, less health hazard, and superior mechanical properties [1]. Over time, global markets have seen a surge in demand for NFRCs; according to the compound annual growth rate, NFRC market demand in all manufacturing sectors is expected to rise by 11% in the Asia-Pacific region between 2021 and 2026. Currently, governments and private statutory research bodies around the world are trying to raise awareness and enforce laws on raw material waste, energy, and pollution, which causes severe depletion of natural resources and landfill abilities by petroleum-based and artificial materials, which has stimulated a rapid growth of more novel uses of natural fibres as reinforcements in polymers to replace traditional composite, metallic, and wood structures [2]. Although natural fibre has many benefits, it also has some drawbacks, such as high moisture absorption, which can be avoided with chemical treatments. Many factors, such as fibre length, aspect ratio, and fibre–matrix adhesion, influence the morphology and crystallinity of the structure, which tailors the mechanical properties of natural fibres [3]. This current study provides a comprehensive review of recent research and developments on NFRCs, including physical, chemical, mechanical, and thermal properties, industrial applications, manufacturing methods, and machinability. In addition, a detailed assessment of critical issues concerning the processing of NFRCs was explored.

2. Natural Fibres and Its Types

Composite material is generally a material structure consisting of two macroscopically recognizable materials that contribute towards the achievement of superior performance. These two material systems are commonly known as continuous and discontinuous phases. The continuous phase is termed matrix phase, whereas the discontinuous phase is the reinforcement phase. Among these, the reinforcement phase is usually tougher and more rigid compared with the matrix phase. The reinforcement phase is available in two main forms: fibre (including whiskers) and particulate matter (having different shapes and sizes). Consequently, these formed the two main groups of composites namely fibre reinforced composites (FRCs) and particle reinforced composites. The matrix phase is generally one among the following: polymers, ceramics, and metals (along with their alloys). Composites using these matrices are known as polymer matrix composites, ceramic matrix composites, and metal matrix composites. Another form of composite includes laminar composites (generally called laminates or laminated composites). Laminates are typically composed of two or more layers, each of which belongs to a similar or different substance. Laminated composite structures tend to be very solid as well as rigid, which are commonly recommended to be used in lightweight structural applications.

Natural fibre reinforced composites (NFRCs) are said to be bio-composite since they contain at least one constituent (e.g., matrix or reinforcement) derived from readily available renewable resources [4]. Nowadays, various industries like building engineering, military, marine, and aerospace industries have employed them to build structural components. The possibility of weight reduction and superior product efficiency also sparked interest among numerous engineering and structural sectors in manufacturing these materials [5]. In addition to that, there are some technical, economic, and ecological benefits in employing natural fibres as reinforcing material over manmade synthetic fibres (carbon and glass) as illustrated in Figure 1. From these reviews, it is concluded that NFRCs seem to be highly suitable for the fabrication of structural materials.

Even though natural fibres have ecological advantages and are employed in soundproofing applications of some automotive, household, and construction applications, they do not have sufficient mechanical strength. The restriction in the use of these fibres in structural-based noise controlling applications is also due to their low resistance to moisture absorption compared with synthetic or man-made fibres. Hybrid composite materials are now becoming more desirable structural materials due to their improved mechanical properties. The term “hybrid” refers to a material structure comprising a complex mixture of matrices coupled with more than one reinforcement and filler material. The key benefit of a hybrid composite material system, which is made up of more than one fibre, is that even if one fibre lacks certain properties, it will be compensated by the other fibre. Hybridization also helps to improve the cost balance as well as efficiency of the composite due to proper material design considerations [6].

Natural fibres, as shown in Figure 2, can be extracted from available biological resources, such as animals, minerals, plants, and vegetables, and are replacing synthetic fibres in a variety of engineering products [7]. Based on the availability, some of the animal natural fibres are alpaca fibre, bird feathers, wool, silk, sheep and rabbits’ wool, goat hair, Angora goat mohair, hog bristle, ox hair, Siberian weasel, camelhair, and horsehair [8–11].

Similarly, mineral fibres are classified as asbestos, ceramic, and metal fibres. Asbestos is a renewable mineral fibre, whereas the latter two mineral fibres are formed by combining various natural materials. Asbestos fibres include amphiboles, anthophyllite, chrysotile, and serpentine. Ceramic fibres include materials such as aluminum oxide, boron carbide, and silicon carbide, whereas aluminum fibre is one type of metal fibre. Plant fibres consist of the cellulose, hemicellulose, and lignin constituents [12–15]. Plant fibres are classified according to their origin, such as bast, leaf, seed, and flower. Bast, often referred to as stem fibres, consists of bundles of fibrous material found within the inner bark of plant stems [16–19], whereas the leaf fibres of monocotyledonous plants run longitudinally across their leaves [20–26]. Some of the examples of plant fibres are cotton, hemp, jute, flax, ramie, sisal, banana, flax, hemp, jute, kenaf, ramie, rattan, vine, soybean, and bagasse fibre.

3. Properties of Natural Fibres

Physical, chemical, mechanical, and thermal properties are briefly outlined in the following sections.

3.1. Physical Characteristics. The fibre’s physical qualities are its diameter, length, and density. This varies from fibre to fibre, as shown in Table 1.

3.2. Chemical Compositions. The native fibrils were composed of cellulose suspended with a formless lignin and polyose matrix, and it can be predominant sources design of spirally situated compound composites [13]. The various chemical compositions, such as lignin, cellulose, pectin, ash, hemicellulose, wax, and moisture content, are listed in

		Natural Fibers	Carbon Fibers	Glass Fibers
Technical	Tensile Failure Strain	Low	High	Low
	Specific Tensile Strength	Moderate	Moderate	High
	Abrasive Nature	No	Yes	Yes
	Density	Low	High	Low
Ecological	Health Risk if Inhaled	No	Yes	Yes
	Renewable Source	Yes	No	No
	Biodegradable	Yes	No	No
	Recylable	Yes	Partially	Partially
Economy	Cost of raw fiber	Low	Low	High
	Annual global manufacturing	Low	High	Moderate

Figure 1: Ecological, technical, and economical differences between natural and man-made synthetic fibres.

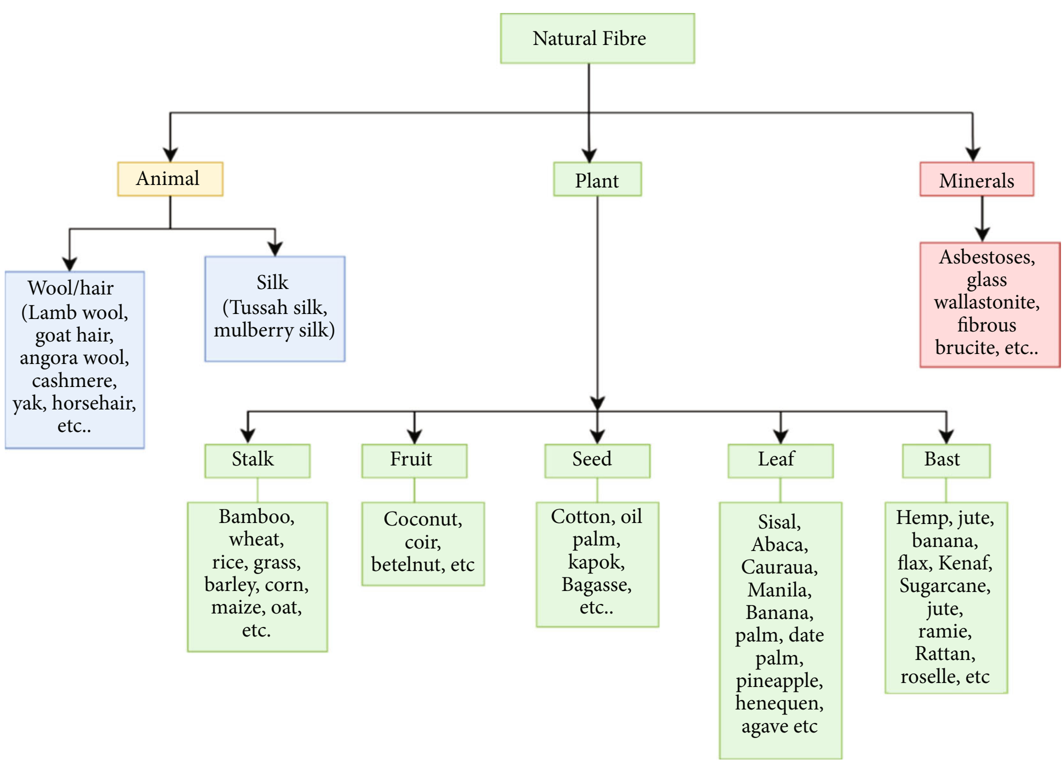

Figure 2: Types of natural fibres.

Table 2. The proportion of chemical components in fibre is influenced by plant tissue location and its growth rate [19]. Even though it has all the needed constituents for binding with polymer matrix, it also has non-cellulosic substituents (that degrades its bonding nature), such as hemicellulose, lignin, pectin, and waxes in it. To eliminate that, some pre-treatment technique was equipped with additional controlled factors [31].

Table 1: Physical properties of natural fibres.

Name of the fibre	Diameter (μm)	Length (mm)	Density (kg/cm^3)	References
Abaca	18.2	4.9	1500	[27]
Alfa	5–10	2–5	890	[27, 28]
Bagasse	20	1.7	900	[27]
Banana	131.76	30	1325	[27, 29]
Bamboo	25	2	1500	[27]
Coir	17.5	1.25	1250	[27]
Cotton	14.5	42	1550	[27]
Curaua	170	—	1400	[27]
Flax	20	31.75	1450	[27]
Hemp	19.9	11.2	1200	[27]
Isora	10–20	—	1200	[27, 30]
Jute	18.4	2.55	1400	[27]
Kapok	25	20	384	[27]
Kenaf	19.8	2.35	1300	[27]
Pineapple	50	—	1540	[27]
Ramie	31.55	160	1550	[27]
Sisal	21	2.5	1400	[27]

Some of the experimental works based on the removal of non-cellulosic contents are presented in this context. Ashok et al. [32] found that multi-layered areca leaf sheath composites treated with 10% NaOH followed by rinsing with distilled water and dehydrated in the micro-oven at 60°C exhibited higher tensile and flexural strength than the 5% NaOH-treated composites. Similarly, Jaiswal et al. [33] also reported by his research that the 10% NaOH chemical pre-treatment influences the crystallinity structure that would tailor the mechanical, physical, and thermal behaviors of the composite. In continuation, Paiva et al. [28] stated that the microfibril alfa fibres were also extracted using NaOH, bleached with NaClO, and then dried, resulting in the removal of foreign components and leaving behind cellulose filaments and some lignin to reinforce the composite material. In addition, NaOH above 10% helps in vanishing the presence of non-cellulosic contents and will lead to fibre pullout, which in turn reduces the mechanical strength of the composites. Similarly, Çakir et al. [34] found that 5–10% NaOH treatment on fibres has tendency to eliminate the wax content in higher percentages, thereby increasing the bonding strength. However, from these studies, 5–10% NaOH will have superior effect on the mechanical properties of the composites.

Sever et al. [35] found that chemical pre-treatments such as alkali, microemulsion, and fluorocarbon can be effective in modifying the properties, particularly in enhancing their tensile, flexural, and interlaminar shear strengths of unidirectional-based composite materials. These treatments can improve the interfacial adhesion between fibres and the matrix, resulting in a stronger and more durable composite material. Furthermore, it can be characterized through X-ray photoelectron spectroscopy and contact angle measurements. With respect to this research, Mahbubul Bashar and Khan [36] examined the effect of enzymatic degradation and successive galacturonic acid analyses on the fibre surface. The finding reveals that, this type of surface modification helps to reduce the pectin content that increases the fibrillation effect and decreases porosity and fibre agglomeration [37, 38]. Similarly, Paula et al. [39] concluded that alkali surface treatment removes lignin at higher percentages, which promotes mechanical interlocking and contributes to the improvement of mechanical properties, which is confirmed through scanning electron microscope.

Ahmed et al. [23] conducted his research on a new class of fibres, including *Elettaria cardamomum* (also known as cardamom), *Epipremnum aureum* (also known as golden pothos), maize tassel, *Napier grass*, and *Arundo donax*, in order to determine the chemical constituents of these fibres. The researchers found that the cellulose content (more than 63.12%) of these plants was a significant factor in their ability to contribute to the reinforcement of the matrix phase. Based on the findings, it can be concluded that the fibres of these plants, which are rich in cellulose, have the potential to be used in a variety of applications where strength and durability are important factors. When natural fibres were subjected to a variety of chemical treatments, their cellulose content increased significantly and their surface qualities altered greatly in comparison with untreated fibres. Likewise, Martel et al. [40] conducted a study to investigate the effect of NaOH treatment on curauá fibres. The researchers found that the pretreatment increased the cellulose content of the fibres and also had a positive effect on their interfacial characteristics. The NaOH treatment was found to be more cost-effective and less time-consuming compared with other treatments, while also exhibiting superior thermal and mechanical properties [41, 42].

Sanjay et al. [43] stated that the moisture concentration present in natural fibres affects crystalline alignment, degree of crystallinity, inflammation, and thermal behavior, as shown in Figure 3. It is a well-known fact that treated fibres with the highest cellulose content have greater cellulose-α values. In addition, the fibre treated with acrylic acid has a lower wax content (0.13 wt.%) than the other fibres, which improves the interfacial interaction between unidirectional and the residual fibres. Similarly, in the research of Chirayi et al. [44], observations indicate a significant reduction in ash and wax content, which provides strong fire prevention capacity and prevents delicate chemical groups from reacting, thereby enhancing thermal stability [45].

For comparison considering investigation on date palm by several researches in this context, Ghori et al. [46] stated in his research that the combination of date palm fibres with epoxy, polypropylene (PP), and unsaturated polyester polymers has yielded composite materials with enhanced properties. To address the hygroscopic tendencies of date palm fibres, chemical treatments, such as NaOH and silane, have been employed to improve their surface characteristics. The resulting surface-treated date palm fibres have demonstrated improved mechanical and thermal properties when used as reinforcement in polymer composites, which can be attributed to their enhanced adhesion with the polymer matrix. Likewise, Alotabi et al. [47] investigated the

Table 2: Chemical constituents of various lignocellulose fibres.

Name of the fibre	Cellulose (%)	Hemi-cellulose (%)	Lignin (%)	Pectin (%)	Waxes (%)	References
Abaca	62.5	21	12	0.8	3.0	[27]
Alfa	45.4	38.5	14.9	—	2.0	[27, 28]
Bagasse	37	21	22	10	—	[27]
Banana	62.4	12.5	7.5	4	—	[27, 29]
Bamboo	34.5	20.5	26	—	—	[27]
Coir	46	0.3	45	4	—	[27]
Cotton	89	4	0.75	6	0.6	[27]
Curaua	73.6	5	7.5	4	—	[27]
Flax	70.5	16.5	2.5	0.9	—	[27]
Hemp	81	20	4	0.9	0.8	[27]
Isora	74	—	23	—	—	[27, 30]
Jute	67	16	9	0.2	0.4	[27]
Kapok	13.16	—	—	—	—	[27]
Kenaf	53.5	21	17	2	—	[27]
Pineapple	80.5	17.5	8.3	4	—	[27]
Ramie	72	14	0.8	1.95	—	[27]
Sisal	60	11.5	8	1.2	—	[27]

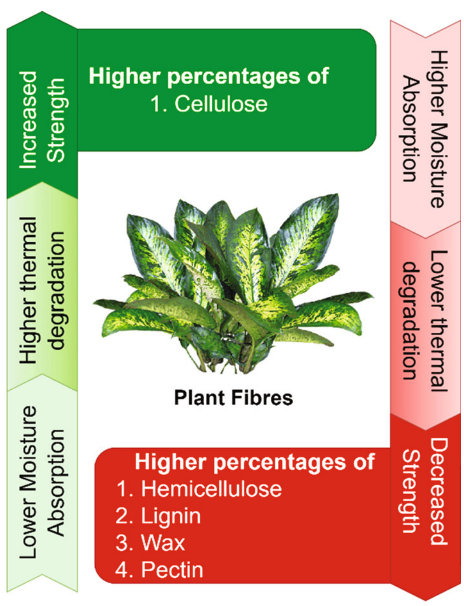

Figure 3: Chemical components of natural fibres.

composition and properties of date palm fibrils when mixed with polymers. The results showed that the fibrils primarily consisted of cellulose and hemicellulose, with a lower percentage of lignin by weight (60–75% and 20%, respectively). The high proportion of cellulose and hemicellulose contributed to a crystallinity degree of 79.4%. Furthermore, it showed better thermal properties for its high weight loss (84.15%), low residual weight (15.44%), and high decomposition temperature (364.2°C) compared with the other fibre samples [48]; the date palm fibrils exhibited superior thermal properties, as demonstrated by their high weight loss (84.15%), low residual weight (15.44%), and high decomposition temperature (364.2°C). Furthermore, the low ash content of date palm biomass, in comparison with wood pellets, sawdust, and bituminous coal [49], enhanced its mechanical and thermal characteristics. In similar manner, the study by Sreekala et al. [50] looked at the effects of pre-treating oil palm fibres on the properties of the resulting composites. The researchers found that when the fibres were pre-treated, they had less moisture and wax concentration than untreated fibres. This reduction in moisture and wax content resulted in better bonding between the fibres and the matrix material in the composites. Additionally, the study found that reducing the ash weight percent of the pre-treated fibres had a positive impact on the mechanical properties of the resulting composites. This suggests that the removal of ash impurities can improve the performance of composite materials made with oil palm fibres [51].

Similarly, certain researchers made an effort to create a composite material by using a novel type of plant fibre that underwent surface modifications. Madival et al. [52] conducted research on *Furcraea foetida*, a plant commonly found in the Caribbean and South America, to determine its potential as a source of fibre for composite materials. The researchers measured the density of the raw fibre and compared it with the density of chemically treated fibres. They found that the raw *F. foetida* had a density of approximately 0.211 g/cm^3. However, after undergoing chemical treatment, the fibres showed an increase in density, ranging from 0.228 to 0.362 g/cm^3. This increase in density can be attributed to the enlargement of the fibre cell walls and the incorporation of grafted molecules. These modifications to the fibre structure resulted in an overall improvement in the mechanical properties of the fibres, making them potentially useful for composite materials [53]. Likewise, Ahmed et al. [54] conducted research on the chemical composition of *Areva javanica* fibre, a type of natural fibre commonly found in Southeast Asia, to better understand its properties and potential uses. The researchers discovered that *A. javanica* fibre contains approximately 72.36 wt.% of cellulose. The high cellulose content of the fibre makes it a strong and durable material. In addition, the researchers found that the fibre contains 10.45 wt.% of lignin, which helps to protect the fibre against biological attack, and the weak interfacial bonding between the fibre and the matrix is produced by wax.

3.3. Mechanical Characteristics. Developing natural fibre composites for structural applications requires careful consideration of their mechanical characteristics, which are crucial for determining the reinforcement of polymer composites. To achieve superior mechanical and thermal properties, it is desirable to have a high cellulose content in the reinforcement. Surface modification of natural fibres can increase the cellulose content while decreasing the hemicellulose and lignin content, resulting in improved mechanical strength. Additionally, modifying the fibre's surface can reduce its hydrophilic properties and increase its hydrophobic properties. Some of the key factors affecting mechanical properties of NFRCs are illustrated in Figure 4. This section summarizes various research studies on novel natural fibre-based NFRCs that have been conducted to enhance the mechanical properties of NFRCs.

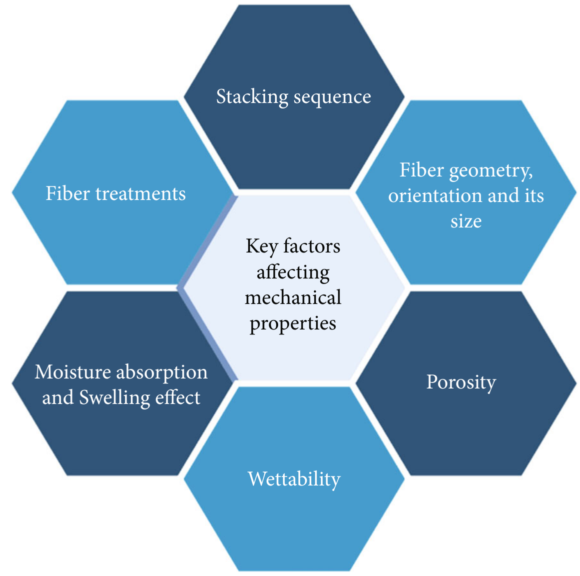

Figure 4: Key factors affecting mechanical properties of NFRCs.

Rathinavelu and Paramathma [55] identified a novel natural plant fibre from *Echinochloa frumentacea* and found it to have good crystallinity, cellulose content, low density, thermal stability, and tensile strength, making it suitable for use in varying temperatures. It reveals that the presence of cellulose content of 60.31% formed a good fibre–matrix adhesion and surface roughness which makes that composite with better tensile strength of 204.32 ± 14.25 MPa. However, for the study by Okafor et al. [56], the tensile strength and tensile modulus of *Dioscorea alata* stem fibres treated with NaOH and CH_3 COOH were found to be 151 MPa and 5.7 GPa, which is greater than *Piliostigma racemose* [57], *Agave americana* L. [58], *Juncus effusus* L. [59], and *Kigelia africana* [60]. This is mainly due to the maintaining gauge length (40 and 60 mm) and chemical treatment temperature (40°C and 60°C). As a result, they reported that the NaOH-treated fibres with dry condition, 40 mm of gauge length, and 60°C treatment temperature exhibited better tensile strength and tensile modulus. Similarly, Rao et al. [61] fabricated banana, bamboo, vakka, and sisal fibre-based composite to test its tensile strength and concluded that the tensile strength of vakka fibre composite is higher than sisal and banana composites, and comparable with bamboo composite at a fibre volume fraction of 0.37. The enhancement is attributed to the strength and stronger bonding of vakka fibre with the polyester matrix compared with sisal and banana. The tensile modulus of all composites increases with fibre volume fraction in the order of banana, sisal, vakka, and bamboo. The tensile modulus of vakka fibre composite is higher than sisal and banana composites, and comparable with bamboo composite at the same fibre volume fraction, due to its lower percentage strain. Again, Rao et al. [3] aimed to examine the tensile characteristics of fibres obtained from elephant grass through retting and chemical (NaOH) extraction techniques. Composites were created by incorporating up to 31% fibre volume, resulting in a tensile strength of 292.3 MPa (for the chemically treated fibre-based composite) and 237.4 MPa (for the retted fibre-based composite). The percentage difference between the composite made of chemically treated fibre and retted fibre is about 18.1%. The lower tensile strength of the retted composite can be primarily attributed to the fibres being catastrophically pulled out from the specimen.

In continuation to mono chemical treatment, Lu et al. [62] explored a new approach to enhance the mechanical properties of bamboo cellulose fibre/epoxy composites by combining silane coupling agent and NaOH treatment. The NaOH solution caused the lignin and amorphous cellulose to dissolve, resulting in the fibres splitting into smaller sizes. This facilitated the permeation of epoxy resin oligomer into the gaps between the fibres, leading to effective interfacial adhesion. As a result, the formation of chemical bonds Si–O–C and Si–O–Si on the cellulose surface improved surface properties and increased the tensile strength and elongation break of the composites. Likewise, Asim et al. [63] evaluated the mechanical properties of alkali, silane, and combined alkali/silane-treated pineapple leaves/kenaf phenol formaldehyde hybrid composites. They observed that hybrid composites treated with silane demonstrated greater tensile strength, but those treated with alkali/silane possessed a high interfacial shear strength. In a similar vein, Dharmalingam et al. [64] explored the mechanical behavior of luffa/epoxy composites treated with NaOH-amino functionalization at varying volume fractions of 2%, 4%, 6%, and 8%. Their findings indicated that the treatment of the fibres with 6 wt.% resulted in a significant increase in both tensile strength and flexural strength, improving by 111.5% and 125%, respectively, compared with untreated fibres. These results suggest that NaOH–amino functionalization can effectively enhance the mechanical properties of luffa/epoxy composites, making them more suitable for various engineering applications. The improved mechanical properties are believed to be due to the formation of chemical bonds between the functionalized fibres and the epoxy resin, resulting in a stronger interfacial adhesion between the two materials.

Dawit et al. [65] extracted the fibres and then treated chemically using NaOH, stearic acid, benzoyl peroxide, and potassium permanganate. The tensile properties of the fibres were found to decrease with 20 wt.% alkali treatment in comparison with 10 wt.% treated fibres. This outcome was attributed to the inconsistent diameter of the fibres, with a 25.9% decrease in diameter observed in 20 wt.% alkali-treated fibres compared with those treated with 10 wt.%. In terms of performance, the fibre treated with 10 wt.% alkali exhibited a tensile strength of 106.81 MPa and a Young's modulus of 6.47 GPa, whereas the 20 wt.% treated fibres scored a tensile strength of 84.76 MPa and Young's modulus of 4.10 Pa. Despite this, the *Acacia tortilis* fibre demonstrated higher tensile performance than common fibres like ramie fibre (0.3 MPa) and coir fibres (44 MPa), but fell short of jute fibre's (393 MPa) tensile strength. Table 3 displays the mechanical properties of different natural fibres from various literatures.

Like tensile strength, an interfacial shear strength of short fibre (aspect ratio less than 20) and ultra-short fibre (aspect ratio less than 10)-based NFRCs were done by Aliotta et al. [66] using Kelly and Tyson's analytical equation. According to their findings, greater embedding lengths exhibited superior stress transfer with fewer variations. Short-fibre composites exhibit different mechanical behaviors compared with long-fibre composites due to the distribution of tensions and load transfer mechanisms. The transfer of load from the matrix to the fibres happens through shear stresses at the fibre surfaces, known as edge or end effects. Although end effects are negligible for long-fibre composites, they cannot be disregarded for short and very short fibre composites.

Yan et al. [67] conducted a study on the fabrication of coir/fibre epoxy composites using alkali-treated coir fibres with different cross-sectional shapes (circular and noncircular fibres). The researchers found that compared with untreated composites, the use of a 5% NaOH solution at 20°C for 30 minutes resulted in a significant increase in the tensile strength, modulus, flexural strength, modulus, fracture energy, and fracture toughness of the composite by 17.8%, 6.9%, 16.7%, 7.4%, 550%, and 424%, respectively. This is due to the fact that the alkali treatment resulted in a much cleaner and rougher surface of the fibres. The improvement in the tensile and flexural properties and reduction in damping ratio are attributed to the enhancement of the interfacial adhesion between the fibre and the epoxy matrix due to the treatment. From this investigation, it is clear that cross-sectional shapes also influence the mechanical properties of the composite. Similarly, fibre weight ratios also have some significant improvement in the mechanical characteristics, and it is demonstrated by Sutradhar et al. [68] in his study. Using a hot-pressing method, composite materials were produced from pp combined with banana/betelnut fibres in different weight ratios (1 : 1, 3 : 1, and 1 : 3). The specimens were divided into two groups based on whether the composite material was treated. The results showed that treating the fibres with 5% NaOH and using a volume proportion of 3 : 1 increased the tensile and flexural strength of the composite. In contrast, untreated composite materials showed fibre structure damage, such as an increase in deep pores and thinning of fibre cell walls, which reduced the tensile properties. It is possible that the presence of foreign substrates caused these damages. The mechanical properties of composites are influenced not only by chemical treatment and fibre weight ratios but also by their stacking sequence. In a study conducted by Vinod et al. [69], the impact of stacking sequence on the mechanical characteristics of hybrid composites made of jute and hemp was investigated. The results showed that the hemp/jute/hemp hybrid composite exhibited the highest tensile strength of 65.44 MPa, with similar trends observed in flexural results. The study also revealed that using hemp fibre as a skin layer and jute fibre as a core layer in the hybridization process can improve the tensile and flexural strength, but may lead to a decrease in interlaminar shear strength. Therefore, the mechanical characteristics of NFRCs are influenced by various factors including chemical treatment, fibre weight ratios, and stacking sequence. These factors play a significant role in determining the tensile strength, flexural strength, and interlaminar shear strength of the composites. Therefore, a thorough understanding of these factors is essential for optimizing the mechanical performance of NFRCs in various applications.

3.4. Thermal Characteristics. In the field of material sciences, thermal analysis is an essential, analytical, and characterization technique. This technique can be used to determine the thermal characteristics of synthetic polymers and biomaterials with distinct phases and morphologies. The conventional approaches for thermal analysis include differential scanning calorimetry, thermogravimetric analysis, thermomechanical analysis, and dynamic mechanic analysis. Before the utilization of natural fibre as reinforcement in polymer composites, it was necessary to examine the thermal behavior of the fibres to determine the thermal stability of the composite to avoid catastrophic failure in high-temperature applications composite. The degradation stages and their influences in NFRC are shown in Figure 5.

This section discusses the exploration of thermal stability in novel natural fibres based on various research conducted in recent times. Arun Ramnath et al. [70] experimented the thermal analysis on *Abutilon indicum* fibres and reported that due to wettability of the raw fibre, its degradation is lower. However, for NaOH-treated *A. indicum* fibres, it shows the better thermal degradation at the range of 335–363°C. In similar manner, Mohan et al. [71] experimented with *Ficus benjamina* aerial root treated with 5% NaOH and determined that the degradation temperature is about 346°C, consequently enhancing its thermal stability. Likewise, Babu et al. [72] investigated the behavior of *Phaseolus vulgaris* fibres (PVF) under varying temperatures. The results indicated that PVF began to degrade between 30°C and 100°C,

Table 3: Mechanical properties of natural fibres.

Name of the fibre	Tensile strength (MPa)	Specific strength	Young's modulus (GPa)	Specific Young's modulus	Failure strain (%)	References
Abaca	12	—	41	—	3.4	[27]
Alfa	350	—	22	—	5.8	[27, 28]
Bagasse	290	—	17	—	—	[27]
Banana	721.5	534.5	29	22	2	[27, 29]
Bamboo	575	383	27	18	—	[27]
Coir	140.5	122	6	5.2	27.5	[27]
Cotton	500	323	8	5.25	7	[27]
Curaua	825	—	9	—	7.5	[27]
Flax	700	482.5	60	41	2.3	[27]
Hemp	530	360	45	30.5	3	[27]
Isora	325	230	37.5	26.5	2.5	[27, 30]
Jute	93.3	300	4	12.9	1.2	[27]
Kapok	743	—	41	—	—	[27]
Kenaf	12	—	41	—	3.4	[27]
Pineapple	1020	708.5	71	49.5	0.8	[27]
Ramie	925	590	23	15	3.7	[27]
Sisal	460	317.5	15.5	—	—	[27]

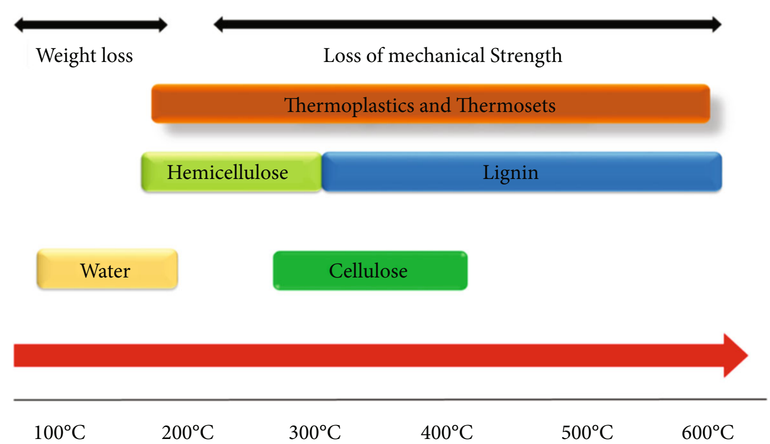

Figure 5: Degradation stages and their influences in NFRCs.

which is attributed to moisture evaporation. The next stage of degradation occurred between 150°C and 250°C and led to a loss of hemicelluloses with various weight losses for both raw and treated fibres. Alkali-treated fibres exhibited greater thermal stability compared with untreated fibres. The lignin content of the fibres began to degrade at temperatures between 230°C and 300°C. Furthermore, alkali treatment increased the cellulose degradation temperature of raw PVFs from 322.1°C to 346.6°C. The findings suggest that alkali treatment removes waxy layers and other impurities on the surface of the fibres, resulting in better thermal stability. Similarly, Divya et al. [73] explored the thermal stability of the novel *Furcraea selloa* and stated that this fibre is more thermally stable (up to 365.8°C) than *A. indicum* [70], *F. benjamina* [71], and PVF [72] due to the presence of secondary metabolites in *F. selloa*; the fibre is more thermally stable.

Similarly, Senthamaraikannan et al. [74] investigated the thermal degradation of *Acacia planifrons* bark fibres (APFs). They found that the first stage of thermal degradation occurred between 50°C and 200°C, during which hemicelluloses and some lignin were degraded. The second stage, which occurred between 200°C and 275°C, involved the degradation of more lignin and cellulose. The final stage, which occurred between 275°C and 400°C, was characterized by the breakdown of cellulose and lignin in APFs. The researchers concluded that the thermal stability of APFs was higher than other novel natural fibres, such as *N. grass*, *Prosopis juliflora*, *Lygeum spartum*, *A. indicum* [70], *F. benjamina* [71], PVF [72], *F. selloa* [73], and *F. foetida*. Furthermore, they found that alkali-treated fibres had significantly higher thermal stability than untreated fibres. The researchers suggested that the higher thermal stability of treated fibres could be attributed to the shift in the main degradation temperature to a higher temperature caused by the loss of hemicellulose and pectin mass [75]. In the same manner, Binoj et al. [76] found that tamarind fruit fibre (TFF) exhibits good thermal stability because it undergoes minimal weight loss due to moisture evaporation at temperatures up to 100°C, whereas other natural fibres like artichoke, okra, hemp, curaua, kenaf, jute, sisal, bagasse, and bamboo experience significant weight loss at temperatures below 238°C. However, beyond this temperature, TFF undergoes cellulose and hemicellulose degradation and polymerization, resulting in a 65% mass reduction up to 360°C, which is similar to *A. planifrons* bark fibres [74]. The Derivative Thermogravimetry (DTG) curve indicates three small peaks at temperatures of 390°C, 420°C, and 440°C, which correspond to cellulose pyrolysis, decomposition, and lignin degradation, respectively.

In view of increasing the thermal stability, another novel fibre *Cissus quadrangularis* root also experimented for the thermal properties [77] with three stages of deterioration. The initial stage of deterioration occurred between 20°C and 230°C, with a 15.5 wt.% weight loss represented moisture evaporation. The second stage occurred in the temperature range between 230°C and 353°C with 55 wt.% weight loss indicating the degradation of hemicellulose and cellulose. Perhaps, the third stage normally appeared in the high temperature above 460°C with a char residue of 35.5% indicating degradation of lignin and wax content, which is higher than the above-discussed novel fibres. Likewise, Saravanakumar et al. [78] found that both chemically modified and unmodified *P. juliflora* fibres (PJFs) undergo two stages of degradation. The first stage occurs between 32°C and 100°C, during which moisture evaporates from the fibres. The second stage, which takes place between 220°C and 400°C, involves a significant amount of degradation that can be attributed to improvements in structural order and a reduction in amorphous material. Lignin degradation, on the other hand, occurs between 200°C and 500°C, with weak bonds breaking between 200°C and 300°C, compared with stronger bonds in aromatic rings that cleave at higher temperatures, which is more similar to *C. quadrangularis* root [77]. The residue at 500°C for the chemically modified PJFs was only slightly higher than that of unmodified PJFs. Overall, these findings suggest that chemically modified PJFs have potential as a reinforcement in polymer matrices, with processing temperatures lower than 250°C. With respect to [77] and [78], Beroual et al. [79] investigated thermal analysis and found that moisture is removed at temperatures ranging from ambient temperature to around 100°C. During the thermal stability investigation of esparto grass fibre, two phases of degradation are identified. The initial phase of degradation happens at temperatures around 200°C and is primarily caused by the heat destruction of fibre, hemicellulose, and lignin connections. The second stage is related to lignin, which has a complex collection of aromatic rings with different branches, breaking down at a relatively slow pace across a broad temperature change, from atmospheric to temperatures above 600°C. Additionally, the weight loss continues between 250°C and 350°C, which is mainly due to cellulose breakdown.

The above-mentioned studies investigated the thermal stability of various novel natural fibres, such as *A. indicum, F. benjamina, P. vulgaris, F. selloa, A. planifrons*, TFF, *C. quadrangularis root,* and *P. juliflora*. From the investigation, it is understood that the alkali treatment increased the thermal stability of fibres by removing impurities and waxy layers. The researchers observed that the thermal degradation of these fibres occurs in two or three stages, involving the degradation of hemicellulose, cellulose, and lignin. The degradation temperature of these fibres varied from 230°C to 363°C, with *C. quadrangularis* root showing the highest thermal stability. Hence, it indicates that these novel natural fibres have the potential to be used as reinforcement materials in high-temperature applications.

3.5. FTIR Spectrum. Numerous research has attempted to increase cellulose content using different chemical treatments to enhance mechanical properties and surface roughness. Therefore, the chemical structure is changed in the functional group of fibre, and it can be observed with the aid of Fourier transform infrared (FTIR) spectroscopy. The FTIR analysis was used to determine the functional groups present in the fibres and composites. The FTIR spectrum of *Grewia damine* flowering plant's stem was observed by Moshi et al. [80]. A broad retention band at 3340 cm^{-1} corresponds to cellulose and hydroxyl groups' hydrogen requirements in cellulose and hemicellulose; the hike at 2917 cm^{-1} indicates C–H extending vibration from CH and CH_2. C=O extending vibration of ester groups and C–O extending vibration of acetyl groups in hemicelluloses cause the solid tops at 1734 and 1241 cm^{-1}, respectively. These pinnacles confirm significant hemicellulose content in the strands and the smelly skeletal vibrations in lignin ingestions is found be in the wavelength band of 1500–1600 cm^{-1}. A pinnacle at 1373 cm^{-1} shows CO expanding acetyl bunch vibration in lignin. The pinnacles are mostly linked to sugars in the range of 1030–1160 cm^{-1}.

The FTIR range of novel *Conium maculatum* was observed as 4000–5000 cm^{-1} by Kilinç et al. [81]. The FTIR spectrum of this novel Conium maculatum shows absorption bands of cellulose, spectrum hemicellulose, and lignin chemical functional groups. The wavelength at 3100–3800 cm^{-1} peaks is due to hydrogen-bonded OH elongating. The peak at 2935 cm^{-1} is produced due to increased cellulosic $-CH_2OH$ groups and the peak at 2844 cm^{-1} is induced by CH_2 in hemicellulose components. For example, the sharp peak at 1647 cm^{-1} is qualified for O–H bending. On the other hand, the peak at 1426 cm^{-1} corresponds to the CH_2 bending frequency of cellulose. The 1023 cm^{-1} peak is due to C–O and O–H stretching in *C. maculatum.*

The FTIR-8400S spectrum spectrometer was used to analyze the raw *Thespesia populnea* barks by Kathirselvam et al. [82]. Initially, pre-compressed *T. populnea* bark pellets (3 g) were pretreated with NaOH. An average of 45 scans were used to capture FTIR spectra with wave numbers from 4000 to 400 cm^{-1}. One of the strongest absorption bands found was 3748 cm^{-1}. Expansion of wax (CC) accounts for the apparent peak at about 2922 cm^{-1}. The *T. populnea* barks have a peak at 1745 cm^{-1} that corresponds to hemicellulose area. In addition, the aromatic ring stretching in lignin methyl groups accounts for the unique peak at 1517 cm^{-1}, and the carbonyl groups in cellulose were given the absorption band at 843 cm^{-1}.

The FTIR analysis was used to determine the functional groups and fibre component present in the *F. foetida* by Shahril et al. [83]. Infrared spectra from 4000 to 400 cm^{-1} were collected with a resolution of 2 cm^{-1} signal-to-noise ratio. In the presence of water–alcohol and cellulose, the first significant intensity peak is seen at 3380 cm^{-1}. The sp3 C–H and CH_2 stretchings caused the following two peaks at 2916 and 2859 cm^{-1}, and vibration indicates the existence of cellulose, hemicellulose, and organic substances. The following peak is seen at 2279 cm^{-1} due to C=C stretching. The following peak at 1440 cm^{-1} shows the existence of lignin due to stretching of C–O. The final two peaks at 1167 and 1020 cm^{-1} shows the presence of acetyl and alkoxy groups in lignin, respectively.

FTIR spectrum (FTIR-8400S, Japan) of tasar silk fibre waste was recorded by Ranakoti et al. [84], and the 4000–5000 cm^{-1} FTIR spectrum was obtained. An adequate signal-to-noise ratio with a 2 cm^{-1} resolution required 32 scans. The APF spectrum functional groups were detected between 4000 and 500 cm^{-1}. The hydrogen bond O–H (alcohol group) stretching causes an elongated "U" shape about 3650–3200 cm^{-1}. The peaks at 1730 and 1527 cm^{-1} correspond to hemicellulose C=O (carbonyl group) stretching and lignin C=C aromatic symmetrical stretching. The spectral peak at 1031 cm^{-1} due to lignin C–O stretching and the modest peak signal absorbance at 912 cm^{-1} indicates glycosidic connections between monosaccharides.

Fourier transform infrared spectroscopy – attenuated total reflectance (FTIR-ATR) spectra of *Hierochloe odarata* fibres were collected using a Perkin Elmer Spectrum BX by Dalmis Serhan Köktas et al. [85]. Each spectrum (totally 25 scans) was captured between 600 and 4000 cm^{-1} with a 2 cm^{-1} resolution. The FTIR spectra of *H. odarata* fibres show cellulose, hemicellulose, and lignin chemical functional groups. The hydrogen linked hydroxyl groups have a wide absorbance between 3500 and 3000 cm^{-1}. In addition, the chloral hydrate and hemicellulose stretching vibrations cause the peak between 2900 and 2700 cm^{-1}. Likewise, the carbonyl groups in hemicellulose cause the tiny shoulder at 1734 cm^{-1}, and hemicellulose O–H bending causes at 1600–1700 cm^{-1} peak. The tiny peak at 1520 cm^{-1} indicates aromatic lignin C=C stretching [86]. It is attributed to C–H symmetric bending of cellulose, C–H vibrational bending, and C–O aromatic ring groups. Lignin's acetyl group has a 1251 cm^{-1} C–O stretching vibration [87]. Fibre C–O and O–H stretching causes the strongest peak at 1033 cm^{-1}. Beta-glycosidic connections between monosaccharides correlate with the peak at 890 cm^{-1} [85]. It is also attributed to *H. odarata* fibres with absorption maxima at 1428 and 93 cm^{-1}.

4. Manufacturing Process of NFRCs

Moisture, fibre type, fibre volume fraction, aspect ratio, and chemical composition are the principal parameters influencing natural fibre composite processing. The manufacturing of composites involves several different factors including types of materials, polymer resin, fibre, and particles, durability, material temperature, parts complexity, and final product design. In addition, polymer industries seek to develop low-cost fabrication techniques, which can manufacture high-quality composite parts. As the fibre volume fraction of the composite increases, it becomes stiffer, stronger, and moisture resistant, and its strain rate decreases. On the other hand, temperature plays an important role in the processing of natural fibre. Natural fibres can be processed at a temperature of limit up to 200°C without degrading the structure of the cell wall. Natural fibre composites may degrade, shrink, and become low durability and strength, when the natural fibre is processed above the temperature limit. This is because of depolymerization, oxidation, hydrolysis, decarboxylation, dehydration, recrystallization, and other physicochemical process.

There are currently several methods available for manufacturing epoxy-based natural fibre composites. The common manufacturing techniques include manual lay-up, compression moulding, sheet moulding, cold pressing, filament winding, vacuum infusion, and pultrusion, which are largely dependent on the material with which they are made. Table 4 presents the advantages and disadvantages of manufacturing techniques.

4.1. Pultrusion. In pultrusion, pull and extrusion are combined. Instead of pushing materials through a die as in extrusion, materials are pulled through the pultrusion process to create a long and uniform cross section of the part [90]. In a thermosetting polymer resin solution, a puller drags continuous fibre roving or tapes through. It is possible to utilize thermosetting polymers, such as epoxy and unsaturated polyester. The resin-impregnated fibre composites emerge from the resin bath and are drawn and passed through a succession of shaping dies. Final products might be round, rectangular, and square, or have I-shaped and H-shaped portions. One of the dies also cures the composite. Rods and bars are often the end products. After the pultrusion process, the products are trimmed to the required lengths [92].

Fairuz et al. [93] described the work on pultruded kenaf fibre–reinforced vinyl ester composites utilizing the pultrusion technique. Kenaf composite rods were created. In this investigation, speeds, temperatures, and filler loadings, were examined. The number of trials to be done was determined by Taguchi's experimental design. Rod-shaped specimens were produced at three different rates by varying the temperature and filler loading. The process is then repeated with varied parameters, temperatures, and filler loadings. As a result of this, the mechanical characteristics of the composite rod specimens were evaluated for each parameter.

4.2. Filament Winding. Manufacturing components with a circular shape using filament winding is a composite manufacturing technique especially for pressure vessels and cylinders [86]. A spinning mandrel is used as a mould in an open-mould method. Through a resin bath, continuous

Table 4: Advantages and disadvantages of manufacturing techniques.

Manufacturing technique	Advantages	Disadvantages	References
Hand layup	Setup time is low and good surface finish	Efficient labor is required and less flat or curved shapes can be fabricated	[88]
Injection moulding	Low setup cost, production run, and highly precise	The initial setup cost is high	[89]
Resin transfer moulding	Better consistent than a compression moulding and tight tolerances	More material waste and production rate are slow	[89]
Pultrusion	High degree of distribution of resin over the entire fibre	High accumulation of excess resin creates more porosity, thereby decreasing the strength and stiffness	[90]
Compression Moulding	Good surface finish, reproducibility, and high production rate	Processable only with short fibre composites	[91]

fibre roving is pulled by a puller. They are then wrapped around the rotating mandrel. An x-axis is also used to move the composites along the mandrel so that they are evenly distributed. In the filament winding process, there are three types of winding patterns: hoop, helical, and polar.

Misri et al. [87] used hollow shafts to develop unsaturated polyester composite fibres reinforced with kenaf fibres and found their mechanical properties. They were drawn through an aluminum spinning mandrel, which was filled with resin, and the reimpregnated composite fibre materials were looped around the mandrel. To compare their findings with the results of finite element analysis, they looked at tensile and twisting characteristics. Developing filament wrapped kenaf fibre composites has several challenges, including how to get a smooth surface on the shafts that is uniform [94].

4.3. Hand Lay-Up. Hand lay-up technique is the older open moulding fabrication method used for producing composite products. This is a labor-intensive technique in which the laminate quality, resin mixing, and laminate resin concentrations are heavily dependent on the skills of the operator as this approach does not allow for considerable fibre loading [88]. The hand lay-up manufacturing method is processed in four phases, and it is described as follows. A mould release agent is sprayed to the mould surface to make it easier to remove the finished composite products. To build a component, a gel is applied to the mould surface. Intended to prevent the formation of fibres, this resin-rich coating is placed on the mould surface. Fibre reinforcement and polymer resin are used to create composites. They are then layered and joined using a roller. Until the required thickness is achieved, further layers are applied. Depending on the kind of composite, the composites are then dried at room temperature or in an oven. Unsaturated polyester and epoxy are among the thermosetting resins most often used today. For decades, natural fibre composite components have been made using hand lay-up, also known as wet lay-up. Natural fibre–reinforced polymer composites based on soya were used by Ford in the early 20th century to construct the vehicle's body by hand. This technique is utilized to construct a miniature watercraft, wind turbine using hybrid palm sugar–glass fibre reinforced unsaturated polymer composite. The mould was made of a glass fibre–reinforced polyester composite and was designed to create an extremely high-quality finish. An anti-adhesion compound was then placed on top of the mould surface to prevent the component from sticking to it. As a hardener, methyl ethyl ketone peroxide was employed. Sugar palm fibres are then added layer by layer until the composites reach the desired thickness. To make bullet-proof composite panels, ramie fibre reinforced composites using epoxy as a matrix were laid out by hand using epoxy [95].

4.4. Resin Transfer Moulding. Resin transfer moulding (RTM) is a recognized fabrication technique of composite that is commonly used for high-volume production and cost effective to make automobile and aerospace products [89]. Using a template and a knife or scissors, fibre reinforcement, either long or weaved, is first cut out. The thermoplastic binder binds these reinforcements, known as performs, which are then inserted into the mould cavity during the closed mould process. A variety of equipment, such as pressure or vacuum, is used to move resin into the mould cavity to avoid the formation of voids [96]. Epoxy, phenolic, polyester, and vinyl ester resins are common resins utilized in this technique. They are used for nonwoven kenaf fibre mat reinforced epoxy composites; RTM will develop composite specimens. Kenaf fibre mats were made after a few processing steps, including opening, carding, cross lapping, and needle punching. The stitching density was refined to investigate its influence on the composite's mechanical properties. Comparatively, the stitched kenaf mat composites show better mechanical characteristics than unstitched kenaf mat composites [97, 98].

4.5. Compression Moulding. To produce high-volume composite components, such as car parts, compression moulding is a typical process [91]. This process has combination of both hot press and autoclave techniques [99]. It is common for thermosetting matrices to use moulding compound as an intermediary material in the process. In thermosetting moulding, sheet moulding compound and bulk moulding compound (BMC) are the most often utilized compounds (BMC) [100]. When it comes to thermoplastic polymers, glass mat thermoplastics are widely used as a moulding compound. Using an internal mixer and twin-screw extruder, composite pellets are frequently generated for compression moulding composite specimens in the laboratory size range. Only pressure is used in the cold press, but both pressure and temperature are utilized in the hot press once the moulding components have been placed in the mould cavity. As opposed to hot press moulding, when heat is applied to the mould and subsequently transferred to the composites, cold compression moulding curing happens at ambient temperature. Polyester, vinyl ester, and phenol are used in thermosetting polymers, whereas pp and polyamide are used in thermoplastics [101].

For example, Palani Kumar et al. [102] assessed the mechanical properties of coconut flower cover fibre–reinforced polymer composites for industrial and automotive applications. Three variations of polyester/fibre samples, including 80 : 20, 70 : 30, and 40 : 60, are fabricated, and the results indicate that the mechanical characteristics of the fibre tend to improve as the fibre concentration rises. In addition, they suggest that hot compression moulding is the superior method for producing composites since it reduces the quantity of voids and air bubbles.

4.6. Vacuum RTM. Vacuum Resin Transfer Moulding (VARTM) is a process that involves a vacuum bag to facilitate the laminate and seal the mould rigid enough to hold the smooth laminate shape to avoid debonding of laminate. Generally, moulds used for vacuum bagging differ widely in size, shape, and construction method. VARTM can be used for fabricating panels, side door, and dashboard. Before fabricating, moisture must be removed from the fibre, and the vacuum pressure is created with aid of a vacuum hose at a pressure of 1.6 bar. Once the full vacuum pressure has been achieved and no leakage has been detected, the resin and hardener are mixed and then drawn into the laminate. Every two hours, 180°C is used to maintain the constant curing temperature; then, 120°C is maintained for one-hour post-curing curing temperature. The resultant moulded parts are produced with both rough (bag) sides and smooth (mould) sides.

5. Significant Issues in the Processing of NFRCs

For NFRCs, the distribution of fibres inside the matrix, the composition, and size of fibres to achieve the matrix–fibre interface, desired strengthening effect, and flaws like porosity are all significant factors in attaining mechanical and functional characteristics [103]. In particular, the fibre content and its properties, like length to diameter ratio (L/D), and concentration have a significant impact on NFRCs. The major concerns with the processing of NFRCs arise primarily from the fundamental properties of natural fibres. The critical processing concerns included are fibre hydrophilicity, machining, fibres having low strength, which results in damage or breakage, fibre thermal stability, water/moisture absorption, and fibre distribution in the matrix [104].

5.1. Hydrophilicity of Natural Fibres. Hydrophilic natural fibres have a low wettability with hydrophobic polymers because of poor adhesion between the fibres and the matrix and mixing problems during the NFRC's processing. Natural fibres, on the other hand, are prone to moisture absorption and microbial degradation due to their high hydrophilicity. Because of this, it is necessary to dry the fibres before they are fed into the processing equipment or during processing. It is also important to handle and store dry fibres carefully to avoid moisture absorption and particle eruptions [105]. The amount of fibre content must be closely regulated since they are dried during processing. Moisture content in the fibres may generate water vapor and porosity inside the NFRCs while manufacturing. The water absorption capacity of fibres can be regulated by hydrothermal treatment by increasing cellulose crystallinity and decreasing hemicellulose. Chemical treatments, such as photo-curable monomer coatings on fibres, might be used to increase moisture resistance [106, 107]. Several physical and chemical treatments are being explored to decrease the moisture absorption of fibres [33]. The other significant effect of fibre hydrophilicity is the difficulty of fibres to establish good bonds with hydrophobic polymeric matrix. The mechanical properties of NFRCs, however, are reliant on the matrix–fibre interface since the matrix–fibre contact is essential in transferring stress to the matrix through the fibre. Fibres or the matrix phase must be treated with compatibilizers/coupling agents to improve the matrix–fibre wettability in NFRCs to achieve desired mechanical properties. Acetylation, alkali treatment (mercerization), electron beam irradiation, grinding, graft copolymerization, gamma-ray irradiation, plasma irradiation, steam explosion, and silanization of monomer or polymer onto fibres are all popular fibre treatments. For example, acetylation in the vapor phase might result in decreased hydrophilicity and increased thermal stability [108].

The ability of absorption of moisture in natural fibres while storing or after treatment can cause fibril bulging and dimensional instability, as shown in Figure 6. Indeed, the inflamed fibres lead to decrease the composite mechanical characteristics and the adhesion between fibre and matrix [109]. Wetness content of fibrils must reduce to less than 3 wt.% to process high-quality fibres. Porous composites are created when any moisture is transformed to water vapor during the manufacturing. Because natural fibres have strong polar groups on their exterior, they can absorb moisture at high and low temperatures. The wetness content of the fibrils relies on the relative humidity during manufacturing and storage, as well as the kind of fibre being utilized. In comparison with composites manufactured with bamboo fibres, pennywort FRCs have a moisture about 57% at 90% relative humidity resulting in degradation of the composite. As stated before, fibre surface treatment may significantly reduce humidity and absorption [110]. To achieve minimum moisture content in composite materials, high L/D screw ratio extruders and container reshaping allow degassing. Even though moisture deterioration of NFRCs has been reported in a few studies, nothing is known about how natural fibres absorb moisture.

5.2. Thermal Stability. It is a critical issue for NFRC processing since most of the natural fibres breakdown as the temperature rises. When fibres are heated between 100°C and

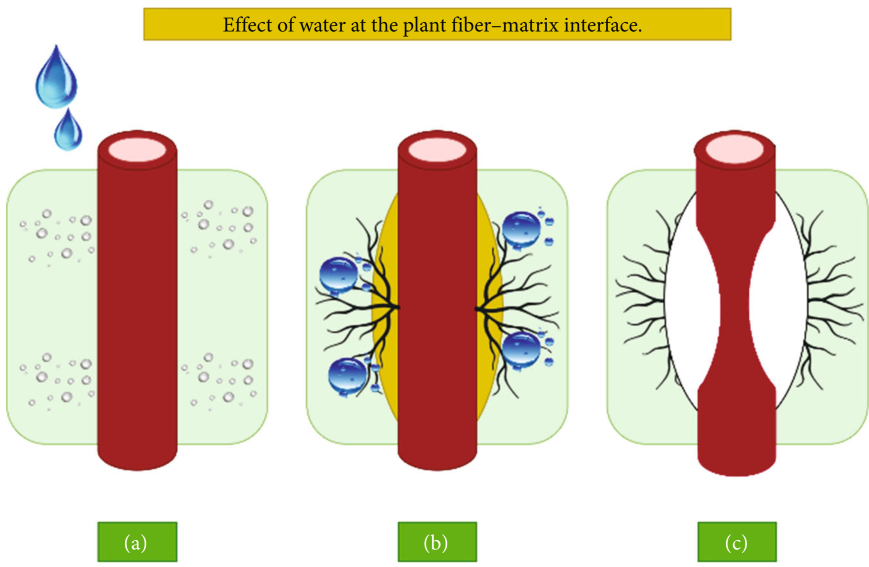

Figure 6: Mechanism of moisture absorption of natural fiber. (a) Water diffusion into the composite (b) Swelling of fibers after moisture adsorption leading to microcracks within the matrix (c) Ultimate fiber-matrix debonding.

300°C, chemical and physical changes occur, resulting in deterioration. Dehydration, discoloration, recrystallization, hydrolysis, oxidation, decarboxylation, and depolymerization are only a few of the important changes that occur throughout the process. Changes in mechanical characteristics, color, and odor can occur because of high temperatures during NFRC processing [111]. It has been observed that after 20 minutes of heating above 160°C, cotton's strength and modulus rapidly degrade. The properties of flax fibre can be degraded by even a brief exposure to high heat. Several additional studies have also shown that high processing temperatures have negative impacts on natural fibre mechanical and other useful characteristics. The characteristics of natural fibrils are highly dependent on their structure, such as cellulose, lignin, and hemicellulose. In the same way, the content and structure of these fibres determine their thermal stability or deterioration over time. Initially, the thermal breakdown of natural fibres begins with hemicellulose destruction, which has been linked both to moisture content and temperature [112]. A high hemicellulose content in natural fibres makes them more susceptible to moisture absorption than those with a low hemicellulose concentration. Increased extractives can potentially lead to decreased thermal stability of fibres, as well. It was found that thermal stability and strength may be improved by fibres with a high crystalline cellulose content. Decomposition temperature of natural fibres was shown to rise when crystallite dimensions and crystallinity mark were increased for cellulose. It is important to investigate the thermal degrading behavior of natural fibrils, according to their composition and structural characteristics in order to develop NFRCs with the appropriate mechanical performance [38]. As previously stated, natural fibres can be strengthened by performing various chemical and physical tests.

5.3. Effect of Composite Strength due to Fibre Breakage. Fibre breaking during compounding and combining is a key issue in the manufacture of NFRCs. In addition to the finer aspect ratio and orientation of natural fibres, the manufacturing technique utilized to manufacture NFRCs has a significant impact on the reinforcement effect of filler [113]. Fibre breaking happens at all stages of IM of NFRCs, as mentioned above. During the first phases, for example, the combined action of warmth and pressure causes fibre rupture. Small fibres used in the injection moulding (IM) of NFRCs may induce attrition owing to large shear values in container and sprue nozzle. There is also the possibility of natural fibres breaking in span owing to collision among the fibrils, or between the fibres and the mould (apparatus). As a result, the concluding composite fibre distance falls below the critical length, resulting in significant fibre strength loss. In this case, the short fibres might cause a flaw in the composite due to its higher flexibility than synthetic fibres which may develop fibre entanglement in some instances. With average fibre lengths ranging from 0.1 to 1.2 mm long, aspect ratios of 20 can result in a significant drop in the strength effect of natural fibres. Regular fibrils breaking at the time of NFRC processing is much less understood than synthetic fibres. Some of the reasons why fibre bundles separate and polymer characteristics like glass transformation temperature and molecular weight change might be too responsible for a drop in the strength of the composite. The strength of the composite is dropped with respect to the change in the weight of the molecules in fibre and glass transformation temperature, also this might be the reason for the separation of fibre bundles [114].

5.4. Effects of NFRC's Distribution in Matrix. In the context of NFRCs, despite their hydrophilicity, it is difficult to regulate fibre dispersion. Weak or crack-prone areas are caused by a poor distribution of fibres, which results in fibre-deficient or fibre-rich regions. To enhance the dispersion in NFRCs, various chemical and physical tests of fibrils were taken. To improve fibre dispersion, coupling chemicals like mining oil and stearic acid may reduce fibre–fibre contacts and tangling. The pectin on the fibre surface may be removed with a simple alkali treatment, which also reduces fibre clustering. High fibre bundle widths restrict the interfacial bonding area, which reduces stress transfer between fibre and matrix. The fibre bundles must be split to produce robust NFRCs with consistent reinforcement distribution. Fibre bundles may be split by mixing energy while avoiding fibre breaking. Most NFRCs, regardless of treatment, have a preferred fibre orientation [115]. Material flow, shape, surface roughness, viscosity, and wettability of the mould all affect fibre orientation. On mould walls, material flow and shear directions are extreme; thus, fibres tend to align themselves. These fibres are arranged in a random pattern on the surface of the skin, which covers a central portion of the part. In a cross-sectional area, the material velocity is more influenced by the surface roughness of the mould or barrel than the outside region. Skin layer thickness is increased by increasing the fibre length since long fibres are easier to orient than short fibres. The skin's mechanical properties are always superior to a core region with random fibre distribution due to the skin's strong fibre alignment with the material flow direction [116]. Intense melt viscosity and fibre-to-fibre contacts may decrease orientation severity [117]. The skin-core effect is dependent on component size, mould gate location, injection pressure, natural fibre type, speed, and temperature [112]. For example, in Polypropylene/flax and PP/jute composites, the large dimensions and high lignin concentration of jute fibres cause changes in fibre orientation [118].

5.5. Challenges Facing During Machining of NFRC's. The inherent microstructural and property variabilities of NFRCs make machining them more difficult than other materials [119]. The complex shapes of NFRC products are generally assembled and fabricated by using various operations, such as drilling, grinding, milling, and turning. High tool wear and poor surface finish are crucial in machining NFRCs. Recent research shows that feed rate and material removal rate may help reduce the impact of machining flaws like peel-up or push-down stratification on the surface [120]. High cutting speeds of the tool induce frictional heat leading to matrix melting, and better surface finish of the composite is always dependent on the fibre orientation [121]. In grinding operation, the feed rate may lead to pullout the fibre, forming of surface burrs, burning, and delamination. In this process, good surface finish can be produced when the fibres are oriented normal to the direction of the grinding [54]. At present, most of the complex shapes of NFRC products are joined by using riveting and fastening methods. During fabrication by these methods, the products are to be drilled, which produce burrs around the hole [122]. Tool geometry also had a strong effect in producing better drilled holes.

6. High-Performance Applications

Studies that primarily concentrate on cellulose fibre have looked into the use of lignocellulosic fibres in bioplastics. In recent years, the use of raw lignocellulosic fibres in bioplastics has drawn more attention [123]. Similar to the way the use of biomass has progressed, it may shortly be capable of overcoming the application difficulties of these substantial materials, particularly in relation to their economic viability, by the development of high-performance polymeric and composite materials. This development would increase the profitability of some agrobusiness sectors, particularly the biofuels industry, which generates large amounts of biomass waste [124, 125].

In order to decrease the environmental impact of the food and pharmaceutical industries, polyvinyl alcohol (PVA), a biodegradable polymer, has gained popularity as a viable substitute for non-biodegradable petrochemical counterparts. Lignocellulosic cellulose nanofibrils (LCNF) hold great promise as a low-cost, multifunctional component that improves PVA's properties for packaging applications [123]. Rechargeable energy storage systems are similarly in high demand in the current environment. Activated porous carbon that is derived from lignocellulose-based biowaste materials serves as a superior electrode material for high-performance supercapacitors [126]. Additionally, this demonstrated its flexibility, high mechanical strength, low cost, and sustainability in flexible electronics. In a study published in [127], it was revealed and proved that LCNF are a renewable and durable substrate that can be used to develop suitable, highly sensitive sensors.

6.1. Inherent Properties of Natural Fibres for Sound Absorption. Researchers have developed natural and synthetic polymeric fibrous materials that are safe, cost-effective, and easily designed for noise control in recording rooms and theatres [128]. Natural fibres, derived from animals or plants, are biodegradable, non-toxic, and recyclable, making them particularly interesting to researchers. The sound absorption of these fibrous materials is primarily due to viscous effects from friction between air molecules and the pore wall, as well as thermal losses from heat transfer between fibres. The sound absorption performance can be improved by using lower fibre density and smaller fibre diameters. The general structure of fibrils from natural fibres consists of cellulose, hemicellulose, and lignin, which can be further processed to improve sound absorption. By processing raw plant fibres into finer fibrils, microfibrils can be formed, resulting in smaller pores and more complex channels that enhance the absorption of sound energy. This can be achieved by using external forces like hammers to beat the fibres [129].

NFRCs are traditionally used only for structural applications, but now, due to the emerging noise pollution crisis made, industry and researchers use these materials in controlling the noises around industrial and living areas, as shown in Figure 7. Sound absorption panels already in use are in the form of single-layer structured (low density and medium- to high-density insulator), multi-layer structured, and sandwich structured (honeycomb and corrugation as core). Many researchers have attempted different studies to optimize the sound-absorbing ability of natural fibres and to eliminate the use of non-biodegradable synthetic sound-absorbing materials [130]. Research on sound-absorbing materials made of natural fibres is emerging in the field of sustainable material development.

6.2. Natural Fibres in Ballistics. Gun-related threats have had a profound impact on human existence, particularly among combatants and public soldiers. Multilayers armor system (MAS) is a system that effectively defends against various dangers. Previously, synthetic materials, such as aluminium and Kevlar fibres, were used to make bullet proof jackets. NFRCs are currently utilised as a supplementary layer in MAS.

da Luz et al. [131] conducted a ballistic investigation using pineapple leaf fibre. This blending with Dyneema plate is intended to provide additional protection in Kevlar level IIIA ballistic protective layer vests. The findings of this investigation indicate that this level of ballistic protection was effective against 7.62 mm rifle ammunition in accordance with the National Institute of Justice (NIJ) global standard for level III security. Similarly, Nurazzi et al. [132] conducted ballistics tests with 7.62 mm bullets according to NIJ Standard class III and concluded that composites fabricated with woven jute reinforced using polyester and employed as a second layer passed the ballistic standard criteria. The presence of the jute polyester composite prevented the third layer of aluminium alloy from perforating and produced a shallow depression in the clay witness. As indicated previously, they also conducted the same test with Curaua fibre [133] as a substitute for woven jute. In this study, it was determined that the epoxy or polyester matrix composite reinforced with 30 vol.% Curaua fibre demonstrated superior performance (withstands high-velocity 7.62 mm bullet) than typical aramid fabric plies with an Al_2O_3 ceramic coat.

Filho et al. [134] assessed the ballistic performance of NFRCs made from cassava fibre. The composites were made with 10–50 vol.%, and 7.62 mm ammunition was used for ballistics testing. The results demonstrated that MASs comprised on piassava fibre composites provide adequate protection. This illustrates that piassava fibre, a sustainable material, can also be utilised efficiently in armur systems.

A new category of natural fibres is currently the subject of intense research. Neuba et al. [135] investigated a relatively new class of natural fibre known as "*Cyperus malaccensis*", a form of sedge fibre that is already utilised in ropes, furniture, and paper. Similar to this, Shaker et al. [136, 137] investigated *Vernonia elaeagnifolia* and *Argyreia speciosa* waste for their potential as waste-to-market products.

6.3. Crashworthiness Performance of Natural Fibre Composite. Crashworthiness is playing a crucial role in the designing of automobiles components as it provides a measure of the structure's ability to protect the occupants from serious injury or death in case of a crash of a specified proportion. A vehicle's crashworthiness is determined by the energy absorption failure mode, which allows for a gradual decrement in the load–displacement curve during the energy absorption of structures. Crashworthiness characteristics depend on many energy-absorbing parameters including total absorbed energy (EA), specific energy absorption (SEA), peak force (PF), and SEA per unit volume (SEAV). Different parameters that affect the crashworthiness parameters are shown in Figure 8.

The SEA is the most significant parameter for comparing the energy absorption of the structures that determines the energy absorption per unit mass of the absorber as shown in Equation (1):

$$\text{SEA} = \frac{E_a}{m}, \quad (1)$$

where E_a is the total energy absorption and m represents energy absorption during a crash as shown in Equation (2). The total energy can be calculated by E_a

$$E_a = \int_0^d f(x)\,dx, \quad (2)$$

where d and f are displacements and impact force, respectively.

During the collision of automobiles, the energy dispersion rate is governed by energy-absorbing capability. Therefore, vehicle collision structures with high EA, SEA, SEAV, and low PF are considered as good crashworthy. Additionally, tube wall thickness was found be key role in better energy-absorbing capability. In general, crushing tests are carried out by quasi-static compression loading in the lateral and axial directions. Natural FRC tubes are compressed between steel plates in a hydraulic press at low crosshead speeds that usually range between 1 and 20 mm/s. Numerous studies discovered that natural fibre can reveal superior energy absorption than metals [138]. In contrast to metal tubing, natural fibres, such as kenaf, jute, silk, and hemp [139], can experience a fracture to attain energy absorption rather than deformation, when subjected to axial crushing [140–142].

Ude et al. [143] discovered that different failure modes of natural fibre including delamination, bending, and local buckling have significant contributions to energy absorption. Likewise, Węcławski et al. [144] explored crashworthiness characteristics of hemp/epoxy composite tube under quasi-static axially loading experimentally with different winding directions including 10°, 20°, 30°, 60°, and 90° and found that fibre orientation with 10° displayed better energy absorption with four different collapse modes, namely, diamond shape buckling, micro buckling, progressive crushing, and concertina. In similar way, Yan and Chouw [145] evaluated the crushing characteristics under different tube geometries including inner diameter, length-to-diameter ratio, and tube thickness and reported that tube geometry had a significant effect on superior energy absorption.

Attia et al. [146] used the inner core as conical and the outer core as circular and discovered that this configuration exhibits superior energy absorption with a low peak load. With respect to previous research, Eshkoor et al. [147] introduced the trigger mechanism to study the axial crushing of silk/epoxy composite tube. They reported that failure mechanisms such as tear onset and tear propagation with progressive failures such as buckling and delamination have occurred. Therefore, an appropriate tube geometry with a proper triggering mechanism is associated with the

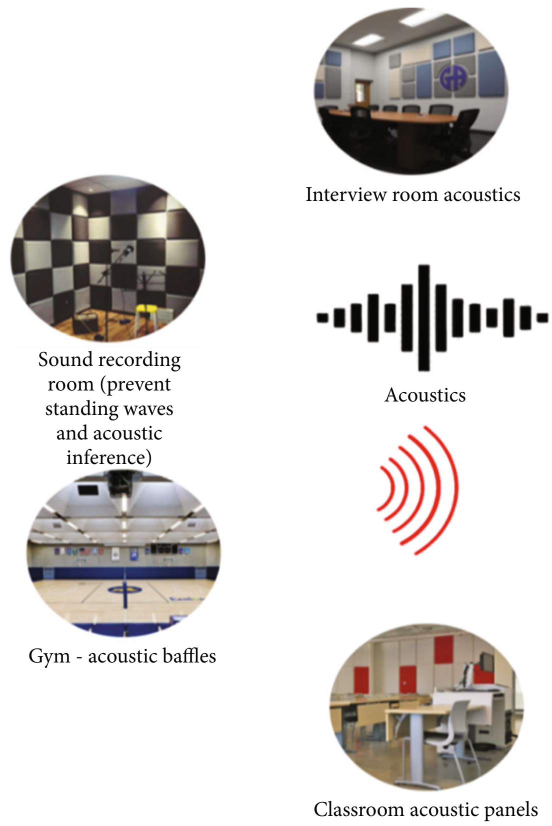

Figure 7: Application of natural fibre in soundproofing.

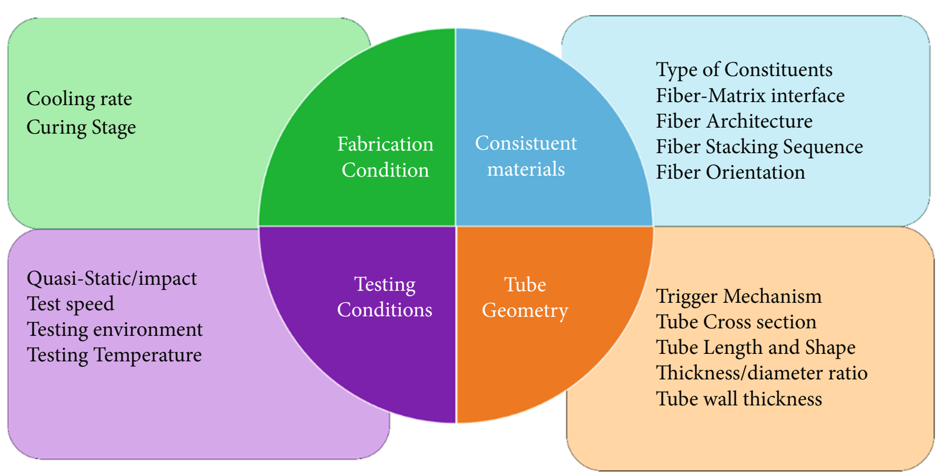

Figure 8: Factors influencing crashworthiness parameters of NFRCs.

suitable material constituent to achieve optimal impact performance [148].

6.4. Analysis of Life Cycle Assessment. Life cycle assessment (LCA) was carried out to assess the environmental sustainability and durability by quantifying the input and output within the structure of organization of the functional inventory unit. The Simapro software was used to implement the lifecycle analysis and calculation and evaluate environmental impacts. There are several LCA methodologies supported by the ISO, including ISO 14040, 14041, 14042, and 14043. The process involves determining the ecological consequences of detrimental factors like radiation, greenhouse gas emissions, ecotoxicity, climate change, carcinogens, and acidification/eutrophication. To achieve this, the method employs the Intergovernmental Panel on Climate Change guidelines for specifying system boundaries, functional units, life cycle inventories, and transportation modes [149], as shown in Figure 9.

Navaratnam et al. [150] compared LCA between natural fibre and synthetic fibre and found that bio-based fibre exhibited lower energy consumption and less environmental

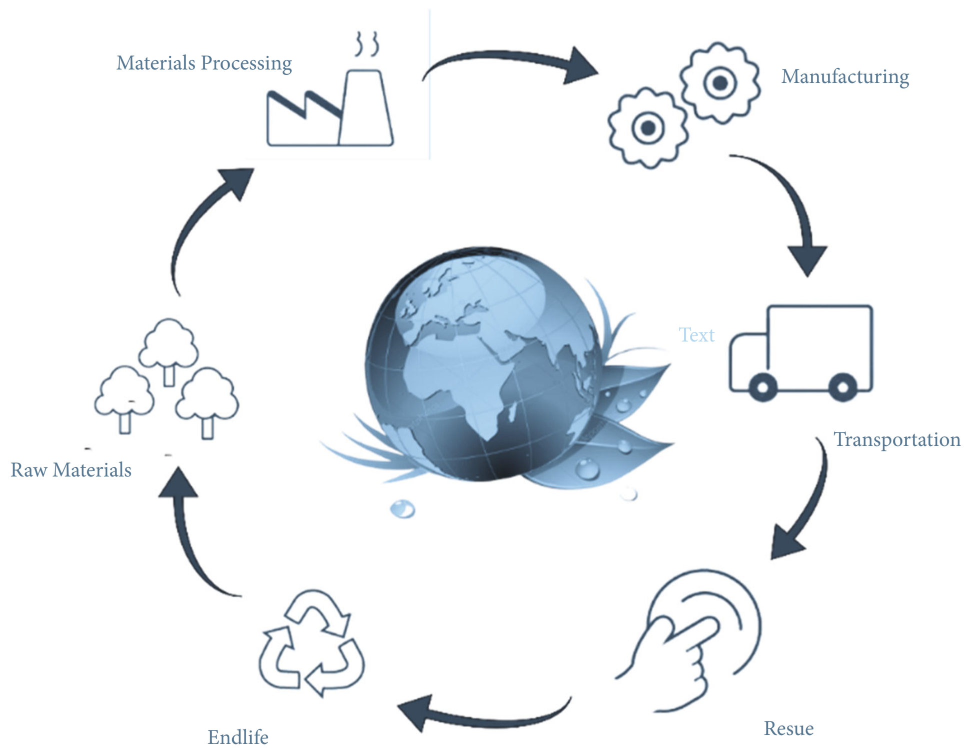

Figure 9: LCA analysis.

impacts when compared with petroleum-based products. Similarly, Gupta et al. [151] introduced green tags that can be assigned to explicit materials by taking into account various factors such as the route towards the end of the material's life cycle and green manufacturing. Likewise, Ahmad et al. [152] analyzed life cycle assessment with natural fibre and synthetic fibre and found that biofibre saves 55% energy when compared with synthetic materials. As a result, plant-based bio-fibre processing has an environmental footprint that must be quantified, critical environmental aspects identified, and systems optimized so that overall impacts can be reduced, as well as the environmental impact of anticipated improvements in the supply chain and manufacturing processes.

7. Conclusion

Fibre–reinforced polymer composites improve component quality in terms of eco-friendly, financial, and technological feasibilities. However, to achieve this objective, some problems must be addressed. In this study, we compare the characteristics of several natural fibres. This review shows that material characteristics are highly reliant on context, that is, where the crop is grown and how it is treated, processed, and applied. This section also shows that many natural fibrils are available on the market, and although most have useful mechanical characteristics, their properties are varied. This is due to the natural cycle as well as each manufacturer's unique technique of producing and utilizing natural fibres. Several studies report findings using various criteria, and some are ambiguous regarding the standards employed. Another significant finding is that certain fibres are more costly than others, while having the same mechanical characteristics. Flax, ramie, cotton, and hemp are said to be cheaper than the others but have worse mechanical qualities. This is due to availability and dependability. Choosing the best natural fibre for a given application requires an integrated study and decision-making process. Despite these problems, natural fibres offer intriguing uses in many sectors and industries, such as ballistics, sound absorbing, and automotive applications. The automobile industry is the most active and knowledge-intensive sector in developing non-structural components. However, other sectors such as furniture, medical, sports, and others have progressively expanded out into natural fibre composite goods.

Data Availability

The data used to support the findings of this study are included in the article.

Conflicts of Interest

The author(s) declare(s) that they have no conflicts of interest.

Authors' Contributions

Conceptualization: Gurupranes SV and Md. Elias Uddin; Methodology: Rajendran I; Formal analysis and investigation: Gurupranes SV; Writing—original draft preparation: Gurupranes SV; Writing—review and revise: Gokulkumar

S, Aravind M, and Md. Elias Uddin; Supervision: Rajendran I and Md. Elias Uddin; Ideology: Sathish S and Md. Elias Uddin.

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