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A Review of Natural Fiber-Reinforced Polymer Composite Chemical, Physical, and Thermo-Mechanical Properties

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Abstract. *The current study reviews provide a brief overview on the properties of natural fiber and natural fiber reinforced composites like chemical, physical, mechanical properties and thermal behavior which is an emerging area in polymer science. The unique properties of these composites are based on the attributes of the individual components, as well as the relative numbers and arrangements of those components within the material system. The widespread acceptance of composites reinforced with natural fibers has attracted many researchers due to its cost, sustainability, low environmental impact and great availability in nature. The processing of natural fibers is not difficult as compared to the production of conventional fibers. In the construction, aerospace, military, building, packaging, consumer products, and transportation industries for ceiling, paneling, partition boards, etc., natural fibers have shown to be a successful substitute for synthetic fiber. Because of these factors, natural fibers are preferred to conventional fibers. However, natural fiber reinforced composites also have some negative aspects such as increased susceptibility to water damage, less durability in the event of a fire, and diminished strength when they are subjected to mechanical stress. In this paper, the overview related to the natural fiber-reinforced composites and their properties is provided.*

Keywords: *Natural Fibers; Physical & Mechanical properties; Polymer composites; Thermal behavior*

1. Introduction

Each component (particles/fibers/reinforcement) in a composite material contributes unique mechanical, thermal, electrical, and thermal properties to the final product. Mixing them together creates a material optimized for a certain use, such as being more durable, lighter, or electrically resistant. Moreover, they can aid with firmness and strength. Their enhanced characteristics and adaptability make them preferable to more conventional materials. New environmental constraints and rising petroleum usage, along with a general increase in public interest in environmental issues, have prompted the search for eco-friendly substitutes. Many problems, including pollution of the environment, improper disposal of trash, excessive use of

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petroleum, and so on, have prompted a worldwide search for alternatives. When compared to synthetic fiber, natural fiber has superior characteristics and is therefore widely regarded as an eco-friendly material [1].

Thus, it's crucial that natural fibers be utilized. Natural fibers provide many advantages over conventional reinforcing materials, including lower density, lower cost, lighter weight, biodegradability, higher specific strength, stiffness, good thermal characteristics, and resistance to corrosion. Fibers derived from plants or animals are considered natural, as opposed to synthetic or artificial [2]. There has been a lot of interest in using natural fibers from renewable and nonrenewable resources including oil palm, sisal, flax, and jute to create composite materials in recent decades [3]. Plants produce many kinds of cellulose fibers, including seed fibers (cotton, coir, etc.), bast fibers (jute, hemp, flax, ramie and kenaf), grass fibers (rice, corn, and wheat), leaf fibers (sisal, pineapple, and abaca), core fibers (hemp and kenaf,), and all other kinds (wood and roots) [4].

Synthetic fiber-based composites have several serious drawbacks, including high price, significant energy consumption in manufacturing and production process, poor reprocessing and non-renewability features, Emissions of carbon dioxide, and health hazards when breathed [5]. As a result of these shortcomings, natural composite materials have emerged as a potential substitute for synthetic fiber composites. When burned at the end of their service life, natural fibers, contrary synthetic fibers, result in increased energy recovery and zero net CO_2 emissions, which is good for carbon credits and reduces the planet-warming impact [6]. Reduced moisture resistance, thermal decomposition and weathering effect of fiber and the matrix, reduced durability, poor interfacial bonding that leads to delamination, poor wettability of polymer matrix impregnated into spots between fibrils, and fiber breakdown during production processes are just some of the issues that prevent natural fibers and reusable polymers from being widely used in emerging novel composites [7]. Over the past few years, the use of natural fiber polymer composites in consumer goods and emerging industry sectors has increased significantly. In several engineering domains, its applications expands quickly [8]. Because of this, striking a reasonable balance between the cost of composite manufacture and the overall qualities maybe easily accomplished by carefully selecting the proper materials and designing the structure.

The term "natural fiber" refers to any raw material which resembles hair like structure and can be derived directly from vegetable, animal, or mineral source. This material can then be transformed into nonwovens such as paper or felt, or woven fabric after being spun into yarns. Natural fibers can be broken down into three categories based upon plants, animals, and minerals, whereas plant fibers are the most common type of natural fiber. Plant fibers are any fibers that contain cellulose in a significant proportion and are produced by plants. Cotton, hemp, flax, jute, ramie, and sisal are some examples of plant fibers. During the production process of cardboard and other materials, the cellulose fibers are given an active state [9]. There are several animal fibers that include proteins, such as mohair, fleece, silk, angora, and alpaca. Animal hairs can come from a variety of sources, including horse hair, sheep's fleece, rabbit's hair, goat hair, alpaca hair, and other animal fibers. After the larvae of silk moths have grown by consuming mulberry leaves, they secrete a type of protein that is fibrous and forms a hard shell around them in the manner of an enclosure. Cocoon refers to the covering that is around the larvae. This cocoon of the silkworm is where the silk is extracted. Avian fibers are a type of natural fiber that are derived from the feathers of birds and other flying animals. Mineral fibers are the most prevalent type of fiber obtained from minerals, yet they are also one of the least suitable types. There are several different categories that it falls under, and they are as follows: The most common type of mineral fiber is known as asbestos. There are several varieties of mineral fibers, some examples of which are anthophyllite, serpentine, etc. Ceramic fibers consist of aluminum oxide, glass fibers, boron carbide, and silicon carbide. Glass fibers are also a type of ceramic fiber. An additional way to define a natural fiber is as an agglomeration of cells that have a tiny diameter in comparison to their length. The some of the advantages and disadvantages of natural fiber and synthetic fiber are shown in Table 1.

Table1. Advantages and disadvantages of natural fibers and synthetic fibers [10].

Type of Fiber	Advantages	Disadvantages
Natural Fiber	Lightweight	Flammable
	Recyclable	Dimensional instability
	Improved specific mechanical properties	High moisture absorption
	Eco-friendly, carbon dioxide neutrality	Anisotropic behavior
	Do not generate any harmful gases during processing, low energy requirements during production	Limited processing temperature (~200-230°C)
	Good thermal properties	Sensitive to UV
	Good acoustic properties	Fugal attack and microbial
	Low cost, availability, renewable resources, disposal by composting	Low strength than synthetic fibers, especially impact strength
	Non-abrasive and great formability	Variable quality, influenced by weather
	No dermal issue for their handling	Low durability
	Safer crash behaviour in tests	Poor fiber/matrix adhesion
Synthetic Fiber	Long lasting	Flammable
	Readily pick-up to various dyes	Prone to heat damage
	Stretchable	Melt easily
	Waterproofing	Not eco-friendly
	Non biodegradability	Cause for microplastic pollution
	Moisture resistance	Not suitable for hot washing
	Strain and wear resistance	Poor insulation capacity
	High production	Moderate recyclability

Although there is a plethora of fibrous materials in the natural world, particularly cellulosic forms such as cotton, wood stems, and straw, a very low percentage of these can be utilized in textiles or other industrial purposes. In addition to economic considerations, the commercial utility of a fiber is determined by characteristics such as its length, strength, uniformity, fineness, resilience, pliability, elasticity, resistance to abrasion, absorbency, and other surface attributes. The comprehensive classification of natural fibers is depicted in Figure 1.

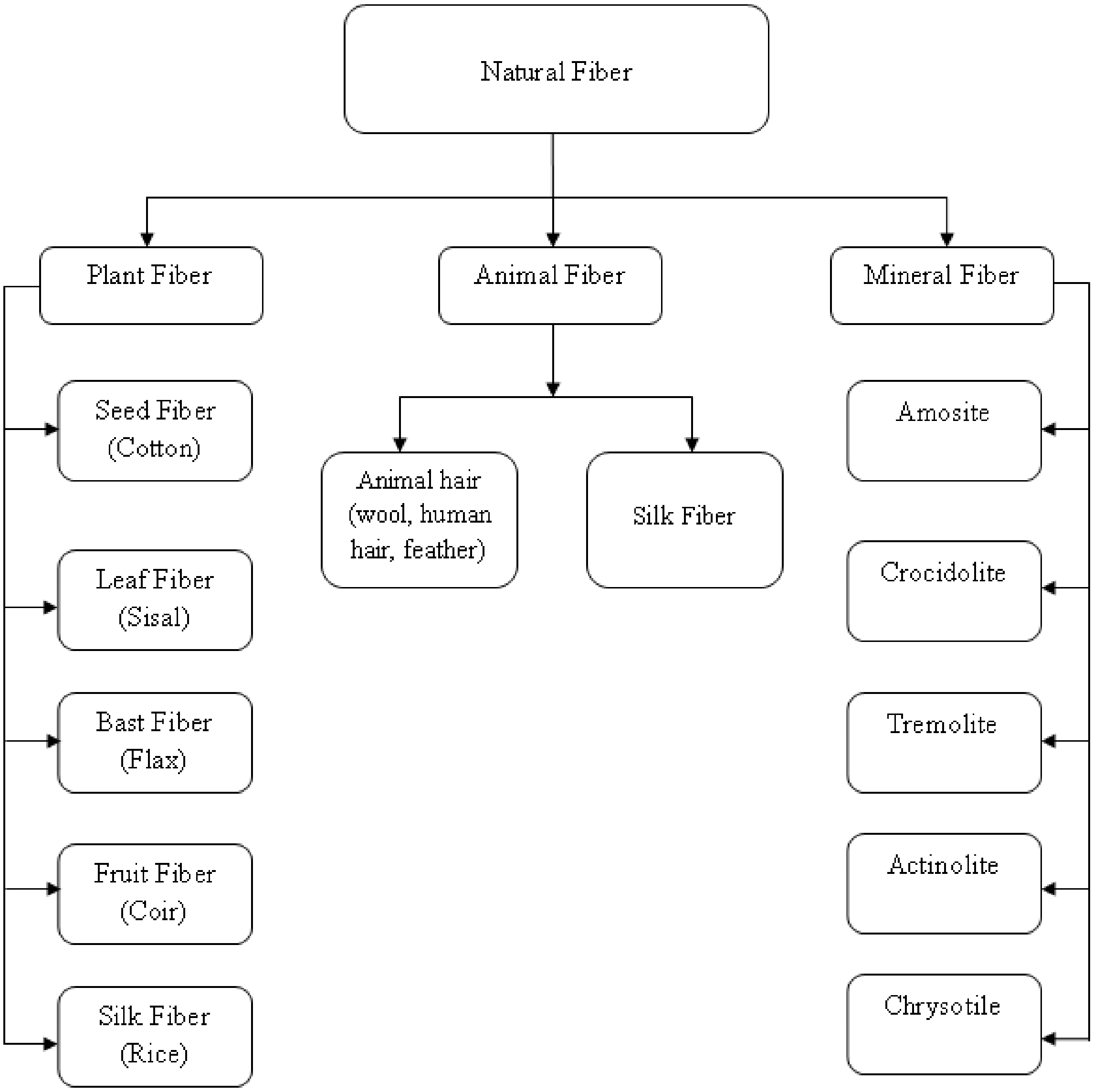

Figure 1. Classification of natural fibers [11]

The scope of use for natural fibers expands daily, especially in the automotive industry, which has significantly increased their use. Based on these natural fibers, researchers have done a lot of work in this field. For applications requiring a high strength-to-weight ratio and additional weight reduction, natural fibers have the potential to be employed in place of conventional reinforcement materials in composites. Therefore, the current work review examines the physical, mechanical properties and thermal behavior of natural fiber reinforced polymer composites over the synthetic fiber reinforced polymer composites.

2. Chemical and Physical Properties of natural fiber reinforced composites

When a substance passes through a chemical reaction, researchers can learn more about its attributes and qualities, which are known as its chemical properties. Chemical habitats can be observed either during or after a reaction since it is necessary to disrupt the connections between atoms that make up a pattern to investigate the attribute [12]. This is different from a body property, which is a trait that can be measured without altering the chemical identity of a sample. Most natural fibers are made up of cellulose (60–80%), hemicelluloses, amorphous lignin, and water (up to 5–20%) [4]. Depending on the weather, natural fibers may also have pectin, wax, protein, tannins, inorganic salt, and a chemical that dissolves in water. It is important to know how polymers react to their surroundings [13]. The plant has cellulose, which is a main part of the cell wall. The number of polymers and organic components varies from plant to plant [14]. Cellulose is the commonlyused organic polymer on the planet, and it doesn't have a taste or smell. Cellulose is made up of crystals, which give the plant a lot of strength. Cellulose has a long polymer chain that is highly polymerized (Degree of polymerization 2000-6000) and has a high molecular weight (3×10^4 – 2×10^5 g mol^{-1}) [15, 16]. Another component of plant cell walls is called hemicellulose. Hemicellulose is a mixture of many plant polysaccharides that have a lower molecular weight as compared to cellulose. Hemicellulose occurs naturally but has a random, unshaped structure that makes it weak, polymerizes slowly, and is highly hydrophilic. Lignin is a class of organic polymers that plays a significant role in the secondary cell walls of plants and is present in the connective tissues of vascular plants and algae. Lignin has greater thermal stability than cellulose and hemicelluloses, and it acts as a bonding agent for cellulose fibers that bind neighbouring cells together [17]. Figure 2 shows the chemical structure of different constituents of natural fibers.

Chemical treatments of natural fibers are the most suitable technique to enhance adhesion with polymers, better strength and water absorption resistance, and enhanced composite characteristics, as described by Parul Sahu *et al*. [18]. Alkali treatment was also mentioned as the most popular and versatile chemical treatment option for modifying the surface of natural fibers.

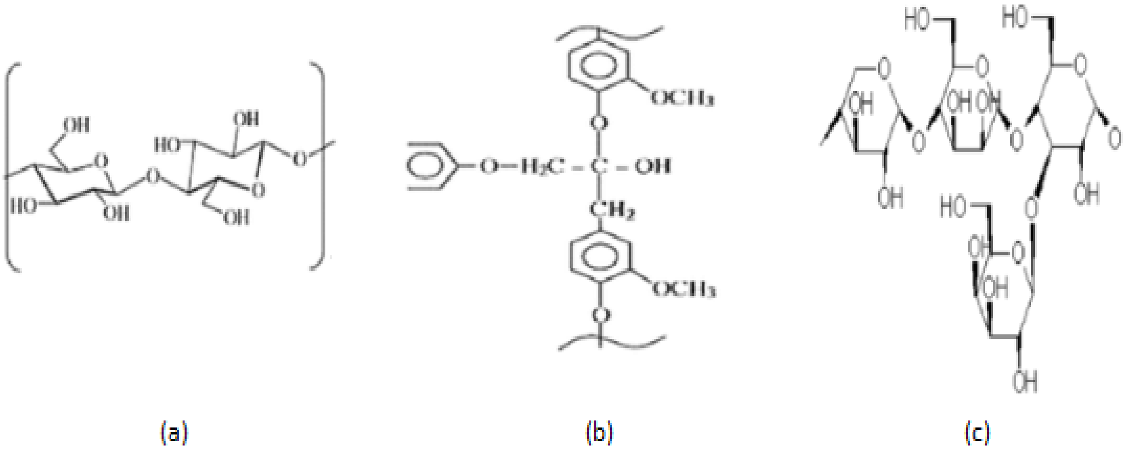

Figure 2: Chemical structure of different constituents of natural fibers [19]
a) Cellulose b) Lignin c) Hemicellulose.

Palm fibers' chemical extraction process was studied by S. Zannen *et al*. [20]. Soda treatment is used as the extraction procedure by the researchers. The outcomes demonstrate that the properties of Palm fibers are modified by soda treatment. The studied fibers had a low density of less than 1, and their diameter and linear density improved with increasing the soda concentration, temperature, and treatment time. The FTIR spectra also show that the alkali treatment causes a structural shift, increasing the amount of exposed cellulose on the fiber surface and, by extension, the number of active reaction sites (OH groups). To improve adhesion between the hydrophilic fibers and the hydrophobic matrix, chemical modification of natural fibers is required, as studied by Anu Gupta *et al*. [21]. Their research shows that almost all natural fibers may be successfully treated using alkali treatment, making it the most popular and effective method of chemical modification. Whereas most chemical treatments weakened the material by breaking down the bond structure and disintegrating non-cellulosic materials, silane treatment led to the development of strong covalent bonds, which improved the material's strength. Thus, composites' chemical treatment is still essential for providing sector-specific functional properties. The Physio-chemical properties of polymer bio composites based on resorcinol-formaldehyde resin matrices, reinforced with pine needles fibers, are studied by Vijay Thakur *et al*. [22]. Researchers found that the hydrophilic nature of the lignocellulosic fiber made polymer composites vulnerable to changes in swelling, moisture, and chemical resistance. Besides these limitations, pine needles can be used as a reinforcing material in place of synthetic fibers in the fabrication of a wide range of environmentally friendly polymer matrix based composites. Table 2 outlines the chemical and physical characteristics of natural fibers.

Table 2. Chemical & Physical Properties of Natural Fibers. [12, 18]

Sr. No.	Name of Fiber	Cellulose (%)	Hemi Cellulose (%)	Lignin (%)	Density (g/cm^3)
1	Abaca	56-63	20-25	7-13	1.5

2	Alfa	45.4	38.5	14.9	0.89
3	Bamboo	26-65	30	5-31	0.91
4	Banana	62-64	19	5	0.8
5	Betel nut	53.2	32.98	7.2	1.34
6	Coir	37	20	42	1.2
7	Cotton	82.7-90	5.7	< 2	1.5-1.6
8	Curaua	70.7-73.6	9.9	7.5-11.1	1.4
9	Flax	71	18.6-21.6	2.2	1.5
10	Hemp	57-77	14-22.4	3.7-13	1.47
11	Henequen	60-77.6	4-28	8-13.1	1.2
12	Jute	59-71.5	13.6-20.4	11.8-13	1.3-1.49
13	Kenaf	45-57	8-13	21.5	1.22-1.4
14	Palm	60-65	-	11-29	1.03
15	Piassava	28.6	25.8	45	1.10-1.45
16	Ramie	68.6-91	5-16.7	0.6-0.7	1.5
17	Sisal	78	25.7	12.1	1.3-1.5

3. Mechanical Properties of natural fiber reinforced composites

The mechanical properties of a substance are utilized for categorizing and distinguishing it from others. The mechanical qualities of a substance describe how it reacts to an applied force. The mechanical properties of natural fiber composites (NFCs) are often tested in tensile, flexural, impact, and water absorption [14]. The durability of composites made from natural fibers is a major factor in choosing the kind of natural fibers to use for different purposes [15]. Matrix choice, polymer interfacial strength, dispersing, orientation, production methods, and porosity all play a role in determining NFC's mechanical properties [23]. Table 3 lists the various mechanical parameters of natural fibers.

Mechanical behaviour of flax, jute, and hemp composite structures under pure compression is studied by M.R. Bambach. If fiber and resin design, as well as structural geometry, are given the consideration they need, natural fiber composites have the potential to become a competitive alternative to traditional building materials soon [24]. The mechanical properties of composites made from woven banana fiber, kenaf fiber, and banana/kenaf hybrid fiber were studied by A. Alavudeen *et al*. [25]. Mechanical strength of woven banana/kenaf fiber hybrid composites is enhanced by hybridization with kenaf. The combined tensile, flexural, and impact strengths of banana and kenaf fibers in a woven hybrid composite are greater than those of either fiber alone. The mechanical characteristics of sisal, jute, and glass fiber reinforced polyester composites were investigated by M. Ramesh *et al*. [26]. According to their research, incorporating glass fiber into a composite made of jute fiber increases its tensile strength. Similarly, they discovered that a sisal fiber composite can attain maximum impact strength and that a jute and sisal mixed composite sample may attain maximum flexural strength and maximum impact strength.Composites with and without silica were made by reinforcing biodegradable sisal fibers with a polyester matrix, as demonstrated by the work of A. Gowthami *et al*. [27]. Both the tensile strength and tensile modulus of composites with silica were found to be greater than those of composites without silica. Additionally, the impact strength of silica-containing composites is higher than that of silica-free composites or plain polyester.Bamboofiber composites packed with cenosphere were the focus of research by Hemalata Jena *et al*. [28]. They discovered that the impact properties of bio-fiber reinforced composites were drastically altered by employing cenosphere as a filler and lamina. Once the impact strength of a laminated composite has been increased by a certain amount of filler, any further increase will reduce the laminate's strength. Girisha, C. *et al*. [29] looked at the mechanical properties of composites made from chemically treated fibers extracted from arecanut husk and fibers from tamarind fruit. They discovered that treated fibers done much better than their untreated counterparts. Strength in hybrid composites was also observed to increase with increasing fiber volume fraction. After studying the impact of jute fiber reinforcement on polypropylene-based composites, Berhanu *et al*. [30] observed that mechanical properties increased with increasing jute weight percentage up to 40%. D. dash *et al*. [31] looked at the mechanical properties of a composite made from natural fibers (bamboo and jute fiber) and compared it to a composite made from glass fibers and epoxy. Laminated bamboo fiber composite was discovered to have more tensile strength and stiffness than jute fiber reinforced composite but less than glass fiber reinforced composite. In their investigation into the effects of hybridization on the mechanical properties of a coir-glass hybrid laminate, Jayabal *et al*. [32] discovered that natural coir fiber fails more quickly than glass fiber, and that the addition of glass fibers at extreme plies improves the mechanical properties of coir laminates.

Ashik *et al*. [33] examined the use and development of natural fibers across time. They also studied the mechanical and physical qualities and potential uses of natural fibers (including hemp, jute, bamboo, and sisal) as a substitute for glass fiber. In a urea-formaldehyde (UF) resin-based polymer matrix, Hibiscus sabdariffa using as a reinforcing material, Singha *et al*. [34] investigated the synthesis and mechanical properties of a new series of green composites. Tensile, compressive, and wear characteristics, etc. were studied as a function of fiber loading in polymer composites containing Hibiscus sabdariffa fibers that were randomly oriented and closely mixed. The researchers discovered that reinforcing the urea-formaldehyde resin with the fiber significantly improved its mechanical qualities. Mechanical testing of natural fiber granulated composites (NFGC) made with a hybrid additive manufacturing process, including tensile, flexural, effects, and stiffness tests, is explored by Anand Kumar *et al*. [35]. Hardness, Tensile, flexural, and impact strength have all increased as a result of their efforts. Additionally, they proposed a new way for generating the composites to replace the more conventional approaches.

Table 3. Mechanical Properties of Natural Fibers [12, 18]

Sr. No.	Name of fiber	Tensile strength (MPa)	Young's modulus (GPa)	Flexural strength (MPa)
1	Abaca	400-980	6.2-20	-
2	Alfa	35	22	-
3	Bamboo	140-800	11-32	32
4	Banana	600	17.85	76.53
5	Coconut	500	2.50	58
6	Coir	175	4-6	6
7	Cotton	400	12	43.3
8	Curaua	87-1150	11.8-96	-
9	Flax	800-1500	60-80	165
10	Fique	200	8-12	-
11	Hemp	550-900	70	-
12	Henequen	430-570	10.1-16.3	95
13	Harakeke	778	32.09	225
14	Jute	320-800	8-78	45
15	Kenaf	930	53	74
16	Palf	170	-	-
17	Palm	377	2.75	24.4
18	Piassava	134-143	1.07-4.59	-
19	Pineapple	413-1627	34.5-84.5	-
20	Ramie	500	44	-
21	Sisal	600-700	38	288.6
22	Vakka	549	15.85	-
23	Wool	120-174	2.3-3.4	-

4. Thermal Properties of natural fiber reinforced composites

Researchers have found that natural fibers decompose at different temperatures, confirming anecdotal evidence from earlier studies. Given the importance of processing temperature in the production of natural fiber composites, it is important to consider the thermal stability of these materials. The mechanical and thermal properties of composites made from natural fibers alter as their mechanical stability deteriorates at increasing temperatures. Recent advances in fiber treatment techniques and modification procedures, the exploration of new natural fibers, and hybridization have overcome some of the limitations of natural fiber reinforced composites. Fiber modification procedures improve fiber-matrix interfacial adhesion, fiber roughness, and wettability, whereas hybridization techniques permit flexible fiber selection for the material's attributes as per the requirements of the ultimate use [36]. Thermal behaviour of thermoplastic polyurethane (TPU) composites reinforced with roselle fiber (RF)/sugar pal fiber was studied by Radzi *et al*. [37]. Researchers were able to identify the different stages of plant fiber degradation from the thermogravimetric (TGA) profile analysis, which analyses the change in weight percentage of the sample depends upon temperature. The thermal characteristics of banana fiber and raw jute reinforced epoxy hybrid composites were investigated by Boopalan *et al*. [38]. The researchers created composites with varied weight ratios of banana and jute fiber, and discovered that an even combination of the two demonstrated the optimum thermal qualities. The thermal stability of hybrid bioepoxy composites made from sisal and kenaf woven fabrics was investigated by Yorseng *et al*. [39] both before and after subjecting them to an accelerated weathering test. The researchers in the study made up five separate samples and epoxy composites showed the same thermal stability regardless of fiber of fabric, fabric sequence, or rapid weathering. The dynamic mechanical evaluation of fiber-reinforced hybrid unsaturated polyester resin composites based on long jute and sisal fibers was studied by Gupta *et al*. [40], who generated five composites with varied fiber content. The results confirmed the feasibility of hybridising natural fibers for improved thermomechanical characteristics as demonstrated by the researchers. The study by Zuhudi *et al*. [41] looked at the hybridized bamboo fabric and glass fiber-reinforced polypropylene composites and investigates theirdynamic and mechanical properties. The results indicated that the storage modulus of the PP was enhanced by the addition of bamboo fibers due to the strengthening effect that the bamboo fiber imparts and the high modulus of the bamboo fibers. However, the storage modulus of the PP composites reinforced with a single bamboo fiber was even further improved when glass fibers were substituted for the bamboo fibers. This is because of glass fiber's high modulus, in comparison to bamboo cloth's low modulus, and has a hybrid effect.

5. Research Gap and future scope

Based on the current study reviews, a potential research gap could be the need for further investigation and improvement of the interfacial bonding between natural fibers and polymer matrices in composite materials. The study mentions that poor interfacial bonding can lead to issues such as delamination, reduced durability, and poor wettability of the polymer matrix. Addressing these challenges and developing effective techniques to enhance interfacial bonding could contribute to the wider utilization of natural fiber-reinforced polymer composites in various industries.

Additionally, this study briefly mentions that the mechanical properties of natural fiber composites are influenced by various factors such as matrix choice, polymer interfacial strength, dispersing, orientation, production methods, and porosity. Exploring these factors in more detail and identifying optimal combinations could be another potential research direction.

Furthermore, although the study discusses the chemical and physical properties of natural fibers, it does not delve into the potential effects of chemical treatments on these properties and the resulting impact on the mechanical behavior of the composites. Investigating the influence of various chemical treatments on natural fibers and their subsequent effects on the mechanical properties could provide valuable insights for composite material design and optimization.

6. Conclusions

In present study natural fibers reinforced composite materials are reviewed in terms of their physical, mechanical, and thermal characteristics. Due to its low density, great flexibility, high specific strength,wide availability, and lower cost, natural fiber is a promising resource material for a wide range of engineering fields, including the electrical, automotive, railway, building material, geotextile, defense, packaging, and household application sectors. To that end, these characteristics make natural fiber reinforced composites a superior alternative to synthetic fiber reinforced composites. Products made from natural fiber composites are better for the environment than those made from synthetic fiber polymer composites. When natural fibers are utilized to reinforce polymers, the polymers' mechanical and thermal characteristics are enhanced. Filler phases can be introduced into the matrix body of a composite to alter its physical, mechanical, and thermal properties. Fillers are added to composites to boost their performance in mechanical and thermal environments. Thus, the hybrid composite is crucial since the basic composite can only be used in semi-structural and non-structural applications. Hybrid composites produce a solution that strikes a good balance between mechanical, chemical, and thermal qualities as well as cost.

References

[1] K. L. Pickering, M. G. A. Efendy, T. M. Le, "A review of recent developments in natural fiber composites and their mechanical performance," *Composites Part A: Applied Science and Manufacturing*, vol 83, pp 98-112, 2016, https://doi.org/10.1016/j.compositesa.2015.08.038

[2] A. Ticoalu, T. Aravinthan, and F. Cardona, "A review ofcurrent development in natural fiber composites for structural and infrastructure applications," *in Proceedings of the Southern Region Engineering Conference (SREC '10)*, Toowoomba, Australia, 2010, pp. 113-117.

[3] L. Mohammed, M. N. M. Ansari, G. Pua, M. Jawaid, and M. S. Islam, "A Review on Natural Fiber Reinforced Polymer Composite and Its Applications," *International Journal of Polymer Science*, vol. 2015, pp 15, 2015, https://doi.org/10.1155/2015/243947

[4] O. Faruk, A. K. Bledzki, H. P. Fink, & M. Sain, "Biocomposites reinforced with natural fibers: 2000-2010," *Progress in Polymer Science*, vol. 37, no. 11, pp. 1552-1596, 2012, https://doi.org/10.1016/j.progpolymsci.2012.04.003

[5] T. Alsaeed, B. F. Yousif, and H. Ku, "A review on the mechanical properties and machinability of natural fiber reinforced composites," *Int J Precis Technol*., vol. 3, no. 2, pp. 152-182, 2013, https://doi.org/10.1504/IJPTECH.2013.053303

[6] A. Lotfi, H. Li, D. V. Dao, and G. Prusty, "Natural fiber–reinforced composites: A review on material, manufacturing, and machinability," *Journal of Thermoplastic Composite Materials*, vol 34, no. 2, pp. 1–47, 2019, https://doi.org/10.1177/0892705719844546

[7] M. J. John, and S. Thomas, "Biofibers and biocomposites," *Carbohydr. Polym.*, vol. 71, no. 3, pp. 343-364, 2008, https://doi.org/10.1016/j.carbpol.2007.05.040

[8] F. I. Mahir, K. N. Keya, B. Sarker, K. M. Nahiun, R. A. Khan, "A brief review on natural fiber used as a replacement of synthetic fiber in polymer composites," *Mater Eng Res*, vol. 1, no. 2, pp. 88-97, 2019, https://doi.org/10.25082/MER.2019.02.007

[9] A. L. Naidu, V. Jagadeesh, and M. V. A. R. Bahubalendruni, "A review on chemical and physical properties of natural fiber reinforced composites," *International Journal of Advanced Research in Engineering and Technology (IJARET)*, vol. 8, no. 1, pp. 56-68, 2017, https://www.academia.edu/download/52099317/IJARET_08_01_006.pdf

[10] M. Z. Asyraf *et al.*, "Development of Natural Fibre-Reinforced Polymer Composites Ballistic Helmet Using Concurrent Engineering Approach: A Brief Review," *Sustainability*, 14, pp. 7092, 2022, https://doi.org/10.3390/su14127092

[11] P. Tesinova, *Advances In Composite Materials - Analysis Of Natural And Man-Made Materials*. Croatia, InTech, Sept. 2011.

[12] K. Srinivas, A. L. Naidu, and M. V. A. R. Bahubalendruni, "A Review on Chemical and Mechanical Properties of Natural Fiber Reinforced Polymer Composites", *International Journal of Performability Engineering*, vol. 13, no. 2, pp. 189-200, 2017, https://doi.org/10.23940/ijpe.17.02.p8.189200

[13] S. Kumar, *et al.*, "Physical and Mechanical Properties of Natural Leaf Fiber-Reinforced Epoxy Polyester Composites," *Polymers*, vol. 13, no. 9, pp. 1369, 2021, https://doi.org/10.3390/polym13091369

[14] A. K. Mohanty, M. Misra, and L. T. Drzal, "Sustainable Bio-composites from Renewable Resources: Opportunities and Challenges in the Green Materials World," *Journal of Polymers and the Environment*, vol. 10, pp. 19–26, 2022, https://doi.org/10.1023/A:1021013921916

[15] A. Gholampour, and T. Ozbakkaloglu, "A review of natural fiber composites: Properties, modification and processing techniques, characterization, applications," *J. Mater. Sci*., vol. 55, pp. 829-892, 2020, https://doi.org/10.1007/s10853-019-03990-y

[16] P. Basu, *Biomass Gasification, Pyrolysis and Torrefaction*. Elsevier: Amsterdam, The Netherlands, Academic Press, 2013.

[17] A. K. Bledzki, "Composites reinforced with cellulose based fibers," *Prog. Polym. Sci*., vol. 24, pp. 221-274, 1994, https://cir.nii.ac.jp/crid/1570009750727183744

[18] P. Sahu, and M. K. Gupta. "A review on the properties of natural fibers and its bio-composites: Effect of alkali treatment," *Journal of Materials: Design and Applications*, vol. 234, no. 1, pp. 198-217, 2020, https://doi.org/10.1177/1464420719875163

[19] S. O. Amiandamhen, M. Meincken, and L. Tyhoda, "Natural fibre modification and its influence on fibre-matrix interfacial properties in bio composite materials," *Fibers and polymers*, vol. 21, pp. 677-689, 2020, https://doi.org/10.1007/s12221-020-9362-5

[20] S. Zannen, L. Ghali, M. T. Halimi, M. Ben Hssen, "Effect of Chemical Extraction on Physicochemical and Mechanical Properties of Doum Palm Fibres," *Advances in Materials Physics and Chemistry*, vol. 4, noo. 10, pp. 203-216, 2014, https://doi.org/10.4236/ampc.2014.410024

[21] A. Gupta, and A. Kumar, "Chemical Properties of Natural Fiber Composites and Mechanisms of Chemical Modifications," *Asian Journal of Chemistry*, vol. 24, no. 4, pp. 1831-1836, 2012, https://www.researchgate.net/profile/Anu-Gupta-15/publication/279909306_Chemical_Properties_of_Natural_Fiber_Composites_and_Mechanisms_of_Chemical_Modifications/links/578b930708ae7a588eeece83/Chemical-Properties-of-Natural-Fiber-Composites-and-Mechanisms-of-Chemical-Modifications.pdf

[22] V. K. Thakur, and A. S. Singha, "Physico-chemical and Mechanical Characterization of Natural Fiber Reinforced Polymer Composites," *Iranian Polymer Journal*, vol. 19, no. 1, pp. 3-16, 2010, https://www.sid.ir/en/vewssid/j_pdf/813201011501.pdf

[23] K. L. Pickering, M. G. A. Efendy, T. M. Le, "A review of recent developments in natural fibre composites and their mechanical performance," *Compos. Part A Appl. Sci. Manuf.*, vol. 83, pp. 98-112, 2016, https://doi.org/10.1016/j.compositesa.2015.08.038

[24] M. R. Bambach, "Compression strength of natural fibre composite plates and sections of flax, jute and hemp," *Thin-Walled Structures*, vol. 119, pp 103-113, 2017, https://doi.org/10.1016/j.tws.2017.05.034

[25] A. Alavudeen, N. Rajini, S. Karthikeyan, M. Thiruchitrambalam, and N. Venkateshwaren, "Mechanical Properties of Banana/Kenaf Fiber-Reinforced Hybrid Polyester Composites: Effect of Woven Fabric and Random Orientation," *Materials and Design*, vol. 66, pp. 246-257, 2015, https://doi.org/10.1016/j.matdes.2014.10.067

[26] M. Ramesh, K. Palanikumar, and K. H. Reddy, "Mechanical Property Evaluation of Sisal-Jute-Glass Fiber Reinforced Polyester Composites," *Composites: Part B*, vol. 48, pp. 1-9, 2013, https://doi.org/10.1016/j.compositesb.2012.12.004

[27] A. Gowthami, K. Ramanaiah, A. V. R. Prasad, K. H. C. Reddy, and K. M. Rao, G. S. Babu, "Effect of Silica on Thermal and Mechanical Properties If Sisal Fiber Reinforced Polyster Composites," *Journal of Material Environment Science*, vol. 4, no. 2, pp. 199-204, 2012 https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=38e2327c3117795af2cf2638d07a3ae91e75c821

[28] H. Jena, M. Ku. Pandit, and A. Ku. Pradhan, "Study the Impact Property of Laminated Bamboo-Fiber Composite Filled with Cenosphere," *International Journal of Environmental Science and Development*, vol. 3, no. 5, pp. 456-459, 2012, https://doi.org/10.7763/IJESD.2012.V3.266

[29] C. Girisha, Sanjeevamurthy, G. Rangasrinivas, and S. Manu, "Mechanical Performance of Natural Fiber-Reinforced Epoxy-Hybrid Composites," *International Journal of Engineering Research and Applications (IJERA)*, vol. 2, no. 5, pp. 615-619, 2012, https://www.ijera.com/papers/Vol2_issue5/DS25715719.pdf

[30] T. Berhanu, P. Kumar, and I. Singh, "Mechanical Behaviour of Jute Fiber Reinforced Polypropylene Composites," in *5th International &26th All India Manufacturing Technology, Design and Research Conference AIMTDR*, Guwahati, Assam, India, 2014, Dec. 12-14, 2014, pp. 289 1-6.

[31] D. Dash, S. Samanta, S. S. Gautam, and M. Murlidhar, "Mechanical Characterizations of Natural Fiber Reinforced Composite Materials," *Advanced Materials Manufacturing & Characterization*, vol. 3, no. 1, pp. 275-279, 2013, http://dx.doi.org/10.11127/ijammc.2013.02.050

[32] S. Jayabal, U. Natarajan, and S. Sathiyamurthy, “Effect of Glass Hybridization and Staking Sequence on Mechanical Behaviour of Interply Coir-Glass Hybrid Laminate,” *Bulletin of Materials Science*, vol. 34, pp. 293-298, 2011, https://doi.org/10.1007/s12034-011-0081-9

[33] K. P. Ashik, and R. S. Sharma, “A Review on Mechanical Properties of Natural Fiber Reinforced Hybrid Polymer Composites,” *Journal of Minerals and Materials Characterization and Engineering*, vol. 3, pp. 420-426, 2015, https://doi.org/10.4236/jmmce.2015.35044

[34] A. S. Singha, and V. K. Thakur, “Mechanical properties of natural fiber reinforced polymer composites,” *Bull. Mater. Sci*., vol. 31, no. 5, pp. 791-799, 2008, https://doi.org/10.1007/s12034-008-0126-x

[35] R. Anandkumar, S. R. Babu, and R. Sathyamurthy, “Investigations on the Mechanical Properties of Natural Fiber Granulated Composite Using Hybrid Additive Manufacturing: A Novel Approach,” *Advances in Materials Science and Engineering*, vol. 2021, pp. 1-12, 2021, https://doi.org/10.1155/2021/5536171

[36] J. S. S. Neto, H. F. M. de Queiroz, R. A. A. Aguiar, and M. D. Banea, “A Review on the Thermal Characterization of Natural and Hybrid Fiber Composites,” *Polymers*, vol. 13, no. 24, pp. 4425, 2021, https://doi.org/10.3390/polym13244425

[37] A. M. Radzi, S. M. Sapuan, M. Jawaid, and M. R. Mansor, “Water absorption, thickness swelling and thermal properties of roselle/sugar palm fiber reinforced thermoplastic polyurethane hybrid composites,” *Journal of Materials Research and Technology*, vol.8, no. 5, pp. 3988–3994, 2019, https://doi.org/10.1016/j.jmrt.2019.07.007

[38] M. Boopalan, M. Niranjanaa, and M. J. Umapathy, “Study on the mechanical properties and thermal properties of jute and banana fiber reinforced epoxy hybrid composites,” *Composites Part B: Engineering*, vol. 51, pp. 54–57, 2013, https://doi.org/10.1016/j.compositesb.2013.02.033

[39] K. Yorseng, S. M. Rangappa, H. Pulikkalparambil, S. Siengchin, and J. Parameswaranpillai, “Accelerated weathering studies of kenaf/sisal fiber fabric reinforced fully biobased hybrid bioepoxy composites for semi-structural applications: morphology, thermo-mechanical, water absorption behavior and surface hydrophobicity,” *Construction and Building Materials*, vol. 235, no. 117464, 2020, https://doi.org/10.1016/j.conbuildmat.2019.117464

[40] M. K. Gupta, N. Choudhary, and V. Agrawal, “Static and dynamic mechanical analysis of hybrid composite reinforced with jute and sisal fibers,” *Journal of the Chinese Advanced Materials Society*, vol. 6, no. 4, pp. 666–678, 2018, https://doi.org/10.1080/22243682.2018.1539643

[41] N. Z. M. Zuhudi, R. J. Lin, and K. Jayaraman, “Flammability, thermal and dynamic mechanical properties of bamboo-glass hybrid composites,” *Journal of Thermoplastic Composite Materials*, vol. 29, no. 9, pp. 1210–1228, 2016, https://doi.org/10.1177/0892705714563118