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Unlocking the Potential of Jute: A Comprehensive Review of Its Innovative Applications in Composite Materials

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ABSTRACT

The environmental hazards of synthetic materials have intensified the global pursuit of sustainable, biodegradable alternatives. Jute, a widely available natural fiber, has emerged as a viable reinforcement in bio-composites due to its low cost, renewability, biodegradability, and mechanical robustness. This review presents a comprehensive and critical evaluation of recent advancements in jute fiber-based composites, covering their structure, morphology, chemical composition, surface modifications, and processing techniques. Notably, it highlights the unique potential of jute in nanotechnology, including the production of nanocellulose and its applications in biodegradable packaging, energy storage, and 3D printing areas that have been sparsely covered in previous literature. The study also synthesizes insights on novel hybrid composites, fiber treatments, and fabrication methods that enhance jute's compatibility with polymer matrices. Key findings indicate that surface modifications significantly improve fiber-matrix adhesion and thermal stability, enabling broader industrial applications. Challenges such as flammability, moisture absorption, and limited thermal resistance are critically assessed, alongside emerging solutions. This review identifies strategic gaps, particularly in scalable processing, high-performance nanocomposites, and the integration of circular economy principles, and outlines future research directions to bridge the gap between laboratory-scale innovation and industrial deployment. By exploring under-researched areas and cross-sector applications, this work extends the frontier of jute-based composite research and supports its evolution into a high-value, environmentally friendly material.

Keywords: Jute, Natural fibers, Synthetic fibers, Green composites, Jute fiber composites.

1 Introduction

Academic and commercial researchers are interested in natural fiber-based solutions for creating environmentally friendly products, despite their low carbon footprint. Environmental pollution, a threat to all life, surrounds us. Leading nations are taking extraordinary measures to replace polluting commodities with renewable ones. Composite materials play a vital role in many load-bearing applications. A substantial investment has been made in developing synthetic composites that exhibit high performance across several applications. Due to environmental concerns, bio-composites have garnered interest recently. This is why these composites have garnered attention in recent years.

Although numerous review articles have examined jute as a sustainable raw material for composite fabrication, most of them have largely emphasized conventional mechanical and processing aspects. In contrast, this review offers a significantly broader and updated perspective. It uniquely integrates discussions on recent developments in nanomaterial-engineered jute composites, including graphene and carbon nanotube functionalization, and explores emerging fabrication techniques such as 3D printing with jute-based filaments. Furthermore, it addresses advanced industrial applications across energy storage, innovative electronics, biodegradable packaging, and medical textiles that remain underexplored in prior reviews. These elements position the present work as a comprehensive, future-forward resource for academic research and industrial innovation in jute-based materials.

These biodegradable bio-composites utilize natural fibers to reduce their carbon footprint and promote environmental benefits. Bio-composites are natural, lightweight, cheap, and release low CO_2 during production. Above all, bio-composites use many of these fibers from nature [1]. Biological composites have recently emerged as the most promising alternative to synthetic composites. In both research and industry, various bio-composites are developed at different stages. Mechanical and physical characteristics of particular bio-composite material are comparable to synthetic composites [2].

Recently, materials that degrade and bio-composites have gained popularity. These materials are being developed for numerous industrial sectors. Fig. 1 shows several plant fibers. Jute constitutes one of the primary natural fibers used to create bio-composites. Tropical countries, including China, Bangladesh, India, and Indonesia, cultivate jute from the bast fiber family. This fiber is manufactured worldwide [3]. Jute plants thrive in warm, moderate to cool temperatures (20-40 °C), high humidity levels (70-80%), and well-draining, grassy soil. They also require 125–150 mm of rainfall per month. Jute is a bast fiber grown on plantations and extracted when the plant is mature. After this, the plants are retted to remove fibers. Jute fibers are sold for processing after drying [4],[5].

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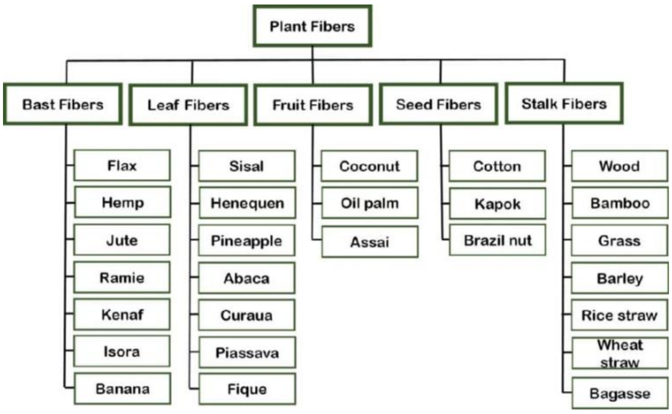

Fig. 1 Types of fibers extracted from plants

Fibers are often spun into yarn, which is used to produce clothes. Jute is sometimes treated with different materials to enhance its practicality [6],[7]. Jute is an environmentally friendly raw material for various chemical products, including pulp, microcrystalline cellulose (MCC), carboxymethyl cellulose (CMC), and composite structural products. Jute fiber outperforms natural and synthetic fibers in terms of sustainability and mechanical characteristics [7]. Thermosets and thermoplastic fiber-reinforced composites are the most popular structural materials. A synthetic polymer matrix with jute fibers could be stronger and more environmentally friendly, using fewer synthetic polymer materials. Jute fibers have been the subject of extensive research and review papers [6],[8]-[19]. Still, these works primarily focused on jute as an environmentally friendly raw material for composite materials. They did not discuss the latest advancements in other jute-based research areas, such as using jute to create nanoparticles, the scientific study of jute fiber through nanoparticles, or modern 3D printing to develop jute products.

Asia is the world's largest producer of jute, accounting for over 95% of the crop produced worldwide [20]. Jute fibers' physical and mechanical qualities (Fig. 2) have drawn much attention recently. Jute fibers are also inexpensive, renewable, biodegradable, and environmentally beneficial [21].

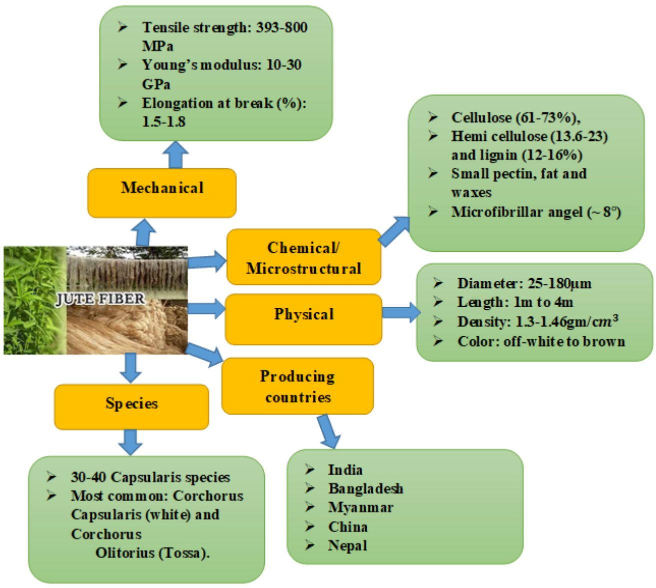

Fig. 2 Essential facts and figures on Jute production and use.

Lignin and cellulose make up the bulk of jute fibers. A polysaccharide called cellulose facilitates the formation of hydrogen bonds between the matrix and natural fibers, thereby strengthening interfacial adhesions [22]. Aside from the composite and bio-polymer industries, jute fiber is highly sought after by the textile sector [23]. The plant's maturity, the fiber's length, and the processing methods applied in fabricating composites often define the characteristics of jute fibers [20]. Now, jute fiber is widely used in various industries, including textiles and automotive manufacturing. The automotive factory utilizes jute composites to manufacture components, including cup holders, trunk liners, and door panels [24]. European and American automakers like Mercedes are keen to incorporate increased amounts of renewable composites and polymers into their vehicles [3]. Table 1 displays the yearly production of different natural fibers [10],[15],[20].

Table 1 Yearly production of various fibers.

Fiber Source	Fiber Category	Yearly Produce (10^3 Tonnes)
Bamboo	Wood	35,000
Jute	Bast and Core	3700
Grass	Grass	700–750
Sugar cane	Wood or Stem	78,000
Ramie	Bast	110–120
Abaca	Leaf	80–90
Sisal	Leaf	370–380
Hemp	Bast and Core	200–220
Coir	Seed	600–700
Kenaf	Bast and Core	950–1000
Flax	Bast	850

2 Green Composites—Historical Perspective

"Green Composites" are composite materials that use natural fibers to reinforce biopolymers. Examples include coir, jute, flax, sisal, and hemp; biopolymers used to create Green Composites include starch and PLA [4].

The first green composites were developed in the late 1980s. They are as affordable as traditional composites, and in addition, they are environmentally beneficial. Green composites have been around for a considerable time and are not a new concept to humanity. For example, they were employed in building China's Great Wall. The Qin dynasty employed rammed earth for wall construction. During the Han dynasty, materials such as red willow, reeds, gravel, and sand were used to construct the walls [5]. By 1200 AD, the Mongolians used bows constructed from laminates of wood, silk, or animal tendons and horns. Natural polymers have been utilized for a long time; examples include paper and silk. Natural fibers have been employed as reinforcements since 300 B.C. Straw was used as reinforcement in clay to create composite bricks, which are still in use today [25],[26]. Messrs. Cladwell and Clay produced aeroplane airscrews in the 1920s using a natural cloth composite. Synthetic composites received little attention for structural purposes until the 1930s. De Bruyne had created a synthetic composite known as Gordon Aerolite. It was a composite made by pressing hot, unbleached flax yarn infused with phenolic resin. The Supermarine Spitfire fighter aircraft fuselage and the whole main wing spar of the Bristol Blenheim light bomber were made from this material [27]. Following World War II, the use of natural fiber composites declined significantly due to the introduction of synthetic polymers made from less expensive petroleum-based materials [28]. Natural fiber-reinforced composites were the focus of aircraft manufacturers' search for sustainable and lightweight materials towards the end of the 1990s [29]. Thus, contemporary bio-composites were born. Sustainable composite materials have garnered significant attention in recent decades as a means of reducing environmental carbon footprints. To create a completely "green composite material," the polymers known as biopolymers, which are derived from renewable resources, are employed as a matrix material and reinforced with natural fibers.

3 Classification of Composite

Composite materials are categorized based on the components that make them up, such as filler and base materials. The filler material may consist of sheets, fragments, particles, fibers, or whiskers composed of natural or manufactured substances. A matrix or binder material is the base substance that places the filler material in constructions. Based on their structure, composites are divided into three major groups, as shown in Fig. 3.

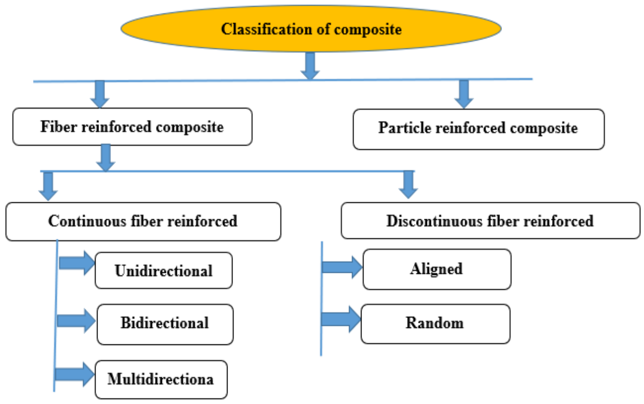

Fig. 3 Classification of composite materials

4 Types of Fiber Used in Composite

Various fiber types are available for composite materials; they can be classified as natural, artificial, or synthetic.

4.1 Natural Fibers

The naturally occurring component known as natural fibers (NFs) is abundant and readily available. They disclose several exceptional material attributes, including high strength, particular stiffness, low cost per unit volume, and biodegradability. NF reinforcement-based composites provide several advantages over synthetic fibers, including lower weight, price, toxicity, environmental pollution, and recyclability. For contemporary applications, NF composites are preferred over synthetic fiber-reinforced composites due to their advantages in both economic and ecological terms [30]. Natural fibers vary in content but share similar structures depending on the type. Table 2 compares the mechanical properties, advantages, and limitations of primary natural fibers (jute, sisal, coir, hemp) against synthetic fibers (glass, carbon) [31]-[35]. High-performance applications have been seen when long and short natural fibers are incorporated into thermoset matrices [31],[32].

4.1.1 Sisal fiber

Composites based on sisal fiber (SF) are frequently used for automobile interiors and furniture upholstery due to their superior tribological properties. Tensile strength rose with fiber volume in SFs reinforced with polyester composites, whereas polyethene (PE) composites reinforced with sisal fibers measuring 6 mm in length exhibited a tensile strength of 12.5 MPa [33]-[35].

4.1.2 Rice Husk

A natural covering called rice husk (RH) forms around rice grains during growth. Although rice husks are considered agricultural waste, they are utilized as reinforcement in composite materials [36],[37] to investigate the enhancement of material properties. Polyurethane (PU) foam with 5% relative humidity (RH) showed the optimum sound absorption capacity for enhancing the material's acoustic qualities [38].

4.1.3 Chicken Feather

After an impact test, a composite material that utilized 5% poultry feathers as reinforcement fibers and epoxy resin as the matrix material achieved the most favorable results. Additionally, a hybrid composite made of these chicken feathers, 1% carbon residue (CR), and epoxy resin significantly increased the material's tensile, flexural, and impact strengths [38].

4.1.4 Jute

Tensile strength and bundle strength of raw jute reeds have been observed to decrease with length; the composites based on the root portion of the reed have been found to have tensile and flexural strengths that are 44% and 35% higher, respectively, than those made from the tip portion of the reed [39],[40].

4.1.5 Coir Fiber

Polypropylene composites reinforced with randomly oriented coir fibers have better damping qualities than those reinforced with synthetic fibers. Greater damping qualities are provided by a high resin content, allowing for reduced fiber loading and increased energy absorption. The coir-PP composite attained a maximum damping ratio of 0.4736 at 10% fiber content; however, increasing the fiber concentration to 30% enhanced the material's natural frequency to 20.92 Hz [41],[42].

4.1.6 Palm Fiber

Palm fibers (PFs) demonstrated outstanding fiber-matrix interfacial contact. Furthermore, adding palm fibers to low-density polyethene (LDPE) increased Young's modulus compared to homopolymers [43].

4.1.7 Kenaf Fiber

Kenaf fiber laminates' tensile and flexural qualities are improved when absorbed water is removed from the fibers before lamination [44]. The flexural strength and flexural modulus of polyester samples without reinforcements were 42.24 MPa and 3.61 GPa, respectively. In contrast, the composite material showed flexural strength and flexural modulus of 69.5 MPa and 7.11 GPa after 11.1% virgin kenaf fibers treated with alkali were added to an unsaturated polyester matrix [45].

4.1.8 Hemp Fiber

The flexural strength of the hemp composite was determined to be 52% superior to that of the glass fiber-reinforced composite with a propylene matrix [46]. Flexural and tensile strength improved by 37% and 68%, respectively, in a composite material reinforced with 15% by weight of alkaline-treated hemp fibers and 5% by weight of maleic anhydride-grafted polypropylene (MAPP) combined with polypropylene (PP) matrix [47].

Table 2 Comparative analysis of natural and synthetic fibers. All data are cited from referenced studies.

Fiber Type	Tensile Strength (MPa)	Young's Modulus (GPa)	Key Advantages	Limitations
Jute	200–800	10–30	Low-cost, biodegradable	Moisture-sensitive
Sisal	300–700	9–22	High toughness	Lower UV resistance
Coir	100–220	4–6	Excellent damping	Low tensile strength
Hemp	300–900	30–70	High stiffness	Requires chemical treatment
Glass	2000–3500	70–85	Superior strength	Non-biodegradable
Carbon	3000–7000	200–500	Ultra-high stiffness	Extremely costly

4.2 Synthetic Fibers or Artificial Fibers

Synthetic fibers are produced through chemical synthesis and can be classified as organic or inorganic based on their composition [48]. Fiber materials generally exhibit significantly greater stiffness and strength than matrix materials, thereby serving as a load-bearing component within the composite structure [49]-[53].

4.2.1 Carbon Fiber

However, in specific applications, greater stiffness is needed. Hence, carbon fibers (CFs) are used instead of graphene fibers (GFs). In thermoplastic short-fiber-reinforced polymers (SFRP), other synthetic fiber types, such as basalt, aramid, polyethene terephthalate (PET-F), polyacrylonitrile (PAN-F), or polypropylene fibers (PP-F), are occasionally employed, albeit with some advantages; these applications are limited to the situations in which their desired properties are applicable [54]. Applications for carbon fiber-reinforced polymer (CFRP) composites have been found in a wide range of industries, including sports, automotive, aerospace, and many others [55]-[57]. The weight percentage of carbon fibers increased from 10% to 30%, resulting in a 78% and 113% increase in Young's modulus for solids and foams, respectively. Using carbon fiber/polypropylene (CF/PP) in microcellular injection-molded composite foams resulted in a 35% enhancement in the foams' Young's modulus, attributable to the optimized cellular architecture [58].

4.2.2 Basalt Fiber

Basalt fiber (BF) has superior mechanical and physical qualities compared to fiberglass. Furthermore, BF is a lot less expensive than carbon fiber. Several studies have investigated the effect of temperature on basalt fiber-reinforced polymer (BFRP) composite elements, and it was found that lower temperatures enhance the fatigue life and static strength of the material at a given maximum stress [59].

4.2.3 Glass Fiber

Among all synthetic fibers, glass fibers (GFs) are the most commonly employed because they possess superior strength, durability, thermal stability, impact resistance, chemical resistance, friction, and wear properties. Glass fiber-reinforced polymers (GFRPs) can be machined using conventional machining equipment. Still, the process is complex and sluggish, resulting in a shorter tool life [60].

4.2.4 Graphene Fiber

Compared to carbon fibers, graphene fibers exhibit superior electrical conductivity and a high tensile strength, making them a novel class of high-performance carbonaceous fibers. Graphene fibers exhibit numerous enhanced characteristics that suggest their applicability across various domains, such as micromotors, lightweight conductive cables and wires, knittable supercapacitors, solar cell textiles, and actuators [60],[61]. According to the molecular dynamics simulation, Young's modulus, shear modulus, and hardness of polymer composites containing graphene reinforcements increased by 150%, 27.6%, and 35%, respectively. Moreover, a 35% and 48% decrease in the coefficient of friction and abrasion rate, respectively, were accomplished [62].

5 Structure, Morphology, and Chemical Composition of Jute

Jute fibers are lignocellulosic because they come from jute plants [63]. Jute plants have multicellular jute fibers in the bast zone that ascend the stem [64]. A strand of jute fibers forms in the stem with these cementing components. The structure, length, and chemical composition of jute fiber are influenced by the growing environment, climatic conditions, flaws, plant maturity, extraction techniques, and modifications [65]. Lumens, center hollow cavities that form low-density fiber, are evident in jute fiber cells [66],[67]. The intermediate lamella, cellulose and lignin connect each fiber cell.

Jute fiber contains lignin and carbohydrates. Polysaccharides contain alpha and hemicellulose [68]. Jute fiber's cell wall is mostly cellulose, which is formed of glucose rings. Cellobiose is a glucose dimer unit that repeats itself and is generated by glucose rings [69]. Linear polymerizing glucose rings make each cell wall and strand of jute. Covalent bonds between these glucose rings contribute to their mechanical and physical properties [70]. This glucose's hydroxyl groups establish hydrogen bonds with the cellulose chain through interactions with other hydroxyl groups and water molecules. These hydroxyl groups generate hydrogen bonds, giving jute fiber its hydrophilic, crystallizing, and three-dimensional qualities. Hydrophilic cellulose dissolves in water. These elements cause cellulose to absorb water, leading to swelling [71]. Examining unit cells under a microscope revealed uneven crystallization of the fiber. Micro-fibril structures are highly organized and tightly packed, while fringed fibril zones are loosely packed and non-homogeneous.

Regions with high organization are crystalline, whereas non-homogeneous areas are amorphous. Plant length is affected by micro-fibril angle, mechanical, and physical properties [72]. There are four varieties of cellulose: I, I beta, II, and III. Cell walls can be primary or secondary. The primary cell wall is typically thin, whereas the secondary cell wall is characterized by its thickness, despite both being composed of microfibrils [73]. The original cell wall has crisscross microfibrils, but the second cell wall has highly organized ones [74]. Microfibrils include cellulose I alpha nanocrystals. Fig. 4 shows a jute fiber cross-section [75]. Lignin, cellulose, waxes, pectin, protein, nitrogenous chemicals, inorganic and mineral materials make up the majority of jute fiber. Alpha cellulose and hemicellulose are subtypes that change somewhat among plants and under various growing environments.

Table 3 An overview of the work done to enhance jute fiber adherence in the polymer matrix with environmental impact.

Type	Modification Performed	Polymeric Matrix Used	Results and Improvements on the Properties	Environmental Impact/ Sustainability	References
Chemical	Functionalization with maleic anhydride	Polypropylene	22% ↑ in tensile modulus, 12% ↑ in tensile strength; SEM: improved adhesion	Moderate (non-green reagent)	[82]
	2% alkaline treatment for 2 h + 3% oligomeric siloxane in epoxy	Epoxy resin	ILSS ↑ 99%, TM ↑ 70%, TS ↑ 41%, FS ↑ 29%; SEM showed small holes	Low (uses siloxanes)	[83]
	2% NaOH for 1 h, followed by silane treatment (γ-MPS)	Polyester resin	ILSS ↑ 97%, TM ↑ 45%, TS ↑ 58%; SEM confirmed enhanced adhesion	Moderate (silane use)	[84]
	Benzenediazonium salts in alkaline medium	Polypropylene	80% ↑ in TM and TS (at 35% fiber content), ↓ in impact strength	Low (toxic reagents)	[85]
	Potassium permanganate + silane + benzoyl peroxide	Polylactic acid	↑ TM and TS; thermal stability ↑; ↓ in impact strength	Low (strong oxidizers)	[86]
Physical	Gamma irradiation (500 krad)	Polypropylene	TM ↑ 17%, Impact strength ↑ 6%; SEM: increased surface roughness	High (no chemicals used)	[87]
	Oxygen plasma + low-ratio frequency treatment	Polyester resin	Improved matrix compatibility; performance ↑ 129%	High (clean tech)	[88]
	Electron beam irradiation (0–100 kGy)	Polylactic acid	ILSS ↑ 15%, TM ↑, TS ↑ 63%; better thermal stability at 10 kGy	High (non-toxic, clean)	[89]
Biological	Fungal treatment (Basidiomycetes, Ascomycetes, Zygomycetes)	Various polymers	Lignin degradation improves surface roughness and enhances mechanical bonding	Very High (natural biodegradation)	[90]

***TM:** Tensile modulus, **TS:** Tensile strength, **FS:** Flexural strength, **ILSS:** Interlaminar shear strength, **SEM:** Scanning electron microscopy.

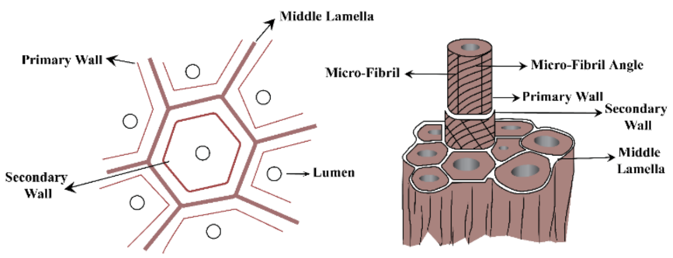

Fig. 4 Cross-section of jute fiber.

The primary component of jute fiber is cellulose. A jute fiber typically comprises the following elements: 59–63% alpha cellulose, 22–26% hemicellulose, 12–14% lignin, 0.4–0.8% waxes, 0.2–0.5% pectin, 0.6–1.2% mineral matter, and trace amounts of other substances [10],[76],[77]. The fundamental component of cellulose is glucose, which is hydrolyzed by acids but is not readily oxidized. Due to its branching structure, hemicellulose exhibits an amorphous quality. Hemicellulose is thought to be a binder for several jute fiber components, including lignin and microfibrils, while pectin provides flexibility to the plant structure. Additionally, trace amounts of jute fiber wax are insoluble in acids and water [23].

One of the most prevalent polymers is lignin, which contains both aromatic and aliphatic groups and is believed to have a complex three-dimensional structure [78]. Low levels of hydrogen and significant levels of carbon make up lignin [79]. Due to its carbon and hydrogen content, lignin contains hydroxyl, carboxyl, and methoxyl groups, contributing to its aromatic or unsaturated nature. Lignin is an amorphous, complex substance comprising methoxyl and hydroxyl groups that make up its basic unit cell. It is resistant to hydrolysis in acidic conditions but readily dissolves in alkaline environments and is subject to oxidation and condensation reactions [80]. Lignin has alkali-sensitive and alkali-resistant linkages that bind it to other jute fiber elements. In the alkali-sensitive linkage, lignin's hydroxyl groups combine with carboxyl groups in cellulose or hemicellulose; in the alkali-resistant linkage, lignin's hydroxyl groups combine with cellulosic components [81]. Lignin is hydrophobic and typically supports plants.

5.1 Surface Modification of the Jute Fibers

Fig. 5 illustrates the categorization of the modification treatments applied to the plant fibers. Depending on the matrix to be reinforced, these can be chemical or physical, suggesting a higher or lower efficacy in enhancing adhesion at the interface. Table 3 presents the most commonly used methods for improving the adhesion of jute fibers to the polymeric matrix. Table 3 illustrates that not all treatments are environmentally sustainable, especially when the objective is to develop a composite for particular applications, such as food packaging.

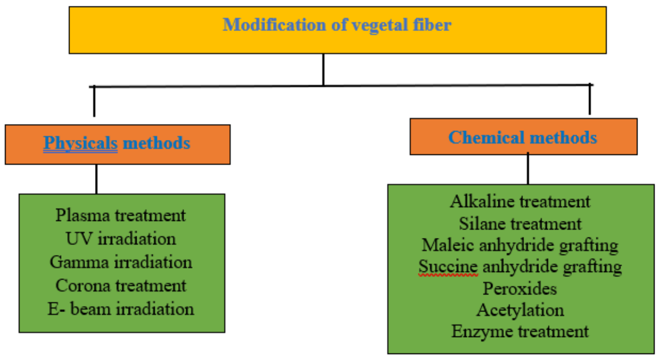

Fig. 5 Categorization of chemical and physical techniques used on vegetable fiber.

6 Properties of Jute Fiber

Table 4 provides a summary of the primary characteristics of jute fibers. The microfibrillar angle, defined as the angle formed between the cellulose microfiber and the axis of the cell wall, warrants particular attention. This value provides a great indication of the fiber's tensile strength. Poor mechanical qualities are caused by a high percentage of cellulose in the fiber with a high microfibrillar angle. The elastic modulus of cotton fiber, which has a microfibrillar angle of 20° to 30° and a cellulose content of over 90%, is 5.5–12 GPa, which is less than that of jute fiber, which has a cellulose content of about 70% and a microfibrillar angle of 7°–9°) [91]. These variations can result from the kingdom Plantae's specialization and evolutionary process. Jute fiber harvested from the plant has an initial length of one to four meters, but it can be altered to suit the needs of a particular product's production process. According to certain researchers, polymeric composites reinforced with natural plant fibers that haven't been treated before can be prepared [92]. In these situations, the fiber's properties are the only factors influencing the composite's behavior. Nonetheless, there was virtually little adhesion or impact strength between the phases. The tensile strength of polypropylene (PP) composites reinforced with 20 weight per cent untreated jute fiber was 45 MPa; however, gamma-irradiated composites containing up to 50 weight per cent of jute fiber were reported to have a tensile strength of 65 MPa.

Table 4 Physical and chemical characteristics of jute fibers [91].

Properties	Jute fiber
Diameter (μm)	50-100
Cellulose content (wt%)	60-70
Lignin content (wt%)	10-12
Hemicellulose content (wt%)	20-25
Pectin (wt%)	0.2-0.6
Waxes (wt%)	0.5-1
Humidity (wt%)	12.5-13.8
Microfibrillar angle (°)	7-10
Density (/g/cm^3)	1.3-1.55
Elongation at break (%)	7.0-8.5
Tensile strength (MPa)	399-776
Tensile modulus (GPa)	10-35

6.1 Physical and Mechanical Properties of Jute Fiber

Compared to other synthetic fibers, the all-natural fibers have unique thermal qualities and superior acoustic insulation because they are lignocellulosic. The mechanical attributes of synthetic fibers are often superior to those of natural fibers. Still, they can be further improved by treating the fibers' surfaces differently, such as silane or alkali. Natural fibers are highly sought after in the industry for the advancement of composites since they have high specific moduli, high specific strength, low densities, etc. Table 5 lists the necessary mechanical characteristics for jute fibers. Glass fiber has a greater tensile strength than plant fibers, yet natural fibers have a higher specific modulus than glass fibers.

Table 5 Characteristics of jute fiber as reported by various researchers.

Tensile strength (MPa)	Young's modulus (GPa)	Elongation atbreak (%)	Length (cm)	Diameter (cm)	Density (g/cm³)	Source
393-773	26.5	1.5-1.8			1.3	[10]
460-553	2.5-1.3	1.16	150-360	.005 - .028	1.3	[21]
393-773	2.5-26.5	1-2		.0025 -.02	1.3-1.45	[12]
400-800	10-30	1.5-1.8			1.46	[25]
393	55	1.5-1.8			1.3	[7]
394	55			.001		[18]
300-700	20-50	1.6-4.0			1.3	[26]
393-773	26.5	1.5-1.8			1.3	[27]
393	55				1.3	[1]

These factors explain why natural fibers are frequently utilized in green composites for various purposes [26]. Their fiber properties are the primary factors influencing the performance enhancement of natural fiber reinforced polymer-based composites. One study found that the moisture content significantly impacts the biological performance of natural fiber reinforced polymer composites [10]. Aspect ratio, micro-fibrillar angle, cell number, and crystalline cellulose content are the variables that affect the chemical characteristics of fibers. A smaller micro-fibrillar angle and a higher cellulose content are essential for high fiber strength. Aspect ratio is a standard characteristic of natural fibers [93],[94]. The researchers found that the Young's modulus, density, and tensile strength of jute fibers were the main physical and mechanical quality factors.

6.2 Processing Methods for Jute-Based Composites

Bio-composites are currently made using conventional techniques comparable to those used to create synthetic composites. The methods include molding, resin transfer, compression molding, extrusion, injection, spray lay-up, hand lay-up, filament winding, and pultrusion [95]. These methods are the result of years of research and industry experience. Although scientists have made many adjustments to these methods and have even created new ones, there is still room for significant advancement in the production of bio-composites that are both affordable and devoid of flaws. These procedures allow bio-composites to be created with little process modifications [10]. To guarantee that the fibers in the composite are properly dispersed, oriented, and have the appropriate aspect ratio for the intended uses, the processing path must be carefully chosen [96]. Selecting a manufacturing route also considers the composite's ultimate design, size, shape, raw material qualities, process speed, and total cost [68]. Superior mechanical attributes result from a high aspect ratio and homogeneous dispersion. The following factors affect production processes: fiber type, fiber orientation, fiber content, and moisture.

These elements likewise influence the ultimate characteristics of composites [68]. Moisture has a significant impact on final characteristics and processing factors. The fibers must be sufficiently dried before processing can begin. Several fiber modification techniques can also lower the moisture level [10]. The type of fiber and its contents are crucial for effective and appropriate processing. When processing bio-composites, temperature is the most critical component to consider. There is typically a limited processing window for natural fibers. Elevated temperatures may cause fiber deterioration [21]. In addition to having an availability of natural fibers, these processing methods must be highly efficient and easily scalable for the commercial manufacturing of bio-composites [97]. To compete with synthetic composites, natural bio-composites must maintain strong both functional and structural consistency during storage, during use, and during the last stages of environmental deterioration [65]. The primary benefit of processing natural fibers is that they do not severely damage the equipment. Since synthetic fibers are more abrasive than natural ones, processing tools and machinery will eventually endure less wear and tear [98]. A couple of things need to be considered before processing. Stresses created during manufacturing may cause the melt to solidify too soon. When the final shape solidifies, it may shrink by up to 8% [99]. Processing also presents the issue of agglomeration. The overuse of fiber is the root cause of this issue. Similar fibers tend to stick together, and this agglomeration can have a negative impact on the composite's final mechanical properties [21]. High melt viscosity affects both the finished product's homogeneity and process speed. The length of the fibers also impacts the end product's homogeneity [100]. Numerous additives can be used to address issues related to processing procedures; however, doing so will raise the cost of the process. Additives can cause new processing issues in addition to solving some existing ones. There are several approaches for producing bio-composites based on jute fiber; choosing the optimal one depends on certain end features. A homogeneous distribution of fibers throughout the matrix is one of the driving forces during processing. A polymeric matrix primarily determines processing temperature, while a homogeneous distribution of fibers guarantees superior mechanical qualities [92]. Moreover, a diverse array of methodologies has been established for fabricating bio-composites. Table 6 summarizes the key parameters of different fabrication methods of jute-based composites, whereas Fig. 6 depicts the various fabrication techniques of Jute-based composites.

6.2.1 Hand Lay-Up Method

One popular technique for creating various bio-composites is the Hand Lay-Up Technique, as shown in Fig. 6(a). Using rollers, this process applies resin to the fibers after they are placed in a mound. A vacuum technique is typically employed thereafter for curing. This procedure has several benefits, including simplicity, low processing costs, and the ability to produce intricate designs. However, it has some drawbacks, including labor-intensiveness and a lengthy processing duration [101]. It is practically impractical from an economic standpoint to use up to 400% more resin than fibers in fabricating jute fiber composites. In addition to using a lot of resin, the procedure can call for pre-treating the fibers, which would increase expenses. Abdullah-Al-Kafi et al. [102] created a composite consisting of glass and jute fibers using a hand lay-up technique. The composite containing 25% jute fibers exhibited superior mechanical capabilities. The ratio of glass fiber to jute was 1:3. Chaudhary et al. [63] developed a hybrid composite reinforced with epoxy composed of jute, hemp, and flax using the hand lay-up technique. The hybrid composite was made with fibers comprising 8% jute, 9% hemp, and 8% flax by weight.

6.2.2 Resin Transfer molding

Compared to manual lay-up methods, the process is thought to yield composites of a higher caliber. Resin transfer molding is a high-production-rate and cost-effective technique.

First, the resin material is injected into the closed cavity mold after placing the fibers. Curing is performed under low vacuum pressure, and due to the vacuum, it takes 30 to 60 minutes to complete. Before resin is injected, the fibers are inserted into the mold. The fibers will then saturate in resin following injection. Process parameters, including temperature, fiber percentage, injection and vacuum pressures, among others, determine the composite's ultimate mechanical and physical characteristics. This process is renowned for its high production rate and is well-suited for producing intricate shapes. In this method, low-viscosity resins are primarily utilized [20]. The distance between the fiber preforms and the mold cavity results in the observation of edge flow in composites. The smoothness and regularity of the flow pattern can be readily disrupted by edge flow, resulting in inadequate fiber wetting. Due to the distance between the fibers and the mold cavity, edge flow is observed in composites. Fig. 6(b) shows the resin transfer molding method for composite fabrication.

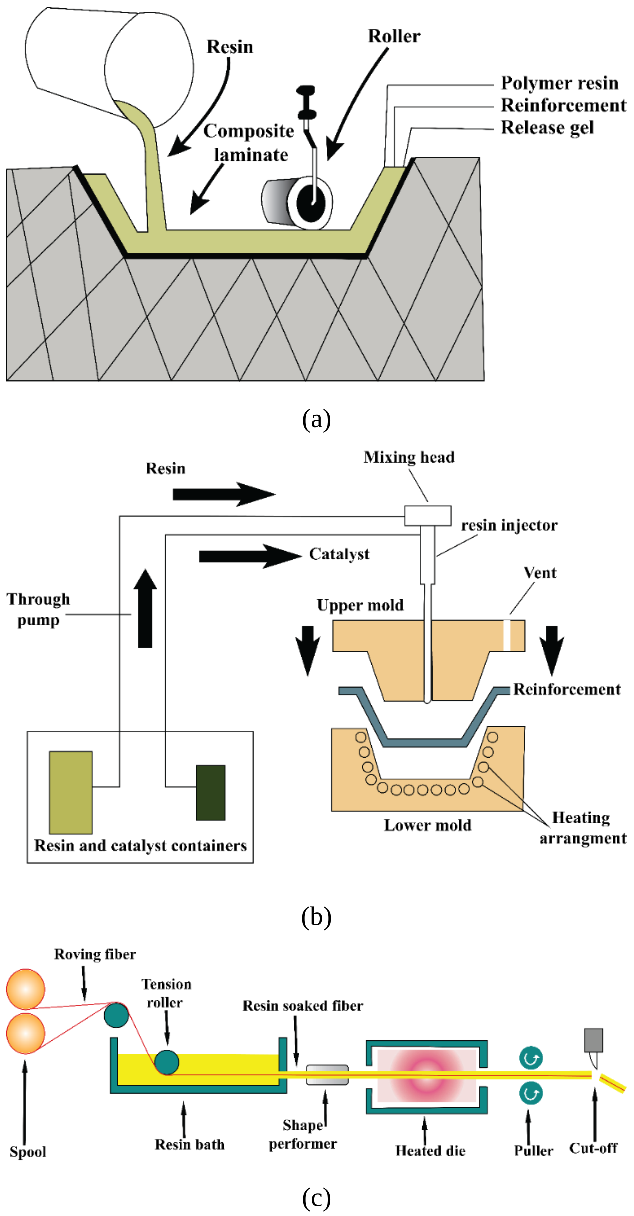

Fig. 6 Different fabrication methods (a) Hand layup (b) Resin Transfer Molding (c) Pultrusion

6.2.3 Pultrusion

Pultrusion, as shown in Fig. 6(c), is the most effective technique for creating composites with a narrow cross-section (Fig. 6(c)). This continuous manufacturing technique creates mats, ropes, yarn, and other products.

In producing jute-based polymers and composites, a resin ingredient is soaked with jute fibers, and the mixture is subsequently run through a heated die. Maintaining continuous fiber orientation during this operation is quite challenging. The method is well-known for producing intricate geometries and narrow cross-sectional shapes with high automation. This method yields goods made from jute with a jute fiber content of up to 70%. In contrast, this method's jute composites exhibit superior electrical insulation, mechanical properties, and corrosion resistance [20],[103]. A composite hybrid of jute and glass fiber reinforced with polyester was investigated by Akil et al. [104].

Table 6 The key parameters of different fabrication methods of jute-based composites

Method	Temp Limit (°C)	Typical Fiber %	Complexity	Cost	High-Volume Suitability	Environmental Impact
Hand Lay-Up	<150	10–30%	Low	Low	Low	Moderate
Spray Lay-Up	<150	10–25%	Medium	Moderate	Medium	Moderate
Compression Molding	140–180	20–50%	Medium	Moderate	High	Low
Injection Molding	180–220	<20%	High	High	High	Moderate
Resin Transfer Molding (RTM)	100–160	20–35%	High	High	Medium	Low
Extrusion	160–200	20–40%	High	Moderate	High	Moderate
Filament Winding	<150	50–70% (continuous)	High	High	Medium	Low
Pultrusion	120–180	50–70% (continuous)	High	High	High	Low

Pultrusion was used in the fabrication of the hybrid composite. The pulling speed for pultrusion was set at 180 mm/min, while the die temperature was maintained at 85 ◦C. The volume ratio of jute to glass fibers was established at 50:50, with the fiber-to-matrix ratio set at 70:30.

6.2.4 Extrusion

The most widely used method in the plastics sector is extrusion, which is renowned for providing a consistent mixing of all ingredients. Because the fibers are dispersed randomly, this approach works well for producing composites where fiber orientation is irrelevant. Single or twin screws that can revolve both clockwise and counterclockwise are utilized in this technique. Because of its low mixing effects, a single-screw extruder is employed in applications where minimal mixing of the matrix material and fiber is necessary. High thrust forces and an excellent mixing effect are characteristics of a twin-screw extruder, which help to spread fibers throughout the composite evenly. Ballets are frequently introduced into a heated chamber through feed screws to facilitate the processing of molten mixtures. Up to 40% of jute fibers are incorporated with a polymeric matrix during the extrusion process in the production of jute composites. After this process, post-processing procedures can be applied to the final output to get a higher quality.

Processing also presents the issue of agglomeration. The overuse of fiber is the root cause of this issue. Similar fibers tend to stick together, and this agglomeration can have a negative impact on the composite's final mechanical properties [21]. Strategies such as surface modification of fibers (e.g., alkali treatment), use of compatibilizers or coupling agents, and applying mechanical stirring or high-shear mixing during compounding can mitigate agglomeration. The pre-dispersion of fibers into a carrier resin before complete mixing is also widely used to ensure uniform fiber dispersion.

High melt viscosity affects the finished product's homogeneity and process speed. The length of the fibers also impacts the end product's homogeneity [100]. To overcome high melt viscosity, manufacturers may reduce fiber length within allowable limits, optimize the polymer matrix composition (e.g., blending with lower-viscosity resins), or increase processing temperatures within safe thermal limits for the fibers. Additionally, plasticizers or processing aids can enhance flow characteristics without significantly compromising mechanical strength.

Numerous additives can be used to address issues related to processing procedures; however, doing so will raise the cost of the process. Additives can cause new processing issues in addition to solving some existing ones.

6.3 Jute Fiber Composites

Jute and soy milk composites were produced through compression molding, utilizing woven and non-woven jute fibers as reinforcement materials.

These composites' mechanical properties included stretch at the break, tear strength, flexural modulus, and tension strength. Composites reinforced with 60% jute felt or cloth yielded the best results. Many studies have studied the breakdown of jute composites in compost soil burial circumstances. Composites made of polymers are environmentally damaging plastic and plastics-reinforced composites in cars, toys, furniture, and tennis balls [105]. Composite materials and polymers are processed like bio-composites. Other names include thermoplastic bio-composites and thermosets. Hand lay-up, resin transfer, and compression molding were used to make thermoset composites using natural jute fiber reinforcement. Press molding and pultrusion were used for short and sliced NFs filament winding. Polypropylene composites reinforced with natural fibers are compounded and extruded [106]. The most common thermosets are unsaturated polymers, phenols, and epoxies. The most common thermoplastic matrices are elastomers, polypropylenes, and polyethylenes [107]. Several researchers have proposed jute fiber composite production methods. Gomes et al. [108] presented the direct, pre-forming, and prepreg sheet methods. Other methods for green composites involve vacuum-assisted resin transfer molding, injection molding, and manual lay-up with compression molding [109],[110].

The choice between thermoplastic and thermoset matrices in jute fiber composites significantly influences the final product's mechanical properties and application scope. Thermoplastics, such as polypropylene and polyethylene, offer advantages like recyclability, ductility, and ease of processing, making them ideal for automotive parts and packaging. In contrast, thermosets such as epoxies, phenolics, and unsaturated polyesters provide superior dimensional stability, thermal resistance, and load-bearing capacity, essential in structural and aerospace components. However, thermosets are not reprocessable after curing, limiting their recyclability. Combining thermoplastic and thermoset matrices, hybrid composites can balance these properties, enhancing strength and environmental performance simultaneously. The matrix selection thus depends on the desired trade-off between performance, cost, and environmental impact.

6.3.1 Jute Fiber Reinforced Thermoplastics Composites

The process of creating woven PLLA composites reinforced with jute fiber involved the use of hot press molding. Compared to non-woven composites, Woven jute fiber demonstrates enhanced mechanical performance under tensile, flexural, and impact loads. As a result, high load-bearing applications can use woven jute fiber composites based on PLLA due to their increased strengths [111]. Composites made of PLA and jute fiber have improved mechanical qualities. Due to the higher strength of ramie fiber over jute fiber, PLA/jute has less mechanical qualities than PLA/ramie; nonetheless, adding fiber lowers the PLA-based composites' breakdown temperature [112]. Previously, studies have developed fully biodegradable NFRP composites utilizing eco-friendly materials and analyzed their mechanical properties with variations in the fiber volume fraction. The findings indicate that hot pressing felt creation and fiber mixing can fabricate materials with a high jute fiber volume fraction. This approach allows for a homogeneous mixing of the fibers. Tests have been conducted on the composite materials' mechanical properties. Observations using a scanning electron microscope also show good adherence [113],[114].

6.3.2 Jute Fiber Reinforced Thermosets Composites

A class of natural fiber called woven jute fibers is gradually being used to compare with glass and carbon fibers used in polymer matrix composites. This type of polymer composite uses epoxy as the general matrix and jute fibers as reinforcement. The majority of researchers conducted their studies using operational parameters and discovered that as the volume proportion of jute fibers in the matrix increases, so does the rate at which moisture diffuses into composites [115]. Researchers looked at how the curing temperature affected the mechanical properties of composites made of jute fiber and epoxy. They discovered that the best curing temperature for epoxy composite development is 100°C, where tensile and flexural strength are at their highest compared to other curing temperatures between 80°C and 120°C.

6.3.3 Jute Fiber Hybrid Composites

Hybrid composites containing jute fibers mix matrix and reinforcing elements. Researchers have usually constructed hybrid composites with a polymer matrix, jute fiber, and another natural fiber as reinforcement. One study used unsaturated polyester as a matrix and kenaf, jute, and bamboo as reinforcement. Hand lay-up and compression molding developed composites. According to mechanical tests, the tensile moduli of jute/unsaturated composites and bamboo/unsaturated polyester composites are comparable to kenaf [116]. Woven glass fiber and epoxy-based hybrids of jute fiber composites were developed. The composite's elasticity increases with the glass fiber volume fraction. Flexural and impact strength are higher in jute/glass woven composites [117]. Natural fibers absorb moisture, which is problematic for materials that touch the environment. As water absorption increased, the flexural and compressive strength dropped. Hybridizing biological and synthetic fibers reduces moisture absorption, thereby improving the mechanical characteristics of the composite [118]. NFs such as sisal and cotton with glass fiber composites are more common than synthetic fibers. Composite glass fiber-sisal/jute-reinforced epoxy-based materials were made and studied. Jute-GFRP composites perform effectively under flex load, and sisal-GFRP composites under tensile load. GFRP performs better than NF composites [119],[120].

6.3.4 Jute Fiber-Reinforced Biodegradable Polymer Composites

Composites called "jute fiber reinforced compostable polymers" use biodegradable polymers as the matrix and jute fibers as reinforcement. Many biodegradable polymers are available, including PLA, PVA, and PHB. These polymers have been used in a lot of research, but there is still more to learn, especially about machining biodegradable polymer composites. A few researchers examined how natural composites with fiber reinforcement decomposed and how age affected their water, enzyme, and soil solubility [121]. Many industries now use biodegradable polymers instead of conventional materials. Jute fibers are the lightest and eco-friendly natural fibers. PLA's tensile, thermal, and processing properties and biodegradability make it a promising non-petroleum-based biodegradable polymer. PLA films coupled with woven jute fiber in mat form can be used to generate renewable and biodegradable composting bags, service ware, and films by stacking films. SEM of the composites' fracture revealed vapors [40]. Finally, woven jute fiber composites made from PLLA may outperform synthetic fiber composites [111]. PLA and jute spun yarn unidirectional composites were made via compression molding. Before the preparation of specimens, the wound-paralleled yarn underwent a drying process in a convection oven at a temperature of 80° C for two hours. Molding temperature affected the mechanical properties of unidirectional composites. Raising the curing temperature enhanced impregnation quality, improved fiber dispersion, and increased the attainment ratio of elastic modulus. The tensile strength achievement ratio decreased as the molding temperature increased due to the breakdown of jute fibers [122]. Degradation refers to the process by which biological environments break down chemicals. Natural fibers and polymers can degrade aerobically or anaerobically. Fig. 7 shows that decomposable monomers and natural fibers originate from regenerated cellulose or starch.

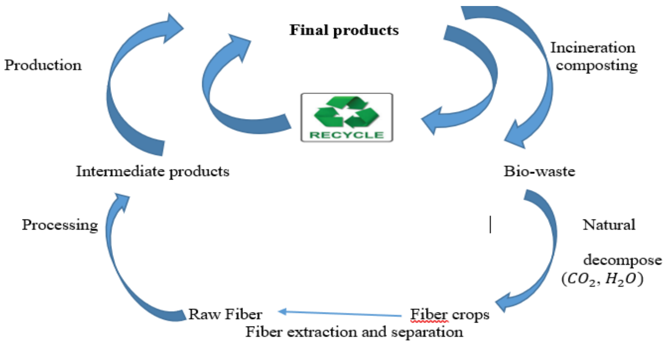

Fig. 7 Life cycle diagram of composite materials made of natural fibers and polymers.

The noteworthy aspect of green composites is their biodegradability. Fig. 7 illustrates how a product composed of green composite can be entirely dissolved and left as carbon dioxide and water after its useful life has ended by being buried in the soil. This full bio waste can also be used as fertilizer for fiber crops to complete the life cycle without harming the environment.

Table 7 presents a comparative analysis of various jute-reinforced polymer composites, focusing on the fabrication methods employed, types of matrix materials used, and the resulting mechanical, thermal, and water absorption properties [119]-[121].

7 Emerging Applications of Jute Fiber

Jute fiber is a crucial bio-composite component due to its many uses. Jute fiber's physical and mechanical characteristics are superior to those of other natural fibers. The nations of Bangladesh, Indonesia, Malaysia, and Sri Lanka have abundant jute fiber plants. Jute fiber is used in the textile industry to create various items, including clothing, ropes, sheets, bags, containers, shoelaces, and more. Interestingly, jute fiber makes door panels, panel components, and cup holders in the automotive sector.

Table 7 Comparative overview of Jute-reinforced polymer composites and their fabrication processes.

Jute Composite	Fabrication Method	Key Parameters and Findings
Jute reinforced epoxy composite	Hand lay-up	The mechanical and water absorption properties of treated and untreated samples were studied.
Jute/glass epoxy composite	Hand lay-up	Jute and glass fibers were used in
Jute/Epoxy glass composite	Hand lay-up	Homogeneous thickness of samples was obtained through the compression technique.
Jute/kenaf fibers reinforced epoxy composite	Hand lay-up	Samples were prepared using 56% jute and kenaf fibers, 40% epoxy, and 4% hardener.
Jute reinforced polyester resin	Hand lay-up	Composite samples were manufactured through hand-lay-up techniques and tested for various mechanical properties.

Many significant American corporations create automotive parts from jute, hemp, and flex [123]. Jute fibers can help automakers reduce weight and boost fuel efficiency. Major automakers like Mercedes and BMW are sponsoring research and development to maximize natural fiber utilization in their cars. Jute fibers are replacing synthetic fibers in packaging. Medical, cosmetic, and paint industries employ them for various applications.

Several industrialized nations are taking considerable steps to integrate natural fibers into their companies to promote a clean environment. Many buildings employ jute fibers for windows, doors, floor mats, walls, and ceilings. They're used to make tables, chairs, and cookware. Due to environmental concerns, European governments are scrambling to adopt natural fibers like jute fiber. Many governments and private entities have worked together to commercialize these fibers. Consumer items and agriculture use jute fiber for many applications. In the coming years, natural fibers like jute fiber, which have many uses, will become more popular. Jute, one of the most extensively utilized fibers, needs a lot of manual labor to be appropriately used in many applications. Jute fiber's delayed commercialization was due to its poor processing, inferior mechanical and physical properties compared to synthetic fibers, and elevated expense of composites [20],[124]. Research is being done to make jute fiber more useful. Many industries are interested in jute fibers due to their many uses. Asia has dominated jute fiber production, and new markets are emerging. Due to its many uses, jute fiber is projected to rise in demand soon. Buyers choose jute fiber composites because they are environmentally friendly. Fig. 8 shows the usage of jute composites.

Scientific research has spent the last several years primarily creating jute fiber-reinforced polymer composites and examining their mechanical and structural properties, and physical characteristics for a range of applications in several industries, including sports, fashion, packaging, home furnishings, automobiles, construction, textile products, and defense [15],[18],[125]. Since jute fiber emits oxygen, absorbs carbon dioxide, and uses less energy during product production, jute-based products are superior than synthetic ones in terms of sustainability. Jute fiber is being studied, though, to expand the range of applications. Jute fiber can be used to create various products in the future, as shown by these examples.

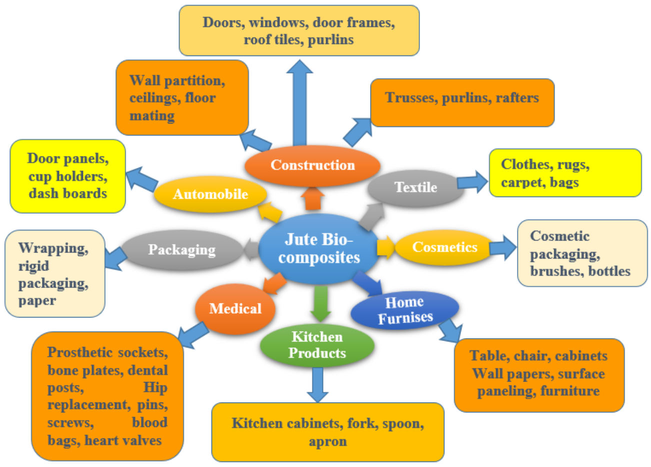

Fig. 8 Applications of jute-based composite materials

7.1 Nanomaterials from Jute

Nowadays, jute fiber can be mechanically and chemically processed to create nanoparticles. Charcoal, MCC, CNC, and CMC may all be made into nanoparticles that can be utilized as standalone particles or combined with polymer matrices to be employed in various industries, including food packaging, medicine delivery, heavy metal absorption, etc.

Because of its unique qualities, such as its high surface area, attractive surface chemistry, crystalline structure, potential rheological qualities, capacity to absorb water, barrier qualities, and nontoxicity, nano-cellulose is a good fit for use in food packaging and film applications [126].

Because jute and its constituents are capable of absorbing things, absorbing materials based on jute-based nanoparticles can be produced for the effective separation of heavy metals [127]. Moreover, the nanocomposite film demonstrated improved strength and physical characteristics upon incorporation of nano-cellulose into the matrix material [128],[129]. Better mechanical qualities can result from improved matrix interaction when enough cellulose nanofibers are present. Recent work discusses the potential uses of jute fiber in various additional nano-technological applications [130].

7.2 3D Printing with Jute

Though its use is constrained by the materials it can print in and the pace at which it can produce, 3D printing has proven helpful in generating objects with intricate shapes that eliminate the need for assembly [131]-[134].

A few polymeric materials could be printed with 3D printing at first. However, thanks to scientific advancements, materials including metals, ceramics, and composites can now be printed in powder or filament form. Complex shapes are difficult to fabricate using conventional methods; here is where 3D printing comes into play. Composite filaments can be created using jute fiber to print jute-based items. The processes involved in producing 3D printed bio-based jute composite are depicted in Fig. 9.

Using fused-deposition modelling, Matsuzaki et al. [135] developed a novel technique for 3D printing continuous jute fiber-based PLA thermoplastic composite in which the twisted jute yarns and the polymer filament were fed to the printer separately. The fibers served as a reinforcing substance within the matrix, although they were not firmly embedded. A PLA composite made of carbon fiber was also created using the same process for comparison.

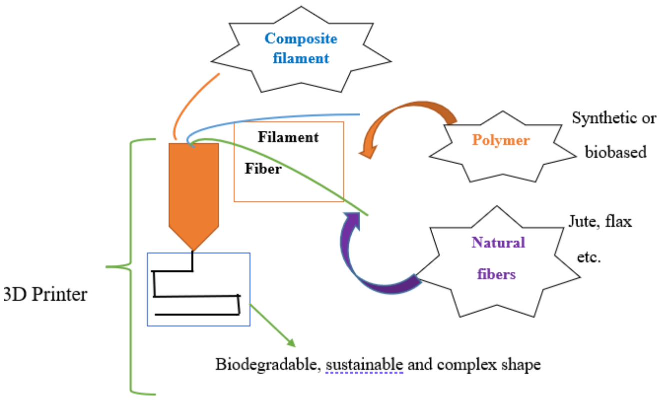

Fig. 9 Incorporating natural fibers into 3D printing filament.

While the jute fiber-reinforced composite outperformed the pure polymer regarding tensile strength, it still fell short of the carbon fiber-based composite. Jute fiber has a relatively low volume fraction of 6.1%.

Nevertheless, considerable success was obtained when PLA was coated onto flax fiber via an extrusion method, and the resulting continuous flax fiber/PLA composite filaments were then printed using a basic 3D printer [136]. An irregular distribution of the yarn within the matrix was noted in the printed samples. A significant improvement was seen in comparing the obtained tensile strength and modulus to previous data on 3D printed continuous natural fiber printed composites.

The mechanical strength and fracture characteristics of FDM 3D printed ABS, including different fillers, including five weight per cent jute fiber, were compared by Perez et al. [137]. Despite having jute fibers embedded in the ABS matrix, the jute-ABS composite's strength was somewhat lower than that of pure ABS. Indicators of increased porosity and inadequate bonding could be the reason for the subpar outcome. Incorporating nanofiber/cellulose or activated carbon from jute fiber into 3D printer filament can enhance its application in medical devices, packaging, and aerospace, including scaffolding [138]. Jute fiber treated with an antibacterial chemical can be encapsulated in polymers to provide a long-lasting, slow-release antibacterial action. Thus, 3D-printed objects made of jute fiber have the potential to open up entirely new research avenues.

7.3 Sensing, Energy Storage, and Electronics

Jute fiber can be converted into activated or non-activated carbon through chemical or physical activation processes, or paralysis without such activations. It has hemicelluloses, cellulose, lignin, and a little ash. Jute-derived carbon has narrow porous structures and an extensive surface area due to its capacitance, filtration, and electrical properties, making it useful for energy storage, water purification, and sensing [139]-[142]. Jute fibers were treated with KOH at 700 °C to make hydrogen-storage activated carbon [143]. Increasing the surface area and microspore volume of activated carbon-retained channel-like fibrous structures is suggested to increase the capacity for hydrogen storage.

A recent investigation explored using micro-mesoporous carbon derived from jute fiber as an anode for lithium-ion batteries [144]. Manjakkal et al.'s [145] energy-autonomous system had temperature and humidity sensors and a jute fiber supercapacitor (SC). Solar cells charged the SC, which powered the bio-based sensor. This technique could be used in innovative packaging for food safety tracking, as a wearable, and as a green choice. Solar cells charged the SC, which powered the bio-based sensor. This technique could be used in innovative packaging for food safety monitoring and wearables as a green choice. Jute fiber was added to PVA, MLG, and MWCNT to make biodegradable conducting composites of polymers [146].

The composites remained viscoelastic, as indicated by dynamic mechanical analysis. The composite also shielded electromagnetic interference and had high electrical conductivity. Delignified jute fiber was used to create Transparent Jute Fiber (TJF) to replace transparent wood since it mimics its properties [147]. LEDs and solar cells are electronic devices that can employ TJFs because of their good visual and mechanical properties, ease of manufacture, and cheaper processing costs [148]. Various reusable transparent films were produced from waste jute fibers through ionic liquid (IL) assisted restoration [149]. These moves may appear in packaging or data-saving devices. Thus, innovative jute-based materials will soon open new research avenues.

7.4 Biodegradable Packaging

7.4.1 Sonali Bag—Resolution for Single-Use Plastics

In recent years, single-use synthetic plastics, including plastic shopping bags, have become integrated into everyday life. Nonetheless, there is rising worry worldwide that its unchecked release into the environment may seriously harm marine life, contribute to global plastic pollution, and upset the ecology.

In the future, single-use plastic will be outlawed in many nations, especially in Europe, and replaced with more ecologically friendly biobased and biodegradable materials [150]. The "Sonali Bag," an economical biodegradable alternative to polyethylene bags, may decompose in soil within three months. A team in Bangladesh recently developed it using modified jute cellulose.

Its mechanical and physical properties were on par with or better than those of synthetic polyethene bags [151]. This innovative biobased packaging has the potential to completely transform the global packaging market and address the growing issue of plastic pollution (Fig. 10). Manufacturing a large quantity would achieve the economic success of this sort of product at a low cost.

7.5 Bioactive Jute for Food Packaging

Red Grape Pomace Extract (RGPE) activated jute fiber in response to the demand for eco-friendly food packaging [152]. Jute fiber impregnated with RGPE shows antibacterial and antioxidant qualities against Staphylococcus aureus, Escherichia coli, and Pseudomonas aeruginosa, indicating that it might be utilized as a food packaging material with better preservation. Research on natural reagents is crucial to the creation of sustainable products.

7.6 Replacement of Cotton/Wool (Absorbent Cotton for Sanitary Products and Medical Disposables)

In response to heightened demand for hygiene and wound dressing products, jute presents a cost-effective alternative to cotton fiber in disposable absorbent goods (Fig. 11). Lower-quality jute can undergo chemical processing to transform into absorbent cotton, suitable for applications such as bandages, sanitary napkins, and baby napkins. To produce these products, jute fiber must be treated with antibacterial and antifungal chemicals. $AgNO_3$ and Co are used to increase antibacterial activity.

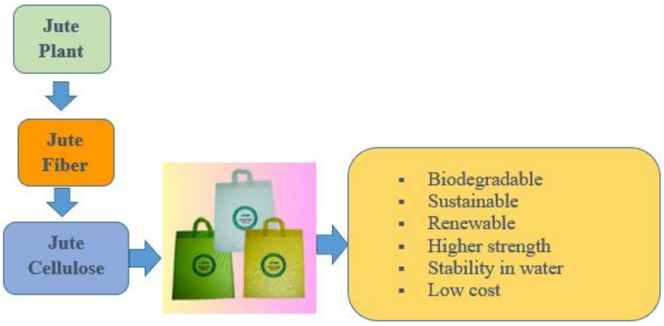

Fig. 10 Manufacturing process of eco-friendly polybags using Jute

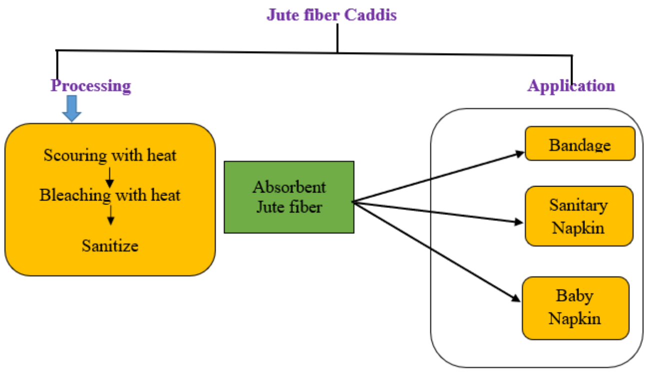

Fig. 11 Jute fiber is processed into an absorbent product resembling cotton and is utilized in medical accessories and personal hygiene items.

Several researchers have begun feasibility studies [153]. Sharma et al. [154] used waste jute and Superabsorbent Polymer to create reusable towels that absorb water better. Much research has shown that jute and SAP can make cheap sanitary pads. A recent survey [155] found that women prefer jute hygienic pads. More research is needed to sell jute-based absorbent products. Therefore, medical device research and development can be done on this topic.

7.7 Jute-Cotton Blending

According to recent studies, jute and cotton can be combined to create sustainable textile goods. Durable goods like polo sweaters and jeans have already incorporated mixed cloth [156]. To make jute fiber softer, it is typically treated with chemicals and bleached. Jute-cotton blended textiles are the subject of research to introduce various functional features through surface treatment applications. For example, wicking and dyeability properties are enhanced by atmospheric plasma treatment, while antibacterial properties are added through chitosan treatment [157],[158]. Jute and other natural fibers can reduce ecological, water, and CO_2 footprints [159] which will benefit the environment in general. Additional advantages of blending jute and cotton are less reliance on cotton, cheaper textile production, increased jute utilization, support for the domestic economies of jute-producing nations, and reinforcement of the garment industry in lower-middle-income nations such as Bangladesh [160]. Westerners are gradually moving toward wearing clothing made of more environmentally friendly fabrics. As a result, jute-cotton blended product sales are anticipated to expand significantly soon.

7.8 Woolenization

Through the simple application of an alkali treatment, jute fiber can be transformed into a substance resembling wool, a process known as "woolenization." It was discovered that making such a transformation was feasible by significantly altering the jute structure using a 15% NaOH treatment [161]. Developing commercial prototypes, such as handbags, proved this technique's efficacy. However, more work needs to be done to identify market prospects and expand jute's applications in the fashion business.

7.9 Jute Engineered with Nanomaterials

Recent research has explored engineering jute fibers with nanomaterials to expand their application potential, particularly in high-performance composites and innovative materials. These efforts mitigate limitations such as jute's lower mechanical strength, moisture sensitivity, and weak interfacial bonding with polymer matrices. Functionalization using nanoparticles (NPs) has emerged as a promising strategy to enhance these properties and introduce new functionalities, such as electrical conductivity, thermal resistance, and flame retardancy.

The following subsections provide detailed insights into two significant nanomaterial modifications of jute fibers: the incorporation of graphene-based materials and carbon nanotubes (CNTs), highlighting their processing techniques and performance benefits in composite systems.

7.10 Graphene

Recent research, especially at the University of Manchester, has involved functionalizing jute fiber with graphene or graphene-like compounds [162]-[166]. A modified jute fiber and epoxy composite outperformed other natural composites in mechanical qualities. Compared to untreated jute fiber composites, stiffness and tension strength increased by 324% and 100%. The jute fibers' individualization, superior packing, a new fiber structure within the composites, and strong matrix attachment contributed to this improvement. Grafted jute fiber and graphene oxide nanoplatelets (GONPs) formed a thermoplastic (polypropylene) composite [167]. The results showed that the matrix and surface-treated jute fiber interlocked to boost the composites' mechanical and thermal properties. This material could replace GFRP or CFRP in transportation, aviation, architecture, and household goods. Composites with diverse matrix constituents can be functionalized by jute fiber with graphene. Nano-engineered jute fiber may be used in electronics. Thus, the jute study will enter a new phase and may rekindle academic interest.

7.11 Carbon Nanotubes (CNT)

With the aid of oxygen plasma, carbon nanotubes can be coated using the dip-drying process [168] This method creates a coating that is consistent, effective, and firmly adhered to the jute fiber surface to make jute fibers conductive. The coating improves the modified fibers' mechanical strength and crystallinity. Functionalizing jute fiber resulted in notable improvements in its electrical conductivity, thermal stability, and flame-resistant properties. Functionalizing jute fiber with carbon nanotubes (CNT) may unveil novel applications in advanced electrical and electronic systems.

8 Drawbacks, Challenges, and Future of Jute Fiber

Jute fibers have been widely explored for real-world applications, but there are still numerous difficulties in fully realizing their benefits. Jute fibers are hydrophilic and have poor adhesion to other fibers in a matrix, poor dispersion, low physical and mechanical properties, flammability, limited thermal characteristics, a narrow processing temperature window, and few processing methods [169],[170]. Natural jute fibers include oils, waxes, lignin, and tannin. Jute fiber has low fire resistance because of these components' intense flammability and combustion under ideal conditions. Fire is a significant barrier to employing these fibers. Even though flame retardants appear to improve these fibers' flammability, additional study is needed to solve this problem. Due to its high cellulose content, jute fiber burns quickly [171].

Jute fiber degrades easily at 450˚C, limiting its usage in low-temperature applications. This deterioration will substantially change the fiber's mechanical and physical properties [77]. Depending on the plant and environmental circumstances, Jute fiber has different amounts of fiber, such as cellulose, pectin, oil, and wax. These quantities, fiber orientation, and structure affect heat and fire properties. Fibers with high levels of cellulose are less fire-resistant than those with low lignin [172]. The lack of jute-based bio-composite manufacturing technologies is another issue. Conventional methods are favored for creating synthetic materials and polymers with minor changes. New processing processes for jute bio-composites are being developed to ensure efficiency.

Jute fibers have been widely explored for real-world applications, but numerous challenges hinder their full potential. Key limitations include hydrophilicity, poor adhesion to matrix materials, inadequate dispersion, suboptimal physical/mechanical properties, flammability, limited thermal stability, a narrow processing temperature window, and a lack of diverse processing methods.

Fire Resistance and Mitigation Strategies: Natural jute fibers contain oils, waxes, lignin, and tannins, contributing to their high flammability. The high cellulose content further accelerates combustion. While flame retardants (e.g., ammonium polyphosphate, boron compounds, or nanoclays) can improve fire resistance, their effectiveness depends on fiber treatment methods (e.g., chemical grafting or coatings). Recent advances include:

Intumescent coatings: Forming a protective char layer to delay ignition.

Hybrid treatments: Combining flame retardants with silica nanoparticles for synergistic effects.

Bio-based solutions: Using lignin-derived additives to enhance fire resistance while maintaining sustainability.

Further research is needed to optimize cost-effectiveness and environmental impact.

Moisture Sensitivity Beyond Surface Treatment: Jute's hydrophilicity leads to swelling and reduced mechanical performance in humid environments. Current solutions (e.g., alkali treatment or silane coupling agents) address surface adhesion but fail to prevent bulk moisture absorption entirely. Emerging approaches include:

Polymer encapsulation: Embedding fibers in hydrophobic matrices (e.g., polypropylene or epoxy).

Nanocellulose reinforcement: Blending jute with cellulose nanocrystals to reduce water permeability.

Cross-linking agents: Covalent bonding with citric acid or maleic anhydride to limit water diffusion.

Insufficient Product Diversity: The limited range of jute-based products stems from reliance on conventional processing methods (e.g., hand lay-up or compression molding). To expand applications, the following strategies are critical:

Advanced manufacturing: Adopting 3D printing and automated fiber placement for complex geometries.

Hybrid composites: Combining jute with synthetic fibers (e.g., glass/carbon) for tailored properties.

End-use diversification: Exploring jute in automotive interiors, construction insulation, and fire-retardant textiles.

8.1 SWOT Analysis of Jute Fiber

In recent years, there have been notable breakthroughs in studies and commercial applications of jute fiber, its derived materials, and related composites. These advancements have been observed in several industries. Fig. 12 shows a SWOT analysis of the jute fiber as an industrial raw material, focusing on its benefits, disadvantages, possibilities, and threats. This list is not comprehensive and does not include all the pros, downsides, opportunities, and hazards. In future decades, the items indicated in the potential and vulnerability sections are predicted to grow, while those listed in the threat sections are expected to decrease. This section summarizes the primary issues with natural fibers, especially jute fibers, and possible solutions [173].

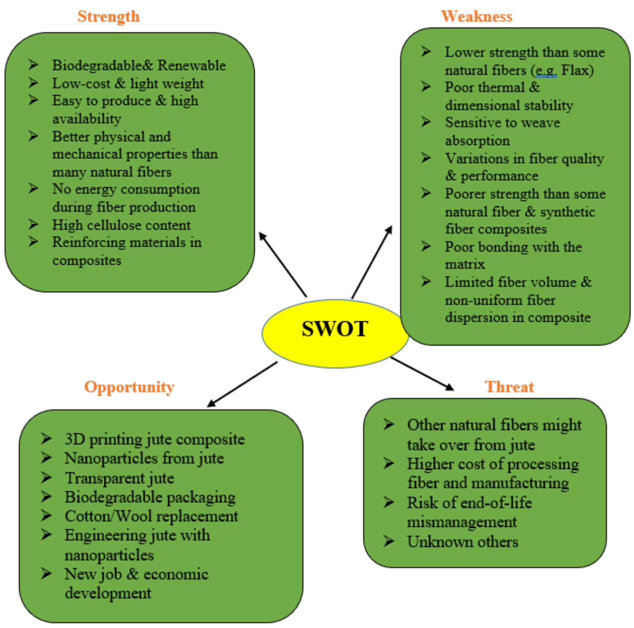

Fig. 12 Analysis of SWOT (strengths, weaknesses, opportunities, and threats) related to jute fiber and its associated products.

8.2 Challenges in Composite Processing

A significant challenge associated with utilizing conventional composite production methods is the need for a consistent ability to generate superior composite products composed of jute. To create exceptional products that are consistent and rich in fiber, it is necessary to develop novel composite processing techniques that priorities the optimization of processing conditions. One method to enhance the fiber ratio to volume in a composite is to replace the usual granules, sheets of paper, or plate shapes of the matrix with fiber. Developing innovative technology is crucial to ensure the quality of composites. Minimizing the manufacturing cost or price per unit while enhancing product quality is necessary. Despite several efforts to produce jute composites utilizing the 3D printing technique, problems related to insufficient fiber content and the generation of empty spaces still require resolution.

8.3 Insufficient Product Diversity

The small selection of goods linked to jute and its low market share globally might result from poor overseas promotion and a lack of product diversity. New ideas with particular purposes must be developed for luxury and generally used products. Two fresh concepts for jute-based goods that have attracted much research attention are the creation of nanocomposite materials and the replacement of cotton; yet, for commercialization, the knowledge gained in the lab must be implemented in the industry. There is much marketing work to expose the jute goods to dealers and overseas consumers. One approach to achieving this is participating in worldwide trade events like the Dubai Expo in 2021–2022.

This will open possibilities for research initiatives involving global partners and attract foreign investment for jute-based product development. Bangladesh and India, two of the biggest jute exporters, should cooperate on collaborative investigation initiatives to provide fresh ideas that will help diversify jute goods in worldwide markets. The nations that grow jute may cooperate to implement laws enabling its greater application in both home and foreign markets. New technology used in producing fiber and composites is anticipated to enhance product quality and expand the market for jute goods.

8.4 Circular Economy, Biodegradability, and Recycling Issues

Despite the financial and environmental appeal of natural fiber-reinforced composites (NFRCs), significant end-of-life (EoL) challenges remain. A primary concern is the recycling limitations, especially for composites made with thermoset matrices. Due to their irreversible cross-linked structure, thermosets cannot be remelted and reshaped like thermoplastics. Consequently, these materials are often landfilled or incinerated, leading to a loss of material value and environmental burden.

Mechanical recycling is one of the most feasible approaches for jute-based thermoplastic composites. It involves shredding and reprocessing the material, typically degrading properties due to fiber damage and polymer degradation. For thermoset-based jute composites, mechanical recycling is more complex and less efficient. Alternatives such as size reduction and incorporation into new composites as fillers have been explored but offer limited value [174].

Chemical recycling of thermoset jute composites is an emerging field. Techniques such as solvolysis or pyrolysis aim to break down the matrix into reusable monomers or oils while recovering fibers. However, the energy input, chemical use, and process cost can offset environmental gains, requiring careful life cycle analysis to justify their implementation.

Biodegradability, though sometimes framed as an advantage of biopolymer-based jute composites, presents its own EoL issues. Many such materials degrade under industrial composting conditions, but not in natural environments or landfills. Moreover, biodegradation forfeits material recovery entirely, countering the principles of a circular economy [175],[176].

A life cycle assessment (LCA) approach is critical to truly aligning with circular economy objectives. This involves evaluating the environmental impacts of jute composites from raw material extraction to EoL disposal, considering factors like energy use, emissions, recyclability, and landfill impact. Design strategies such as using thermoplastics over thermosets, simplifying material composition, or designing for disassembly can greatly enhance circularity [177].

Promising research includes repurposing jute-polypropylene carpet industry waste into new composite applications, highlighting the potential for industrial symbiosis. However, standardized protocols, eco-design principles, and investment in recycling infrastructure are required for broader adoption. Ultimately, sustainability in the jute composite industry depends not just on the use of natural fibers but on closing the material loop through technically and economically viable EoL pathways.

8.5 Future Research Direction of Jute Fibers

With their natural biodegradability, mechanical strength, and economy of cost, jute fibers have great promise for innovative uses in many different spheres. In biomedical engineering, jute has the potential to transform wound care by providing antimicrobial dressings enhanced with silver nanoparticles or chitosan, presenting sustainable alternatives to synthetic options. Reflecting natural extracellular matrices for regenerative medicine, its nanocellulose structure makes it a contender for 3D-printed tissue scaffolds. While hydrophobic jute mats enhanced with silica nanoparticles can address oil-spill cleanup issues, jute-derived activated carbon or graphene oxide composites could effectively absorb heavy metals (e.g., Pb^{2+}, Cd^{2+}) from wastewater. Jute-based carbon fibers could provide biodegradable sensors for IoT-enabled smart agriculture or flexible supercapacitors (specific capacitance: ~250 F/g) in the energy industry. Upcycled jute-mycelium hybrid composites for building insulation or enzyme-assisted recycling to retrieve fibers from end-of-life items could help the circular economy. For lightweight radiation shielding in satellites, even space technology might use jute-epoxy composites, including boron nitride nanoparticles. These developments call for cooperation among materials scientists, environmental engineers, doctors, and energy analysts to position jute as a flexible, sustainable resource to handle worldwide issues in healthcare, environmental sustainability, and advanced technology.

9 Conclusion

Jute-based composites present an up-and-coming and eco-friendly alternative to synthetic materials, offering advantages such as biodegradability, renewability, lightweight characteristics, and cost-effectiveness. This review has comprehensively examined the structural, mechanical, and chemical properties of jute fibers, along with their processing techniques and diverse applications—from automotive and packaging to emerging sectors like electronics, 3D printing, and bioactive medical devices. Notable progress has been made in enhancing jute fiber performance through chemical and physical modifications, nanoparticle integration, and hybridization with synthetic and natural fibers. Despite these advancements, significant challenges remain. Key limitations include poor fiber-matrix adhesion, high moisture sensitivity, flammability, limited thermal stability, and a narrow processing window. Moreover, the current commercial exploitation of jute is constrained by inadequate product diversity, underdeveloped large-scale processing technologies, and insufficient promotion in global markets.

To fully unlock the potential of jute composites, future research should prioritize: (1) development of advanced surface treatments and coupling agents to improve fiber-matrix compatibility; (2) innovation in processing techniques that enhance fiber dispersion and allow higher fiber loadings in complex geometries; (3) integration of jute with emerging nanomaterials for high-performance applications; and (4) life-cycle and recyclability assessments aligned with circular economy models.

Furthermore, scalable and economically viable fabrication strategies—such as optimized 3D printing formulations—must be developed to meet industrial demands. The transition from laboratory success to real-world implementation will require interdisciplinary collaboration, policy support, and international partnerships to promote sustainable, bio-based economies. With targeted innovations and strategic commercialization, jute can be repositioned as a traditional fiber and a cornerstone of next-generation green technologies.

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