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Jute Fibre Reinforced Polymer Composites in Structural Applications: A Review

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Abstract

Jute fibre is commonly used as a natural fibre in composites for various industrial applications, including automobiles and buildings. It is used as a non-structural material to reduce weight and production costs. Jute fibre has inherent structural properties that can be modified to create structural components. However, to achieve this, the mechanical and physical properties of the fibre structure must be altered. Numerous studies have demonstrated that chemically treating jute fibre enhances mechanical and adhesive composite properties. Due to its short length, jute fibre presents a discontinuity challenge. Continuous fibres are essential for fabricating high-performance composite materials because they allow fibres to be aligned in the matrix according to their optimal load-bearing capacity. For this reason, short jute fibres must be spun into continuous strands to align fibre yarns in the matrix during the manufacturing of high-performance composites. However, twisting yarn has a detrimental impact on fibre alignment in the matrix, significantly affecting composite properties.

Researchers have shown that reducing yarn twists improves the wettability of matrix fibres. Therefore, more research is needed to understand the relationship between yarn twist, yarn linear density, and composite performance to appreciate how to align fibre yarns in the matrix to produce high-performance composites.

Keywords: natural fibre, composite materials, composites manufacturing, jute composites, structural application.

Introduction

Fibre-reinforced polymer composites are materials made up of two distinct components: a reinforcement phase (fibre) and a polymer phase (resin). These components work together to ensure that the composite structure can withstand any service conditions that may be applied. When viewed under a microscope, each material remains distinct (Ma et al., 2016).

In recent years, synthetic composites have become popular as alternative materials to conventional metals due to their unique properties, such as weight-saving, high tensile strength, high stiffness, and corrosion resistance. Synthetic composites are also cost-effective compared to conventional metals. However, synthetic materials are not naturally degradable or recyclable, which creates environmental problems in terms of waste management. Additionally, the sources of synthetic materials are petrochemical by-products that are predicted to become extinct in the next 50-60 years. To address these environmental concerns and meet the demands of various sectors, there has been an increasing demand for natural fibre-reinforced polymer composites. Natural fibres are eco-friendly, biodegradable, self-sustainable, and inexpensive. They are also lighter in weight than synthetic materials and require less energy to manufacture without posing any health risks. Natural plants absorb more carbon than they produce, which reduces carbon dioxide emissions. Natural fibres are derived from plants, animals, and geomaterials, and their most important properties are that they are biodegradable, environmentally friendly, and self-sustainable (See Figure 1) (Ekundayo & Sam, 2019; Ho et al., 2012; Kumar & Srivastava, 2017; Singh, et al., 2018).

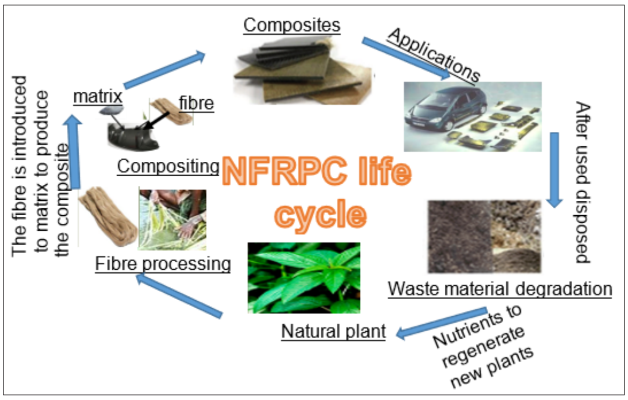

Figure 1: Life cycle of natural fibre-reinforced polymer composites life (Syduzzaman et al., 2020).

Natural plants are grown in different conditions worldwide, producing fibres with inconsistent chemical and mechanical properties. The plant's growing conditions, harvesting age,

and methods of extracting the fibres all play a role in the inconsistency of the fibre's mechanical properties. Plant fibres are abundantly available and cheap compared to synthetic glass and carbon fibres. However, synthetic fibres have superior mechanical properties to natural fibres, especially in strength and stiffness. Meanwhile, natural fibre can compete with E-glass on a weight-to-weight basis (Sood & Dwivedi, 2018).
Natural fibres are economically valuable, producing no waste; after fibre extraction, the waste can be used to fertilise crops or generate biogas. Natural fibre-reinforced composite materials are extensively used in automobiles to reduce weight, improve fuel efficiency, and reduce environmental impacts such as car door panels, armrests, seatbacks, and inner protectors between the car's tyres, bonnets, and bumpers (Figure 2) (Zwawi, 2021). Other areas of plant fibre-reinforced polymer composite applications, especially in their interior parts, are trains, aircraft, and buildings for weight and cost savings (Botelho et al., 2006).

Natural fibre-reinforced composites have low fire resistance, restricted processing temperature, poor thermal resistance, and low mechanical properties; the composite reinforcement (fibre) is hydrophilic, with poor adhesion to the hydrophobic matrix, resulting in poor fibre-matrix interfacial strength. When exposed to humidity, the composite absorbs water due to the hydrophilic nature of the reinforcement; Composite swell and delamination occur between the fibre and the matrix and weaken the composite properties. Therefore, these drawbacks restrict natural fibre-reinforced polymer composites to non-structural applications (Sepe et al., 2018).

Sood and Dwivedi (2018) reported that if natural fibres are treated chemically using alkalis or silane agents, the adhesion between the polar matrices and the fibres will improve, promoting fibre wettability to increase the interlaminar strength of the composites with improved mechanical properties such as their tensile and modulus properties. Table 1 shows the various mechanical properties of some selected natural fibres compared to some conventional fibres. For example, the density of natural fibres is more than 50% lighter than conventional fibres, giving the advantage of producing a strong composite with good weight-saving materials.

Fibres	Density (g/cm^3)	Elongation (%)	Tensile strength (MPa)	Elastic Modulus(GPa)
Cotton	1.5	3.0-10	287-597	5.5-12.6
Jute	1.3-1.46	1.5-1.8	393-800	10-30
Flax	1.4-1.5	1.2-3.2	345-1500	27.6-80
Hemp	1.48	1.6	550-900	70
Ramie	1.5	2.0-3.8	220-938	44-128
Sisal	1.33-1.5	2.0-2.4	400-700	9.0-38.0
Coir	1.2	15.0-30.0	175-220	4.0-6.0
Softwood	1.5	-	1000	40.0
E-glass	2.5	2.5-3.0	2000-3500	70.0
S-glass	2.5	2.8	4570	86.0
Aramid	1.4	3.3-3.7	3000-3150	63.0-67.0

Table 1: Mechanical properties of natural fibres compared to synthetic fibres (Mishra, 2019).

Jute, flax, hemp, and sisal fibres are the most commonly used plant fibres because they are eco-friendly, self-sustaining, and easily grown in tropical climates. They are also inexpensive and require less processing energy. These fibres have a greater aspect ratio than other plant fibres, and they can be modified into staple fibre yarn to make them continuous. Moreover, they have high specific tensile and modulus properties closely related to glass fibre properties due to their percentage of cellulose content (Sepe et al., 2018).

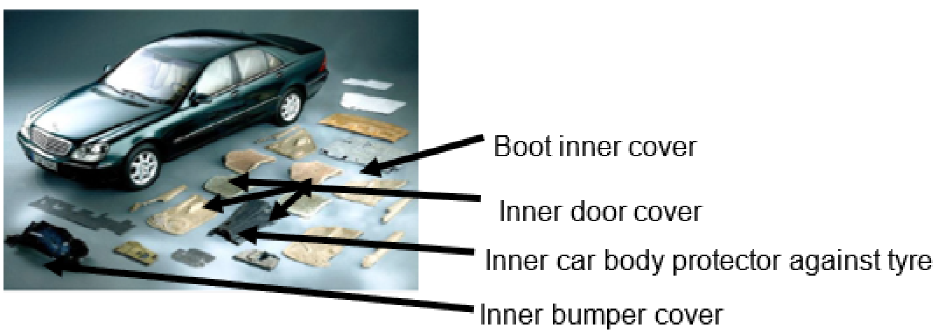

Figure 2: Application of natural fibre-reinforced polymer composite in a Mercedes Benz (Pollit, (n.d.)) (online) Available from: http://www.globalhemp.com/2018/12/illinois-department-of-agriculture-publishes-proposed-industrial-hemp-rules.html [Accessed 10/03/2022]

There are many methods available to produce synthetic fibre-reinforced polymer composites, and these methods are adaptable to the production of natural fibre-reinforced polymer composites. The choice of method depends on the fibre form, whether short or continuous, particulate or filler and the purpose of production (Ho et al., 2012). Composite manufacturing methods are divided into open, closed, and continuous production systems (Ekundayo & Sam, 2019).

According to Ho et al. (2012), natural fibres were first used in automobiles in 1940, and one of the succeeding plant fibres used is the jute fibre, which has a high specific tensile strength and is biodegradable, making it suitable to replace the conventional E-glass fibre. Jute fibre has a long history of use in traditional applications such as fishing nets, sacks, twine or rope, and coarse cloth in the textile industry. Jute plants are used in agriculture to stop erosion, prevent flooding, reforest areas that have been deforested industrially, and make sacks for plant nurseries. It is less expensive and more economically viable, and it can be used in various industries such as cottage, textile, and engineering. Jute fibre is woven into fabric and used in the furniture industry; jute fibres are useful in various applications, either mono-material or combined with other materials (Chand & Rohtagi, 1994).

However, they are limited to producing non-structural composites because the fibres are extracted from plant stems with a discontinuous length (Ma et al., 2016); for example, jute fibres are between 1 and 4 metres long. To fully exploit the structural potential of plant fibres as reinforcement agents, the highest possible reinforcement properties of the plant fibre must be used. As a result, it is essential to use plant fibre as continuous reinforcement in the matrix to fabricate high-performance composite materials (Shah et al., 2013).

There are several reports on continuous plant fibre yarns used in the textile industry produced by spinning processes of ring spinning machines. Many researchers have investigated them with their property reports tailored for use in the textile industry (Ma et al., 2016; Pan et al., 2001; Platt, 1950).

However, recent studies have shown that plant fibre yarn structure can be optimised and properly aligned in the matrix by introducing the textile architecture; for example, jute fibre can be spun into staple yarn to manufacture structural composites using the continuous method of producing conventional structural composites.

This paper discusses current developments in jute fibre-reinforced polymer composites. It proposes additional research into modifying jute fibre to optimise its unidirectional arrangement in matrices, which will allow the manufacture of composites suitable for structural applications.

Sources of Natural Fibre and Their Chemical Composition

Sources of Natural Fibres

Natural fibres are derived from plants, animals, and geological resources. Sisal, jute, hemp, flax, pineapple, abaca, coir, wool, silk, animal hair, feathers, and asbestos are examples of plant, animal, and geological fibres, as shown in the figure below. Plants provide the majority of natural fibres needed for composite production, and the plants are grouped according to their species as bast, leaves (vegetables), seeds, woods, and straws. As shown in Figure 1, the jute plant is in the group of best plants (Tara & Jagannatha, 2011).

According to Ekundayo and Adejuyigbe (2019), the plants are processed using retting or decortication methods to extract fibres from the plants and process the fibre for further use in composites or textile materials.

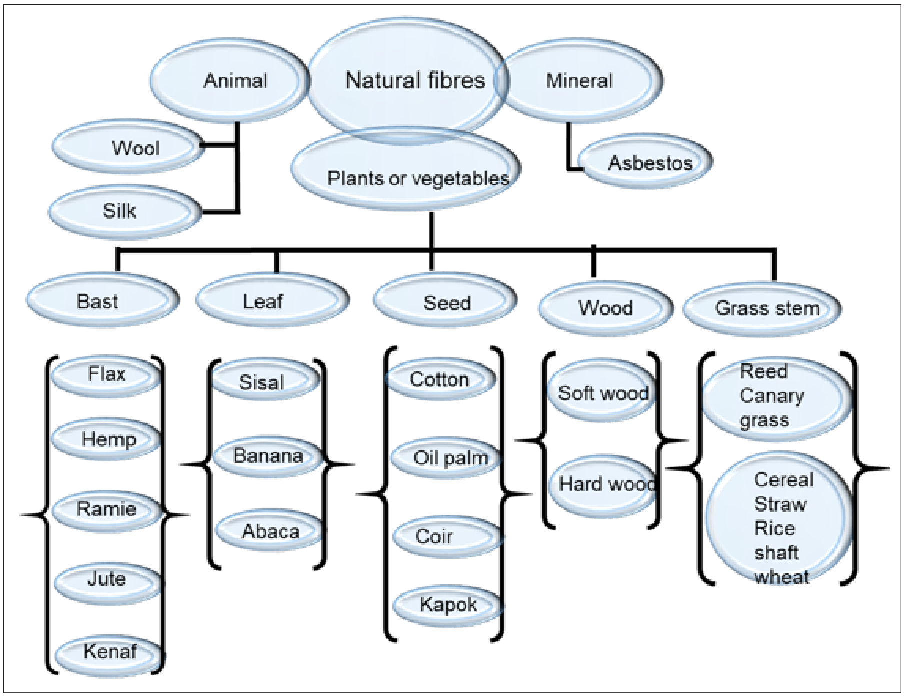

Figure 3: Sources of plant fibres (Ekundayo & Adejuyigbe, 2019)

Sisal, jute, coir, banana, hemp, flax, and bamboo are commonly used as matrix reinforcement in the production of composites. They have comparable specific tensile, flexural, and impact strength and a high specific modulus of elasticity to glass fibre (Rowell & D. McSweeny, 2008; Tara & Jagannatha, 2011).

Structural Composition of Natural Fibres

Natural fibre qualities are influenced by the plant's structural makeup, including cellulose, hemicellulose, pectin, lignin, and wax. As illustrated below, the structure of plant fibres consists of one primary wall and three secondary walls (Figure 4). Cellulose is the primary ingredient of natural fibres, providing the fibres with strength, stability, and stiffness, and the percentage content of cellulose determines the fibre's mechanical properties (Beepa et al., 2011; Tamrat, 2013). The composition of a few natural fibres is listed in Table 2.

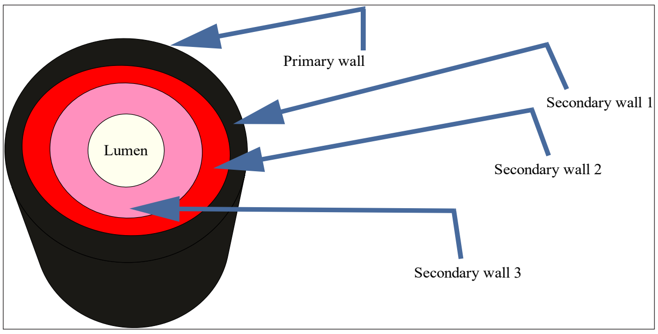

Figure 4: Structural composition of plant fibre

The mechanical properties of plant fibres also varied with other factors such as extraction technique, harvesting age, growth conditions, and plant morphologies, even when the fibres are from the same species. Because of these issues, it has become practically impossible to make theoretical predictions about the properties of natural fibres for structural composites; thus, composites made of plant fibres are restricted to non-structural applications (Ekundayo & Sam, 2019).

Jute fibre, among others, is widely used because it has a high cellulose content, as shown in Table 2, and its fibres are long, soft, and shiny, and it can be spun into a strong yarn that can be used to make textiles and composite materials. Jute fibre is recyclable, biodegradable, and inexpensive, with higher specific tensile and modulus properties than E-glass fibres. As a result, it is commonly used as reinforcement in composites used in automobiles, buildings, and other engineering applications, such as seat covers, dashboards, and practitioners where load carrying is not required.

Although natural fibres have good mechanical properties such as high specific tensile and flexural strength, are non-abrasive, non-toxic, and require less energy to produce, they have inherent problems. For example, one of the essential properties of natural fibres is cellulose, a basic element of an hydro-D-glucose, which is responsible for plant fibre's hydrophilic behaviour. The plant's cell wall comprises microfibrils, which are the most fundamental structural elements. The angle at which the microfibril fibre connects to the cell wall directly impacts the mechanical characteristics of the plant fibre as reinforcement (Zwawi, 2021). The hydrophilic nature of the plant fibre is responsible for the poor adhesion of the fibre with hydrophobic matrices, and they are thermally unstable and degradable at temperatures greater than 230-250 degrees Celsius as Reinforcement (John et al., 2010).

Fibre type	Cellulose	Hemicellulose	Lignin	Pectin
Abaca	61-64	21	12	0.8
Bagasse	32-48	21	19.9-24	10
Banana	60-65	6-19	5-10	3-5
Bamboo	26-43	15-26	21-31	
Coir	46	0.3	45	4
Cotton	82-96	2-6	0.5-1	5-7
Flax	60-81	14-19	2-3	0.9
Hemp	70-92	18-22	3.5	0.9
Jute	51-84	12-20	5-13	0.2
Kapok	13-16			
Kenaf	44-57	21	15-19	2
Phormium	67	30	11	
Pineapple	80-81	16-19	4-6-12	2-3
Ramie	68-76	13-15	0.6-1	1.9-2
Sisal	43-78	10-13	4-12	0.8-2
Wood	45-50	23-30	27	2-2.5

Table 2: Chemical content (%) of some plant fibres (Tamrat, 2013).

Physical and Chemical Modification of Natural Fibres and Their Composites

Interfacial bonding between fibre/matrix significantly impacts on its composite properties. The matrix in fibre reinforced polymer composites will transfer the applied stress to the fibre if the interfacial bonding is good. Meanwhile, plant fibre has poor adhesion with hydrophobic matrix due to its hydrophilic nature, and it absorbs water easily in humid environments. These disadvantages can be solved by modifying the fibre's physical structure and chemical compositions by employing (either or both) physical and chemical treatments to improve plant fibre adherence to the matrix and lower water absorption rates (Senthilkumar et al., 2018). Flexural properties are essential for structural members, and glass and carbon fibre have enough to replace metal. Therefore, to make natural fibre a good option to replace synthetic fibre, the fibre's mechanical properties must be improved to manufacture strong and reliable natural fibre-reinforced polymer composites (NFRPC) (Sood & Dwivedi, 2018).

Treatment of natural fibre is one of the effective methods of improving its mechanical properties. The natural fibre is physically and chemically treated to improve its surface roughness and remove its hydroxyl groups to promote good wettability with resin and increase its adhesion properties.

According to Bledzki et al. (1996), the cellulose molecules of each fibre differ in their degree of polymerisation (DP), and the bast fibre usually has the highest DP among all the plant fibres. The fibrils of the cellulose macromolecules form spirals along the fibre axis; hence, bast fibres are considered the best fibre for natural composites. The strength and stiffness of hemp, ramie, and jute correlate with the angle between the fibre's axis and fibril. The lower the microfibril's angle, the higher the fibre's mechanical properties. Other substances like lignin, hemicellulose and wax, lignin/hemicellulose only act as the binder that cements the plant materials; they influence the fibre structure and morphology and are the causes of the poor fibre wettability and adhesion problems; therefore, treatment of fibres removed these substances to increase the surface roughness of the fibre leading to a better interlock between the fibre and the matrices. Several studies have been published on changes in the mechanical properties of plant fibre-reinforced polymer composites after physically and chemically treating its fibres (Bledzki & Gassan, 1999; Favaro et al., 2010; Fuentes et al., 2013; Giuseppe et al., 2010; Yan et al., 2000; Zhong et al., 2007).

A study by Kabir et al. (2012) investigated the tensile properties of single hemp fibres while accounting for variations in fibre diameters caused by alkali, acetyl, and silane treatments. The relationship between the properties of the treated fibres and their diameter variation was also investigated.

Table 3 shows the comparative values of bast fibre microfibril angle to other plant's fibre, coupled with their densities, making it possible to produce composites that combine good mechanical properties with low specific weight (Boopalan et al., 2012; Kabir et al., 2013; Fuentes et al., 2013; Christopher et al., 2015; Oladele et al., 2010; Rong et al., 2001).

Plant Fibre	Diameter(μm)	Length(mm)	Aspect ratio (l/d)	Microfibril's angle (α)	Bulk Density (kg/m^3)	Moisture re-claim (%)
Flax	8-21.6	5-900	1258	5.0	1140-1507	12.00
Kapok	15-35	8-32	724	-	384	10.90
Kenaf	17.7-21.9	20-27	119	-	1220-1400	17.00
Jute	15.9-20.7	1.5-120	157	8.1	1300-1500	17.00
Hemp	17.0-22.8	5-55	549	6.2	1400-1500	12.00
Ramie	28.1-35.0	900-1200	4639	-	1550	8.50
Abaca	17.0-21.4	4.6-5.2	257	-	1500	14.00
Sisal	18.3-23.7	900	115	10-22	1300-1500	14.00
Cotton	11.5-17.0	20-61	2752	20-30	1550	8.50
Bamboo	10-40	2.7	-	-	1500	-
Phormium	15.1-16.4	5.0-5.7	337	-	-	-
Pineapple	20-80	-	-	6-164	1520-1560	-

Table 3: Physical properties of selected natural fibre[1]

Physical Treatments of Natural Fibres Plant's

Physical treatment of plant fibres roughens the fibre's surface, removes surface impurities like oil, pectin, and wax, and separates fibre bundles into individual strands (Christopher et al., 2015). Physical treatments include mechanical, water extraction, and electrical discharge procedures. Traditional physical treatments include stretching, calendaring, thermo-treatment, and the production of fibre hybrids (Ahmad et al., 2019). Other types of physical plant fibre (PF) treatment include plasma, corona, gamma-ray, and steam explosion.

Cordeiro (2016) investigated the effect of sulphur hexafluoride (SF6) gas at low plasma pressure on flax and wood fibres. Composites were made with polypropylene as the matrix, and the effect of treatment on the composites was studied. The results show that the strength and modulus properties of the flax and wood composites have improved significantly. In addition, the steam explosion treatment smoothed the surface of the fibre, improving its flexibility and distribution in the matrix (Panigrahi et al., 2012).

One of the simplest methods, among others, is to use mechanical means to increase surface roughness. This, in turn, increases the interlocking areas of the fibres with the matrix by removing all soluble impurities, particularly short fibres and fillers (Wang et al., 2019). Lee et al. (2011) identified mechanical means as an efficient method of separating a compound based on the solubility of the organic solvent in the mixed water. However, this method was not widely adopted because the fibres deteriorated due to the reduced aspect ratio and water pollution, making the technique unsuitable for ecosystems.

The corona ionisation cycle produces an electrical discharge that improves the surface adhesion properties of the reinforced fibre. A grounded and inductive corona air jet creates a corona with a high-voltage and high-frequency discharge. Corona air jets have an electrical current of 9,000 to 15,000 volts per square millimetre. The electrical discharge bursts from the air jets carrying high-capacity ions and node-rush, penetrating the surface of the fibre and destroying the molecular fibre structures through electric discharging. The oxidation and polarisation of the fibre surface and the discharged ion improve the adhesion of the fibre surface.

Fibres	Density (g/cm^3)	Elongation (%)	Tensile strength (MPa)	Elastic Modulus(GPa)
Cotton	1.5	3.0-10	287-597	5.5-12.6
Jute	1.3-1.46	1.5-1.8	393-800	10-30
Flax	1.4-1.5	1.2-3.2	345-1500	27.6-80
Hemp	1.48	1.6	550-900	70
Ramie	1.5	2.0-3.8	220-938	44-128
Sisal	1.33-1.5	2.0-2.4	400-700	9.0-38.0
Coir	1.2	15.0-30.0	175-220	4.0-6.0
Softwood	1.5	-	1000	40.0
E-glass	2.5	2.5-3.0	2000-3500	70.0
S-glass	2.5	2.8	4570	86.0
Aramid	1.4	3.3-3.7	3000-3150	63.0-67.0

Table 4: Comparison of mechanical properties between natural fibres and synthetic fibres (Mishra, 2019).

Chemical Modifications of Plant Fibres

The hydroxyl groups in cellulose and lignin are removed by chemical treatment of plant fibre; the reaction removes the hydroxyl and introduces new molecules that effectively interlock with the matrix (Panigrahi et al., 2012). Chemical treatment of fibres changes the shape of the cells, cleanses the fibre surfaces, and improves resin wettability (Liu et al., 2019). Numerous chemical treatment experiments have demonstrated that the technique removes fibre wax and other substances added to the fibre substrate, increases fibre surface roughness, and reduces water absorption of the fibre as reinforcement. In addition, the treatment aims to improve the interfacial strength of the fibres/matrix composite mechanical properties and improve its load-carrying capacity.

Favaro et al. (2010); Fuentes et al. (2013); Kabir et al., (2012); Min et al. 2001; Xue et al. (2007) have reported alkaline, silane, acetylation, benzoylation, Acrylation/acrylonitrile grafting, Malleated, peroxide, isocyanate, and other chemical treatments.

Liu et al. (2019) used silane to treat Corn Stalk Fibre (CSF) and investigated its effect on its mechanical characteristics. The treated CSF has a maximum tensile strength of 223.33 MPa and the highest Young's modulus of 18.98 GPa. The silane treatments improve the interfacial bonding between the fibres and the matrix and the impact strength of the polymer composites.

Edeerozey et al. (2007) described the morphological and structural changes in an alkali-treated kenaf fibre modified with 3, 6, and 9 per cent NaOH. According to their SEM, those treated with 3 and 6 per cent NaOH showed better results. However, at 9% NaOH, the solution became too strong and attacked the fibre structure, decreasing tensile strength.

Sood and Dwivedi (2018) reviewed the effects of treatment of the flexural properties of natural fibre-reinforced composites and concluded that either physical or chemical treatment of natural fibres would result in changes in the mechanical properties of their composites. However, if alkali and silane agents are combined to treat natural fibre, the highest flexural properties, with an alkali solution of 5%, 6% and 10% of natural composite, will be realised compared to a single treatment.

Jute Fibre

The Titiaceae family includes the jute plant. Jute fibre (also known as jute) is derived from two species: Corchorus Capsularis (grown in India, Bangladesh, Thailand, China, and Burma) and Corchorus Olitorus (grown in Egypt) (Wikipedia the Free Encyclopaedia, 2014).

Jute fibre is brittle because it contains a high lignin content (12–16%), absorbs moisture quickly when exposed to humidity, and is affected by acid and ultraviolet light.

Jute fibre, also known as golden fibre, is one of the longest and most colourful fibres (between 1 to 4 m long). It grows best in tropical lowlands with relative humidity levels ranging from 60% to 90% (FAO, 2009). The retting process is required to extract the fibre from the jute plant. The stalks are harvested, tied into bundles, and submerged in soft running water for approximately 20 days. The stem of the jute plant is then peeled to remove the fibre from the plant's skin (Wigglesworth, 2014). The most common retting processes are mechanical (hammering), chemical (boiling and chemical applications), stem/vapour/dew, and water or microbial retting. Water or microbial retting is the most ancient and effective method of extracting high-quality fibres from bast plants like jute. They are then bundled and struck with a long wooden hammer, causing the jute hurd or core to fall out of the fibre (FAO, 2009).

The fibre is then washed, squeezed, washed, dried again, tied into bales, and sold to primary marketers.

Jute fibre is widely used in sacks, clothing, fishnets, mattresses, ropes, and pillow filling. Jute, like all-natural fibres, degrades naturally and emits no toxic gases when burned. Jute fibre's properties can compete favourably with E-glass fibre and other fibres. Jute fibre density is more than half that of glass fibre density, and it has a high specific tensile and modulus of elasticity comparable to E-glass fibre. Due to their fine texture and high resistance to heat and fire, these fibres are used in various applications, including textiles, buildings, and automobiles.

Figure 5: (a) Jute plantation, (b) Jute fibres, (c) harvested bundles ready for supplies Adopted from (Anon, (n.d.)) https://www.researchgate.net/figure/Jute-plant-Fig310-Scheme-of-jute-fiber-structure-Jute-fiber-is-obtained-from-two_fig5_321756571 Accessed 21/01/2022)

Chemical Properties of Jute Fibre

The chemical properties of jute fibre often reflect the growing conditions, harvesting age, and extraction methods; hence, the chemical properties vary. Table 2 shows the various chemical properties obtained from different researchers as compiled by (Singh, 2018), and this is one of the reasons natural fibres are restricted because there are no standard properties, and they cannot be designed in the abstract; hence, the properties of the material must be confirmed before determining where to apply them. Table 2 shows how the chemical properties of the jute can be varied. For example, the fibre cellulose content is a major factor determining the fibre's mechanical properties; while some Researchers recorded as much as 73.2%, others have 45% and 58%, which would mean a major difference in their mechanical properties. However, compared to other natural fibres, jute fibre has a high cellulose content, so it has the mechanical properties to compete with E-glass fibre. Like other plant fibres, Jute fibre is composed of cellulose, hemicellulose, pectin, lignin, wax, and other impurities (Myvizhirajeswari & Saravanan, 2011; Singh et al., 2018).

Cellulose (%)	Hemicellulose (%)	Pectin (%)	Wax (%)	Moisture (%)	Lignin (%)	Others
61-71	13.6-20.4	-0.2	0.5	-12.6	12-13	-0.5-2.0
61-71.5	13.6-20.6	2.3	-1.7	-	12-13	-
61-71.5	12-13	0.2	-0.5	12.6	13.6-20.4	-8.0
61.0	20.4	-	-	12.6	13.0	-
45-63	-	410	-0.5	12-13	12-25	-8.0
71.0	14.0		0.5		17.0	
61-71	14-20	-	-	-	12-13	-
61-63	13.0		0.5		5-13	
61-71	14-20	-	-	-	12-13	
58-63	13.021-24				12-14	-2
61-73.2	13.6-20.4	-	-	-	12-16	-
72.0	13.0	-	-	-	13.0	-

Table 5: Chemical properties of jute fibre (Singh, 2018)

Mechanical Properties of Jute Fibre

Jute has comparable mechanical properties to E-glass, as seen in Table 3. Jute has a high specific modulus than glass fibre, and jute fibres' diameter influences its tensile strength. In addition, growing conditions, processing methods, fibre ratio, and chemical treatment can alter jute fibre mechanical characteristics.

Fibre	Diameter	Density (g/cm^3)	Length (mm)	Aspect Ratio (l_f/d_f)	Failure strain (%)	Tensile Strength (MPa)	Young Modulus	Specific Tensile strength (MPa/ gcm^3)	Specific Young Modulus (GPa/gcm^3)
*Jute	15.9-20.7	1.3-1.5	1.5-120	157	1.5-1.8	393-800	10-55	300-610	7.1-39*
*E-glass		2.5	Continuous		2.5	2000-3000	70	800-1400	29*

Table 6: The mechanical properties of jute fibre compared to the E-glass fibre

Effect of Chemical Treatment on Jute Fibre Properties

Natural fibres have high specific properties, and they are environmentally friendly when used as a replacement for synthetic composite; however, they are hydrophilic, having poor adhesion with hydrophobic matrices. Therefore, natural fibre structure and chemical composition are chemically and physically treated to roughen the fibre surface and enhance its adhesion with the polar matrix, reducing water absorption rate and improving its composite's mechanical properties (Christopher et al., 2015).

To manufacture strong and reliable natural fibre composites with mechanical properties comparable to synthetic composites, the fibre's surface must be treated physically and chemically to modify the fibre surface (Myvizhirajeswari & Saravanan, 2011). Physical treatment, such as calendering, stretching, thermotreatment, and the production of hybrid yarns, is the traditional method of treating fibre, and it does not affect the chemical composition of the fibre (Christopher et al., 2015).

Plant fibres are chemically treated to improve their overall properties, reduce water absorption rate and remove other hydroxyl substances, including hemicellulose, lignin, pectin and wax, from the fibre surface to strengthen the fibre adhesion to the matrix (Adekunle, 2015). Jute fibre is the second most-produced natural fibre, and it is an excellent alternative to synthetic glass fibre when strength, weight and cost are the major concerns. In addition, there have been several reports on the treatment of jute fibres; this includes silane treatment, alkali treatment and silane plus alkali treatment of the jute fibre and the jute/matrix composites produced using various methods of composites production were investigated (Myvizhirajeswari & Saravanan, 2011; Kumar & Srivastava, 2017; Singh et al., 2018).

Hossen & Rahman (2021), Kabir et al. (2010) investigated the effect of chemical treatment on woven jute fabric composites manufactured by hot-pressing. The experiment was conducted on jute composites treated with alkali, silane, and a combination of alkali and silane and untreated composites. According to the investigation findings, alkali-silane composites have the highest tensile strength than alkali, silane, and untreated composites. The water absorption rate of the composite was determined, and the results indicate that the alkali-silane treated composite has a high resistance to water absorption and absorbs less. The figure below illustrates the research findings, with the untreated composite absorbing significantly more water than the other composites.

Gassan & Bledzk (1999) physically treated jute fibres with a corona discharge and ultraviolet rays and reinforced them into an epoxy matrix. Results after investigation show a 30% increase in the composite flexural strength. Seki (2009) investigated jute/polyester and jute /epoxy composites with jute fibres treated with alkali and silane agents. The investigation results show that composites treated with alkali and silane agents remarkably gave higher flexural modulus and strength than the untreated jute/polyester and jute/epoxy. However, when the jute/polyester and jute/epoxy alkali and silane treated composites were compared, the silane treated composite provided the highest strength and modulus.

Treatment of natural fibres (jute) is a function of the type of fibre, percentage concentration of the chosen chemical, soaking time and the reactions on the fibre's surface. The overall modification of the structural properties of the fibre, coupled with the inherent properties of the fibre, would determine the level of fibre properties optimization (Seki, 2009; Cruz & Fangueiro, 2016).

Jute Composites

The need for a clean environment free of carbon emissions and the preparation for the extinction of fossil fuels has shifted research attention to green materials as an alternative to metals and synthetic composites.

Jute fibre has strength, and its mechanical properties can be sustained and improved if chemically treated to promote adhesion with polar matrices. This is why jute composites are produced in many forms, either as hybrid materials or jute fibre in many matrices to serve as weight reduction materials or for economic gain. However, these composites can only be used for non-structural purposes.

Many researchers have used thermoplastics and thermosetting matrices of polypropylene, poly(lactic acid), epoxy, polyester, phenols, and polyethylene to fabricate jute fibre composites using opened mould of hand-layup and closed moulding, compression methods and resin transfer moulding system and characterized. Compared to other natural and synthetic composites, jute composite is cost-effective, having technical viability, the reason they are commonly utilized as building and construction materials (panels, partition boards, fake ceilings, etc.), packaging, vehicle and railway coach interiors, and storage devices (Seki, 2009). The manufacturing of jute fibre composite was carried out with the jute fibre in different forms depending on the purpose and areas of applications. The fibre forms are either short, continuous or filler forms, using production methods similar to conventional composites.

Singh et al. (2018) prepared and characterized jute/soy milk composites reinforced with woven and nonwoven jute fibres. The composites testing results indicate that the best mechanical properties are obtained at a fibre and fabric content of 60% wt. Also, investigated the curing temperature of jute/epoxy composites between 80 and 120 degrees Celsius. They reported that 100 degrees Celsius was the ideal curing temperature for achieving jute composites' maximal tensile and flexural strengths, which is advantageous to the jute composite since the temperature is far below the natural fibre degradation temperature.

The problem of water absorption associated with natural fibre composites occasionally led to using their fibres in combination with other fibre(s) and using thermosetting resin to reduce moisture absorption (Ekundayo & Sam, 2019). Hybrid natural composites involving glass/Jute epoxy fibre composites are very common in reducing moisture absorption and producing high tensile and flexural strength cost-saving composites (Ramesh et al., 2013; Zhao et al., 2017).

Ahmed and Vijayarangan (2008) produced jute mono composite and the hybrid of jute/glass composites, with each composite having 42% weight fractions. The hybrid composite of jute /glass at a 40:60 laminate composite showed an increase in tensile strength, Young modulus, flexural strength and flexural modulus of 53, 30, 31and 62%, respectively compared to the jute mono composite.

Application of Jute Composite in Structural Areas

Jute fibre reinforced polymer composites are used in various engineering and non-engineering applications, such as buildings, furniture industries, automobiles, packaging bags, ropes, or twines, where load carrying is not critical. Jute fibre reinforced polymer composites have gained acceptance, largely in non-structural applications. To improve and continue using jute fibre as reinforcement while trying to meet its requirements, additional modifications are needed to optimize its properties, particularly for structural use.

For structural applications, the most important property to consider is the mechanical properties of the fibre, which will aid in predicting the material's behaviour under stress. Although the requirements for structural materials vary depending on their area of use and purpose, the factors required to determine a material's strength and toughness are the same. For fibre reinforced polymer composites, these factors include the type of fibre, the source of the fibre, the type of modification required, the matrix, and the interfacial bond between the fibre and the matrix. Other factors include fibre length, fibre alignment and distribution in the matrix, and fibre volume/weight fraction; thus, these factors can be manipulated to achieve the required mechanical strength and stiffness required for the manufacturing of a structural composite depending on the inherent properties of the fibre (Shesan et al., 2019).

Because of the limited length of plant organs, Jute fibre, like other natural fibres, has inconsistencies in physical, mechanical, and chemical properties with a discontinuous fibre; however, continuous fibre is a factor in producing high-performance composite capable of being used for structural purposes (Ma et al., 2016). As a result, jute fibre must be spun into yarn using traditional ring-spinning techniques, in which bundles of jute fibres in parallel are twisted together in helical form, with the friction between the fibres keeping the integrity of the yarn and allowing for the alignment of the yarn in the matrix for structural composites.

Shah et al. [61]described spinning natural fibres into yarn as a way to improve the yarn's processability in terms of alignment in the matrix, but the negative effect is that the fibres in the yarn are misaligned, causing a decrease in their composite mechanical properties. According to Rask & Madsen (2011), the off-axis between the principal yarn axis and the constituting fibres reduces yarn fibre composites' strength.

Many recent research reports have demanded that the potential for aligning plant fibre reinforced polymer composites be determined so that the demand for and implementation of legislation prohibiting the use of fossil fuels materials can be achieved and promote the use of natural fibre reinforced polymer composite to replace the synthetic composites.

Pinto et al. (2014) investigated the tensile strength and modulus of unidirectional jute yarn reinforced epoxy composites and recorded 76.6 MPa and 11.9 GPa, respectively. Madsen and Lilholt (2003) reported the axial stiffness and strength of unidirectional flax yarn reinforced polypropylene composites with a fibre weight fraction ranging from 56 percent to 72 percent, with values ranging from 27–29 GPa 251–321 MPa, respectively, using flax/polypropylene commingled wrap yarns. Ma et al. (2016) investigated the effect of yarn linear density on ramie yarn reinforced composites with yarn linear density ranging from 15.8, 26.7, 67.3, and 202.2 tex for single yarns and 63.5 and 182.4 tex for plied yarns. According to the findings of their investigation, the maximum tensile strength of the composites produced was 171.52 MPa with a single ramie yarn of 67.3 tex, after which a drastic reduction was recorded. This result was similar for both single and plied yarn, demonstrating that increasing the yarn linear density will affect the properties of the composite until an optimum level is reached. The interlaminar strength of composites with lower linear densities was also greater than those with higher linear densities. Flexural strength of 145.6 MPa and modulus of 15.3 GPa were reported by Zhang and Miao (2010) for 31.4 percent fibre volume fraction composites. These examples suggested that the mechanical performance of the PFRC could be improved further by optimizing plant yarn structures that will be used for composite reinforcements and serve effectively as structural materials.

The ring-spinning method is used to make staple fibre yarn, and twists are added to the yarn to keep the fibres in place with the yarn structure and give the yarn the appropriate qualities for subsequent processing. Many studies on the influence of twist and yarn linear density on the mechanical characteristics of yarn composites have established that the twist has a negative effect on the mechanical properties of such composites, particularly the tensile and modulus properties (Khalifa & Bagawan, 2014; Ma et al., 2016; Shah, 2013; Shah et al., 2012; Zaidi et al., 2018; Hafiz et al., 2016).

Ma et al. (2016) studied the effect of yarn linear density on the mechanical characteristics of ramie fibre yarn composites. The results of tensile and modulus tests performed on yarn composites with different yarn linear densities of 15.8, 26.7, 67.3, and 202.3 tex, as single yarn, and 63.5 and 182.4 as plied yarn, show that the tensile and modulus properties of the yarn composites increase with linear density and decrease dramatically after reaching their maximum at 67.3tex linear density. The results reveal that composites with higher linear densities, both single and plied, have low tensile strength due to poor resin impregnation. Rask & Madsen (2011) investigated the twisting of fibres in yarn for natural fibre composites. It was concluded that the tighter the yarn (indicating a higher twist level), the more difficult it is for the matrix to penetrate all the fibres in the yarn; as a result, there is a propensity for increased porosity in the composites, which will impair the composite's properties.

However, the influence of the yarn twist factor and the yarn linear density on plant fibre reinforced polymer composites received little attention even though they can be utilized to optimize the properties of the composites made from the various yarn linear densities. The twist factor and linear density are two important factors for staple fibre yarn structure.

The twist factor is a factor that relates the twisting level to the yarn's linear density. This factor is proportional to the twist angle of the yarn (if the yarn density is constant), which is the angle between the tangent of the helix formed by fibre at the surface of the yarn and the yarn axis. An increase in the angle will affect the yarn properties, which means that the twist angles can be used to determine yarn characteristics (16)(16)(16) (Mandal, 2013). If the twist factor is known, the twist density of the yarn can be calculated using the formula provided below(the subscript 't' stands for tex measurement of yarn linear density; the twist density is measured in turns per meter).

$$Twist\ factor(\ K_t) = Twist\ density\ x\sqrt{yarn\ count} \qquad (1)$$

More research needs to be done on the yarn twist factor and linear density to see how the yarn structure can be optimised for composite applications.

Conclusion

This paper review has shown how physical and chemical treatment can influence and optimise the mechanical properties of jute fibre. Treating jute fibre with alkali plus silane agents has been described as the best method to modify the fibre's tensile and flexural properties. However, to produce high-performance composites with jute fibre, the fibre needs to be made into a continuous form, and the simplest method is to convert the fibre into a staple yarn to align unidirectionally in the matrix. Many researchers have reported the effects of twisted plant fibre yarns on the yarn-reinforced composites (Adusumalli et al., 2019; Shah, 2013; Ma et al., 2016; Pan et al., 2001; Shah et al., 2013). The twisting of fibres affects plant fibres' orientation efficiency, impairs the permeability of plant fibre yarns, and reduces the mechanical properties of plant fibre-reinforced composite (PFRC). However, considering the required strength of the yarns for the composites manufacturing process, some of the researchers proposed a reduction in the twist level of plant fibre yarns to improve the yarn wettability during composites production. To achieve this goal, more research must be carried out on how the combined yarn twist and linear density can be optimised for composite production.

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