A Comprehensive Review of Natural Fibre Reinforced Polymer Composites

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Abstract

In this article, concept of composite materials is discussed with an emphasis on composites made of natural fibres and polymers. Composites are made up of various elements or phases that significantly affect the material's general characteristics. The matrix, the continuous phase, is typically made up of ceramics, metals, or polymers. Natural fibres that provide stiffness and strength make up the reinforcement component in natural fibre reinforced (NFR) composites. These composite materials have uses in the consumer goods, packaging, sports, and construction industries, in addition to providing environmental advantages. The paper presents detailed review on the creation and characterization of composites reinforced by natural fibres. To improve the properties of the composites, numerous studies have looked at various kinds of natural fibres, surface modifications, coupling agents, and processing methods. The advantages and limitations of using NFR composites are discussed in the article. It gives a general overview of how NFR composites have evolved and what uses they might have in the future. The article highlights current research initiatives and difficulties in enhancing the performance and compatibility of NFR polymer matrices. The research advances the use of natural fibre composites as environmentally friendly substitutes across a range of industries by fostering a better understanding of their advantages and disadvantages.

Keywords: Composite Materials, Natural Fibre-Reinforced Composites, Environmental Suitability, Fibre Matrix Adhesion, Sustainable Alternatives.

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Introduction

A composite refers to a combination of two or more distinct components or phases. However, being classified as a composite requires meeting specific criteria. All the components need to be present in significant proportions, typically exceeding five percentage and the properties of the composite must show noticeable differences from those of its constituent phases, resulting from the distinct characteristics of each component. A composite is recognized when it consists of two or more phases separated by a distinct interface on a macroscopic scale. Primary phase is called the "matrix" which is present in larger quantities and can be composed of ceramics, metals, or polymers. The "reinforcement" component, which is frequently stronger, harder, and stiffer than the matrix, offers strength, stiffness, and load-carrying capabilities. A natural fibre composite (NFC) with cellulose-fibres embedded in a lignin-matrix and arranged at different spiral angles is wood, which makes an interesting example [1]. Fibre-reinforced Reinforced composites (FRC) are frequently used in manufacturing and use fibres as reinforcement. Matrix materials like mud, metals, ceramics, cement, and polymers are used to incorporate these reinforcements. In recent years, both in academia and various industries, there has been a significant increase in interest in the use of natural fibre-reinforced polymer composites [2–4]. Due to their desirable properties and widespread availability, a variety of natural fibres, including flax, hemp, Calotropis procera, jute, kenaf, and sisal, are frequently used as reinforcements or fillers in composite materials. Utilizing post-consumer recycled plastic instead of virgin polymer matrices improves the environmental suitability of these composite materials [5].

Literature Review

Research was done by Ferreira *et al.* [6] to increase the endurance capacity of fibre composites by adding hybrid fibres. A layer of polypropylene hemp was purposefully positioned close to the bond interface to encourage uniform stress distribution in transitional regions. Even within the same cultivation, natural (plant) fibres exhibit inconsistent mechanical properties due to their inherent non-uniformity and large range of dimensions [7]. The current study concentrated on microwave processing techniques for the fabrication of composite materials that are partially and completely biodegradable, using natural fibres (NFs) like

bamboo, rattan, and coir as potential reinforcements [8]. For the purpose of better understanding the mould filling procedure for phenolic composites reinforced with hemp mats, Richardson and Zhang [9] conducted flow visualisation experiments. The modulus and tensile strength of thermoplastic starch were significantly enhanced by adding Eucalyptus urograndis pulp as reinforcement [10]. The mechanical performance of plastic composites made from waste wood fibre was examined in the study by Jayaraman and Bhattacharya [11], which found that changes in fibre content had little impact on tensile strength. In their study of natural rubber- polypropylene (NR-PP) composites, Zulkifli and his co-researchers [12] discovered that adding more NR enhanced fracture properties but decreased toughness. The resistance of bamboo fibre-polypropylene hybrid composites to hygrothermal ageing and fatigue behaviour was studied by Thwe and Liao [13], who successfully reduced moisture absorption and degradation by incorporating a coupling agent. The importance of fibre-matrix adhesion and surface modification techniques in henequen fibre-HDPE composites, which significantly improved tensile and flexural properties, was discussed by Herrera-Franco and Valadez-Gonzalez [14]. While Mitra *et al.* [15] used precondensates to treat jute fibres and reduce their moisture absorbance, Naik and Mishra [16] looked into the electrical characteristics of wood polymer composites made from agricultural materials. While Eichhorn and his co-researcher Young [17] investigated the microscale deformation behaviour of natural cellulose fibre composites and networks, Kandola and his co-researchers [18] developed novel composites made of glass reinforced epoxy containing phosphate. Flax-based materials were used as reinforcing agents by Kaith [19- 20] and A. S. Singha *et al.* [21], who noted appreciable improvements in load-bearing capacity. By grafting Hibiscus sabdariffa stem fibres with different monomers and analysing their physico-chemical-thermal properties [22], Chauhan [23] used them as reinforcements in phenol-formaldehyde matrix composites. The role of fibre orientation was highlighted by researchers [24–27] as they concentrated on the pultrusion technique for mass production of kenaf fibre composites. Fibre dispersion, dimensional stability, and interface in composites were found to be improved by etherification [28–29]. These investigations advance knowledge of NFC, their reinforcement-methods, and the development of mechanical properties for various uses.

Natural Fibre

While "fibre" refers to a structure with a high aspect ratio that resembles hair or thread, "natural" refers to substances that occur in nature and are unmanmade. These fibres can be found as discrete, elongated pieces that resemble threads or as continuous filaments. They are used in several different forms, including filaments, threads, ropes, and sheets for the creation of composite materials and paper [30]. Six main groups of natural fibres can be distinguished: bast fibres (jute, hemp, flax, kenaf and ramie), stem fibres (Calotropis procera), leaf fibres (sisal, pineapple, and abaca), seed fibres (kapok, cotton, and coir), core fibres (jute, hemp, and kenaf), and grass and reed fibres (rice, corn, and wheat). An example of a miscellaneous item is wood and roots. Natural fibres have a number of benefits, such as recyclability, low density, minimal carbon dioxide footprint, impressive specific mechanical properties, non-abrasiveness, efficient thermal and acoustic insulation, biodegradability, and cost-effectiveness. The drawbacks of natural fibres include their hydrophilicity, susceptibility to dimensional instability, low heat resistance, variability in properties, anisotropic behaviour, and propensity for discontinuity.

Structure and Composition of Natural Fibres (NFs)

Microfibrils of cellulose, hemicelluloses, lignin, wax, and water-soluble substances make up plant fibres. The main ingredients are cellulose, hemicelluloses, and lignin [31]. Figure 1 depicts the composition of the plant cell wall, which includes these elements.

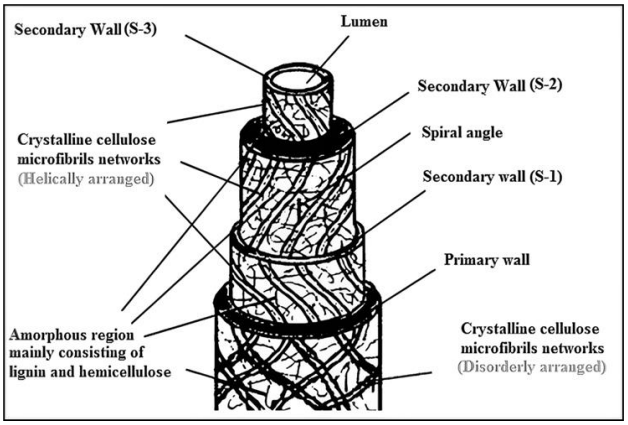

Figure 1: Schematic representation of a plant's cell wall

A primary cell wall, 3 secondary cell walls, and a central lumen make up the specific structure known as the microfibril, microfiber, or primary fibre [32]. Together, these layers create a hollow, tube-like structure. Natural fibres can be viewed as composites in which a matrix of lignin and hemicelluloses holds hollow cellulose fibrils together [33]. α-cellulose, hemicellulose, pectins, lignin, and wax make up the majority of these fibres. Repeating units of D-anhydroglucose in cellulose, a naturally occurring linear crystalline polymer, are connected by 1-4 ß-D--glycosidic linkages at positions C_1 and C_4. The physical characteristics of cellulose and its crystalline packing are significantly influenced by hydrogen bonds. The fact that hemicellulose contains different sugar units, including xylose, galactose, and mannose, and exhibits a non-crystalline nature as a result of chain branching and pendant side groups sets it apart from cellulose. The crystallinity of cellulose is ten to hundred times greater than

that of hemicelluloses. Amorphous and hydrophobic in nature, lignin is a complex hydrocarbon polymer made up of aromatic and aliphatic components. It is thought that the building blocks of lignin molecules are derivatives of 4-hydroxy-3-methoxy phenylpropane. Natural fibre's characteristics can change depending on their age, source, and separation method [34].

Applications of Natural Fibre Composites (NFC)

Natural fibre-based composites have seen a significant increase in use in the automotive and transportation industries because of Due to their low density and specific high-quality properties. In the 1990s, Mercedes-Benz was a pioneer in the use of natural fibre-filled polymers, particularly jute fibres, in their manufacturing process [35]. Numerous industrial uses have since been investigated, including packaging, door frames, railway-sleepers, window frames, shelves, furniture, gardening supplies, automotive panels, and cost-sensitive uses that prioritise moderate mechanical strength [36]. Additionally, it has been demonstrated that it is feasible and economical to use recycled polymers as reinforcement in thermoset polymer-based composites (TSPc) and thermoplastic polymer-based composites (TPPc). These recycled polymers have been widely used in a variety of transportation contexts, including the interiors of cars, trains, boats, and more. Technical literature and online resources both provide comprehensive information on these applications. Leading producers of products like automotive panels, indoor-furniture panels, platforms, footboards, and noise-insulating panels have come from United States, Germany, Japan, Britain, and Italy [37]. As evidenced by the creation of bulletproof panels using ramie fibre-reinforced composites, the automotive industry, in particular, has played a crucial role. Through a hand lay-up process, these panels were painstakingly created using epoxy as the matrix material [38-40]. Bulletproof panels were designed to be more affordable and lightweight in comparison to traditional options.

Chemical Properties of Natural Fibre Composites (NFC)

Distinct types and qualities of fibres have effect on the chemical composition of NFs. The characteristics of fibre's component materials have a significant impact on the composition of fibre. Not only between different plants but also within the same plant's parts, different chemical compositions can be seen. Cellulose and hemicellulose, sugar-based polymers, are the primary components present in the cell walls of natural fibres, particularly in their dry state [41]. The complex cell architecture and chemical make-up of natural fibres are part of what give them their special qualities. These fibres exhibit differences in the percentages of cellulose, hemicellulose, lignin, and wax, which determine their suitability for various applications, such as textiles, paper production, and utilisation as raw materials in different industries. Bagasse, a byproduct of sugarcane processing, has a cellulose content of about 55.2%, a hemicellulose content of 16.8%, and a lignin content of 25.3%. Bamboo, on the other hand, exhibits a cellulose content ranging from 26% to 43%, with hemicellulose at 30% and lignin between 21% and 31%. Flax, a fibre that is frequently used to make textiles, contains 71 percent cellulose, 18 to 20 percent hemicellulose, 2 percent lignin, and 1.5 percent wax. Kenaf, a fibre commonly employed in paper production, contains 72% cellulose, 20.3% hemicellulose, and 9% lignin. Similarly, jute, which is popular in textile applications, has cellulose content ranging between 61% and 71%, hemicellulose ranging from 14% to 20%, lignin ranging from 12% to 13%, and wax at 0.5%. Lastly, hemp, renowned for its versatility, comprises 68% cellulose, 15% hemicellulose, 10% lignin, and 0.8% wax [42]. Ramie, abaca, sisal, coir, wheat straw, rice husk, rice straw, and milkweed exhibit diverse chemical compositions. Ramie contains cellulose in the range of 68.6% to 76.2%, hemicellulose between 13% and 16%, lignin ranging from 0.6% to 0.7%, and 0.3% wax. Abaca has cellulose content varying from 56% to 63%, hemicellulose between 20% and 25%, lignin ranging from 7% to 9%, and 3% wax. 65% of sisal is made up of cellulose; 12% of it is hemicellulose; 9.9% is lignin; and 2% is wax. Coir, derived from coconut husks, contains cellulose in the range of 32% to 43%, hemicellulose between 0.15% and 0.25%, lignin ranging from 40% to 45%, and no specified wax. Wheat straw exhibits cellulose content between 38% and 45%, hemicellulose ranging from 15% to 31%, lignin varying from 12% to 20%, and no specified wax. Rice husk has cellulose content ranging from 35% to 45%, hemicellulose between 19% and 25%, lignin at 20%, and wax ranging from 14% to 17%. Rice straw displays cellulose content between 41% and 57%, hemicellulose at 33%, lignin varying from 8% to 19%, and wax ranging from 8% to 38%. Milkweed, specifically Calotropis procera, shows cellulose content ranging from 60% to 75%, hemicellulose between 10% and 25%, lignin varying from 5% to 15%, and wax between 1% and 5% [43]. According to one theory, natural fibres are made up of cellulose microfibrils arranged in a helical structure and encased in the amorphous lignin matrix. α-cellulose, pectins, lignin, wax, and hemicellulose make up the majority of these fibres. The fibre's thermal degradation, moisture absorption, and biodegradation are all caused by hemicellulose, which works as a compatibilizer between lignin and cellulose [44]. On the other hand, lignin, a thermally stable phenylpropane derivative, controls fluid transfer within the plant and contributes significantly to UV degradation [45]. The cellulose content of the fibre is an important factor influencing the composite material strength, according to research by Bismark [46].

Mechanical Properties of Natural Fibre Composites

(NFC)

Natural fibre orientation, fibre shape, properties of matrix, volume fraction, and adhesion of the fibres to the polymer matrix affect the mechanical properties of composite materials made of natural fibres. In general, natural fibres have weaker mechanical characteristics than synthetic fibres. Mechanical properties of these composites are influenced by the fibre's volume fraction. Composites with higher fibre contents produce better properties. The arrangement and orientation of the fibres, however, dictate the maximum volume fraction that can be achieved [47]. Another crucial element influencing the performance of NFC is the strength of the interface between fibres and matrix [48]. Through shear stresses along the fibre-matrix interface, this interface helps load transfer from matrix to fibres. High interfacial adhesion typically results in the desired functionality, efficient stress transfer, and higher strength. Through particular failure mechanisms, weaker interfacial adhesion can result in fibre pullout and energy absorption. The efficiency of stress transfer is significantly affected by bonding between matrix and fibres, especially when the matrix cracks under load [49]. Cotton is a popular natural fibre with 1.5 to 1.6 g/cm3 density that is used extensively. It exhibits 400 MPa tensile strength, an elongation between 7.0% and 8.0%, and an elastic modulus between 5.5 and 12.6 GPa. Another widely used fibre is jute, which has 1.3 g/cm3 density. It has 26.5 GPa elastic modulus, an elongation between 1.5% and 1.8%, and tensile strengths between 393 MPa and 773 MPa. Flax exhibits an elongation between 2.7% and 3.2% and has 1.5 g/cm3 density. Its elastic modulus is roughly 27.6 GPa, and tensile strength ranges from 500 MPa-1500 MPa. Hemp has 1.47 g/cm3 density, and it stretches between 2% and 4%. It has a high elastic modulus of 70 GPa and a high tensile strength of 690 MPa. Kenaf has an elongation of 1.6% and 1.45 g/cm3 density. It exhibits 53 GPa elastic modulus and 930 MPa tensile strength. Ramie exhibits an elongation of between 3.6% and 3.8%. While the elastic modulus varies from 61.4 GPa to 128 GPa, the tensile strength ranges from 400 MPa to 938 MPa. Sisal has an elongation of 2.0% to 2.5% and 1.5 g/cm3 density. Its elastic modulus ranges from 9.4 GPa to 22 GPa, and its tensile strength ranges from 511 MPa to 635 MPa. The density of milkweed, Calotropis procera, ranges from 1.3 to 1.5 g/cm3. Its elastic modulus ranges from 5 GPa to 10 GPa, its elongation ranges from 2% to 5%, and its tensile strength ranges from 100 MPa to 400 MPa. Coir, which is made of coconut husks, has 1.2 g/cm3 density. It exhibits a 30% high elongation, a 593 MPa tensile strength, and an elastic modulus ranging from 4.0 GPa to 6.0 GPa [50-52].

Conclusion

The applications of NFR polymer composites has seen notable rise in interest in recent years. This interest can be attributed to their compatibility with the environment, use of sustainable resources, and potential to improve mechanical properties. Different natural fibres like- jute, flax, hemp, kenaf, sisal, and Calotropis procera, have a variety of properties and are widely accessible, making them appropriate for a variety of applications in a variety of industries. These fibres have been shown to improve strength, stiffness, and impact resistance when used as reinforcements in polymer matrices like thermoplastics and thermosets. To improve composite performance, it is necessary to address the issues brought on by the conflict between hydrophilic natural fibres (HNF) and hydrophobic polymer matrices (HPM). Researchers have investigated modifications at the fibre-polymer interface to increase adhesion and compatibility, such as the use of coupling agents and surface treatments. These methods have produced encouraging results in improving the characteristics of composites.

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