NATURAL FIBER REINFORCED POLYMER COMPOSITES – AN REVIEW

Abstract

Because of their sustainability and devotion to the environment, natural fibers are drawing increased attention from scientists and academics for usage in polymer composites. This review article's goal is to provide a comprehensive examination of the most well-liked and pertinent natural fiber reinforced polymer composites (NFPCs) and their applications. Additionally, it gives a brief summary of the several natural fiber surface treatments that have been applied to them and how those treatments alter the properties of NFPCs. The fiber source, fiber type, and fiber structure all affect the properties of NFPCs. study of the effects of chemical treatments on the properties of thermosetting and thermoplastic composites reinforced with natural fibers. Numerous limitations, such as increased water absorption, worse fire resistance, and lower mechanical properties, limited the uses for NFPCs. The impacts of chemical treatment on NFPCs' water absorption, tribology, viscoelastic behavior, relaxation behavior, energy absorption, flame retardancy, and biodegradability were also highlighted. It is demonstrated how to apply NFPCs to a variety of industries, including the construction and automotive sectors. The study's findings demonstrated that chemically treating natural fiber enhanced adhesion between the fiber surface and polymer matrix, enhancing the NFPCs' mechanical, thermochemical, and physical characteristics.

Keywords: natural fibers, NFPCs', chemical treatments, water absorption, flame retardancy, biodegradability.

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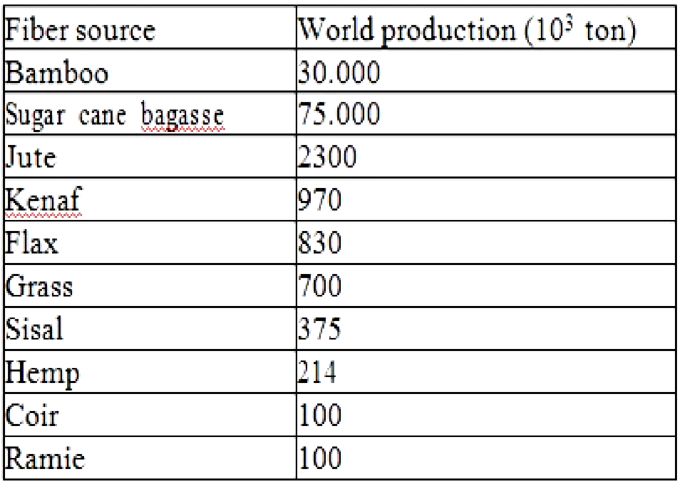
I. INTRODUCTION

The consumption of ecologically friendly materials has been taken into account as a result of rising public awareness of environmental issues, new environmental regulations, and the unsustainable consumption of petroleum. In comparison to synthetic fiber, natural fiber is thought to be one of the more environmentally beneficial materials. [1].

The market for natural fiber reinforced polymer composites reached US$2.1 billion in 2010, according to recent market figures. According to current trends, global interest in NFPCs will only continue to grow. Over the past few years, NFPC employment in emerging consumer goods manufacturing sectors has significantly increased. The global NFPCs market is anticipated to expand 10% over the period of five years (2011-2016) [2]. Simply described, natural fibers are ones that aren't synthetic or manufactured. They could come from both plants and animals [3]. Making composite materials from of natural fibers like jute, flax, sisal, and oil palm, which includes resources that are both renewable and non-renewable, has attracted a lot of interest recently. The plants, which produce cellulose fibers can be classified into bast fibers (jute, flax, ramie, hemp, and kenaf), seed fibers (cotton, coir, and kapok), leaf fibers (sisal, pineapple, and abaca), grass and reed fibers (rice, corn, and wheat), and core fibers (hemp, kenaf, and jute) as well as all other kinds (wood and roots) [4]. The list under in Table1 includes the natural fibers that are grown and utilized the most across various regions of the world.



Fiber source	World production (10^3 ton)
Bamboo	30.000
Sugar cane bagasse	75.000
Jute	2300
Kenaf	970
Flax	830
Grass	700
Sisal	375
Hemp	214
Coir	100
Ramie	100

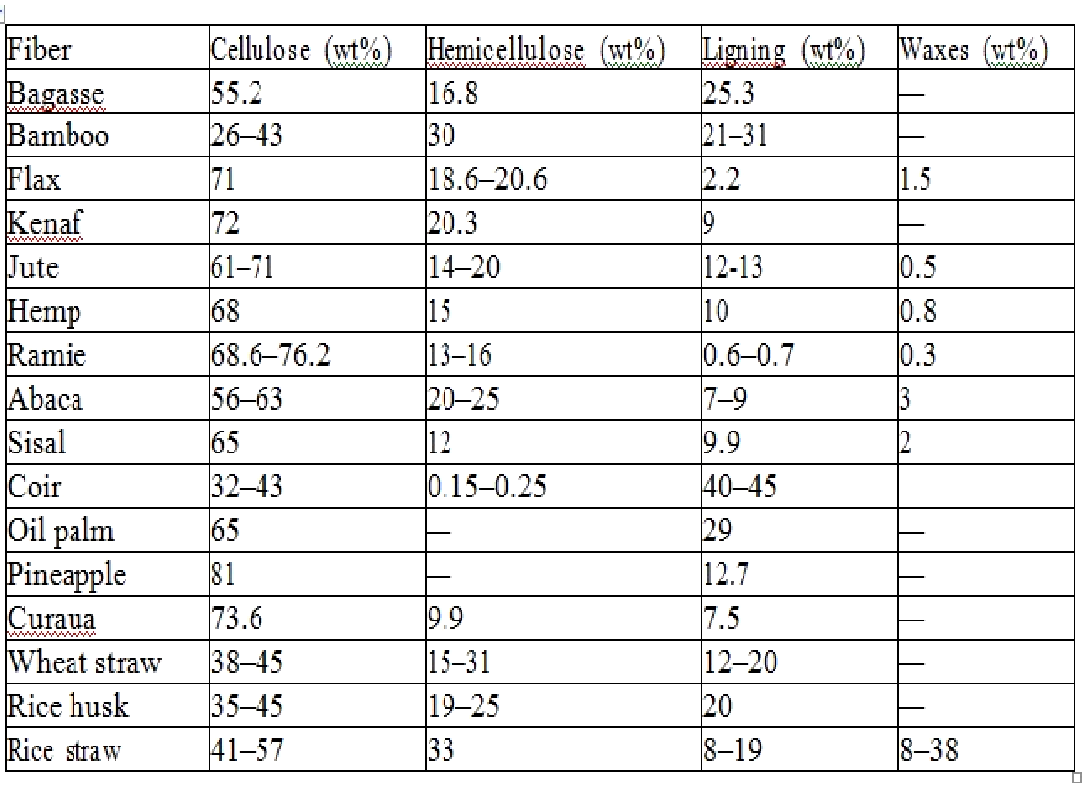
Natural fibers are becoming more and more common in a wide range of applications due to their superior qualities and advantages over synthetic fibers, including their relative light weight, low cost, less harm to processing equipment, good relative mechanical properties like tensile modulus and flexural modulus, improved surface finish of composite molded parts, renewable resources, abundance [5], flexibility during processing, and biodegradability. The combination of the strong and light natural fiber with polymer (thermoplastic and thermoset) can result in NFPCs with high specific stiffness and strength [6]. However, there are several issues and glaring flaws in the features of natural fibers. The structural components of natural fibres include cellulose, hemicelluloses, lignin, pectin, and waxy components), and moisture absorption from the environment resulting in weak connections between the fibre and polymer. Furthermore, couplings between natural fibre and polymer are regarded as difficult due to variations in the chemical structures of the fibres and matrix. These are the causes of ineffective stress transfer at the interface of manufactured composites. As a result, natural fibre alterations using certain treatments are definitely required. These changes are frequently concentrated on the use of reagent functional groups that may respond to fibre topologies and change their composition. As a result, fibre modifications reduce natural fibre moisture absorption, resulting in a considerable decrease in fibre incompatibility.

In several areas of technology, the number of NFPC applications is swiftly rising. Many automakers have given natural fibre strengthened polymer composites a lot of attention in a variety of automotive applications, including Malaysian and German national automakers (BMW, Audi Group, Ford, Opel, Volkswagen, Daimler Chrysler, and Mercedes), as well as the United States' Cambridge Industry. Natural fiber composites are used in a variety of industries outside the automotive one, including building and construction, sports, aerospace, and the manufacture of panels, window frames, decking, and frames for bikes [8].

In the study of chemical treatments of natural fibers, Kabir and colleagues [9] recognized that treatment is an important concern that must be addressed when processing natural fibers. They discovered that hydroxyl groups may be taken out of fibers using a number of chemical processes, which decreases the fibers' hydrophilicity while boosting the mechanical strength and dimensional stability of natural fiber reinforced polymer composites. Overall, they found that chemically modifying natural fibers results in NFPCs that are considerably better.

1. **Natural Fiber Reinforced Composites (NFPCs):** Natural fiber polymer composites (NFPC) are made by combining a polymer matrix with high-strength natural fibers such jute, oil palm, sisal, kenaf, and flax [10]. Thermosets and thermoplastics are the two main subgroups of polymers. Because of their one- or two-dimensional molecular structure, thermoplastic matrix materials have a propensity to soften at higher temperatures and to regain their original characteristics as they cool. When subjected to heat, pressure, light, or any combination of these, thermosets, which are strongly cross-linked polymers, cure. The thermoset polymer benefits from this structure's high strength and modulus as well as significant flexibility for modifying desirable final properties [3, 4]. To make biofibers, thermoplastic materials like polyethylene [11], polypropylene (PP) [12], and poly vinyl chloride (PVC) are frequently employed, as opposed to thermosetting matrices like phenolic, polyester, and epoxy resins [10]. The characteristics and functionality of NFPCs can be influenced by a variety of factors. The characteristics of the composite are influenced by various factors [5, fiber loading], including the hydrophilicity of the natural fiber [13]. Substantial fiber loading is frequently required to provide satisfactory NFPC characteristics [14]. Generally speaking, observe how the tensile characteristics of composites improve with increasing fiber content [8Another important element that significantly affects the characteristics and surface features of the composites is the process parameters that were employed. The process parameters that were used are yet another key factor that profoundly influences the properties and surface aspects of the composites. The ideal attributes for making composite should be provided by the production techniques and parameters, which should be carefully chosen [10]. The proportions of cellulose, hemicellulose, lignin, and waxes are indicators of the chemical composition of natural fibers, which has a big influence on the composite's qualities. A few well-known natural fibers' chemical compositions are shown in Table 2 [4].

The appropriateness, competitiveness, and capability of natural fibers embedded in polymeric matrix have been examined and studied by several researchers [8, 11, 15–17]. The investigation's major objective was to determine the significance of production procedures and fiber surface alterations in enhancing fiber/polymer compatibility [4, 18, 19]. However, additional research have compared the stability of various natural fiber composites in various kinds of applications [20]. The features of jute/plastic composites, such as crystallinity, fiber modification, thermal stability, weathering resistance, and durability, as well as their relevance to the automobile industry through ecodesign components, were studied by Al-Oqla and Sapuan [20]. Jute fiber's impact on the mechanical characteristics of pure biodegradable polymer (Biopol) was studied by Mohanty et al. When compared to pure Biopol, the mechanical properties of the generated composites—such as impact strength, tensile strength, and bending strength—rose.



Fiber	Cellulose (wt%)	Hemicellulose (wt%)	Ligning (wt%)	Waxes (wt%)
Bagasse	55.2	16.8	25.3	—
Bamboo	26–43	30	21–31	—
Flax	71	18.6–20.6	2.2	1.5
Kenaf	72	20.3	9	—
Jute	61–71	14–20	12-13	0.5
Hemp	68	15	10	0.8
Ramie	68.6–76.2	13–16	0.6–0.7	0.3
Abaca	56–63	20–25	7–9	3
Sisal	65	12	9.9	2
Coir	32–43	0.15–0.25	40–45	
Oil palm	65	—	29	—
Pineapple	81	—	12.7	—
Curaua	73.6	9.9	7.5	—
Wheat straw	38–45	15–31	12–20	—
Rice husk	35–45	19–25	20	—
Rice straw	41–57	33	8–19	8–38

2. **General Characteristics of NFPCs:** Previous research have shown that different fiber types, sources, and moisture levels have distinct effects on the characteristics of natural fiber composites. A few of the factors affecting NFPC performance comprise mechanical composition, microfibrillar angle, structure, defects, cell size, physical properties, chemical qualities, and a fiber's interaction with the matrix. The negative aspects of natural fiber reinforced polymer composites are the same as those of any other product on the market. The chemical differences between these two phases make it challenging to couple natural fiber with polymer matrix. As a result, the stress transfer at the NFPC contact is ineffective. Chemical treatments are thus required to give natural fibers the proper interface properties. Reagent functional groups interact with fiber structures during chemical processes to alter their makeup [9]. Natural fibres are hydrophilic due to the hydroxyl group, which serves as a functional element. The hydroxyl group in natural

fibres makes it more difficult for hydrophilic natural fibre and hydrophobic polymer matrices to join together during the manufacturing of NFPCs. As a result, NFPCs may exhibit poor mechanical and physical properties [8].

II. MECHANICAL PROPERTIES OF THE NFPCs

Natural fibers might greatly benefit from modifications and suggestions that could be implemented to enhance their mechanical properties, resulting in high strength and structure. If the essential structures are reinforced, the polymers may easily be improved and strengthened [26]. Only a few of the many variables that might affect a composite's performance level or activities are listed below:

- Fiber Orientation
- Fiber Strength
- Fiber Physical Characteristics
- Fiber Inter Facial Adhesion Property and many others

These composites are known as NFPCs, and their mechanical performance is influenced by the interface that the fiber-matrix provides as well as the stress transfer function that transfers stress from the matrix to the fiber. This has been verified by multiple investigations conducted by various experts [1, 23, 29]. A few elements that impact the mechanical properties of NFPCs include the orientation [30], moisture absorption [31], impurities [32], physical characteristics [33], and volume fraction [34] of natural fibers. A few of the impacts that various natural fiber types may have on the mechanical characteristics of PLA, epoxy, PP, and polyester matrices are depicted in Figure 1.

In this case, the addition of jute fibers enhanced the tensile strength of PLA by 75.8%; flax fibers, however, had a negative effect on this addition. When jute fibers are added to PLA (polylactic acid), NFPCs exhibit mechanical qualities that are even superior than those of a pure matrix. The addition of flax fiber reduced the composites' tensile strength by 16%. On the other hand, hemp, kenaf, and cotton were added to improve PP composites [5]. Maximum growth is by far only perceptible in these composites that contain polyester or jute; in comparison to pure polyester, a total of 121% advancement is shown [5].

Because the rubber portion of the gum combination decreases stiffness and storage modulus, these materials are more flexible across a larger range.

Furthermore, it is well known that increasing the amount of fiber either makes composites stiffer and better at transferring stress, which increases their loss and storage moduli. Adding fiber is also supposed to improve the loss modulus from 415 MPa of gum to 756 MPa after 50 hours [8].

Table 3: Physicomechanical Properties of Natural Fibers [38].

Fiber	Density (g/cm^3)	Tensile strength (MPa)	Young's modulus (GPa)	Elongation at break (%)
OPEFB	0.7–1.55	248	3.2	2.5
Flax	1.4	88–1500	60–80	1.2–1.6
Hemp	1.48	550–900	70	1.6
Jute	1.46	400–800	10–30	1.8
Ramie	1.5	500	44	2
Coir	1.25	220	6	15–25
Sisal	1.33	600–700	38	2-3
Abaca	1.5	980	—	—
Cotton	1.51	400	12	3–10
Kenaf (bast)	1.2	295	—	2.7–6.9
Kenaf (core)	0.21	—	—	—
Bagasse	1.2	20–290	19.7–27.1	1.1
Henequen	1.4	430–580	—	3–4.7
pineapple	1.5	170–1672	82	1–3
Banana	1.35	355	33.8	53

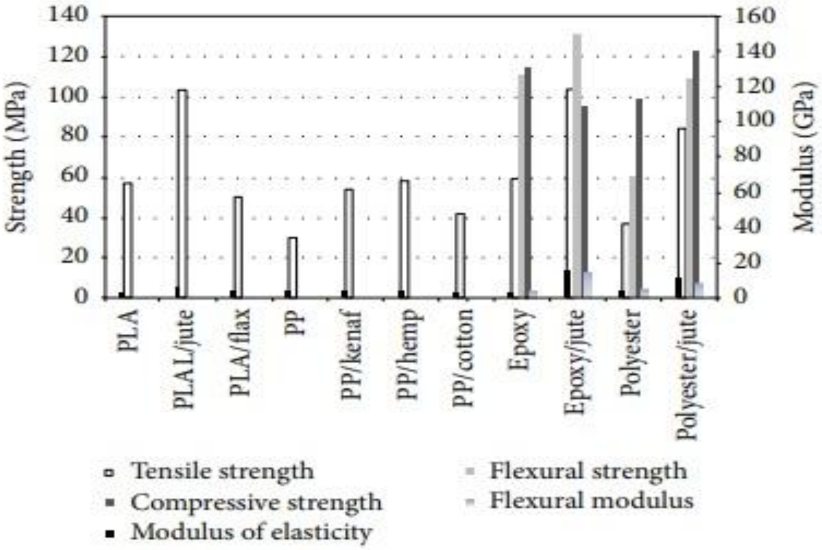


Figure 1: Some of mechanical properties of natural fiber reinforced polymer composite [5].

Ismail et al.'s study team [37] examined the impact of fiber properties that heal a wound or any part of the body on size and filler content. Furthermore, the mechanical behavior of Oil Palm Wood Flour (OPWF), reinforced with composites made of epoxidized natural rubber (ENR), was investigated. The smallest OPWF particle size produced the greatest torque, and as the fiber content rose, so did the torque of the fibers. However, the tensile strength was decreased and there was clear elongation at the break in ENR compounds when the OPWF factor was raised. With higher stress, the OPWF exhibits a clear increase in elongation, rip strength, tensile modulus, and hardness. Even a little amount of OPWF loading increased the composites' tensile strength, rip strength, and tensile modulus [10]. The fracture behavior of composites is significantly influenced by the nonlinear mechanical behavior of natural fibers under the influence of tensile-shear stresses [1]. Table 3 shows the mechanical characteristics of significant natural fiber varieties from throughout the world.

The bonding strength between the fiber and polymer matrix in the composite must be evaluated in order to deliver enhanced fiber reinforcement composite properties. The fiber's dangling hydroxyl and polar groups lead it to absorb a lot of moisture, which causes it to have poor interfacial contact with the hydrophobic matrix polymers. Fibers are chemically changed to minimize their hydrophilic behavior and moisture absorption in order to produce composite materials with improved mechanical qualities. [15, 39].

The numerous surface treatments applied in applications for advanced composites have been researched by several researchers [40–42]. Additionally, research was done on how different chemical processes affected cellulosic fibers used as thermoplastic and thermoset reinforcements. Silane [43], alkali [44], acrylation [45], benzoylation [46], maleated coupling agents [47], permanganate [48], acrylonitrile and acetylation grafting [49], stearic acid [50], peroxide [51], isocyanate [52], triazine [53], fatty acid derivate (oleoyl chloride), sodium chloride, and fungal [9] are some of the various chemical treatments. The major goals of natural fiber surface treatments are to enhance the connection between the fiber and matrix and the ability of composites to transfer stresses.

Cordeiroa et al. [54] conducted research in Iran to examine the effects of alkaline treatment on the surface properties of naturally occurring natural fibers. The study asserts that alkaline treatment eliminates nonpolar molecules linked to partial lignin depolymerization, uranic acid (hemicellulose), aromatic moieties (extractives), and other chemical components on the fiber surface. More harm is done to the chemical components of other fibers. Compared to nonwood fibers, the crystallinity of softwood fiber only slightly rises. Alkaline treatment can therefore significantly enhance both wettability and fiber-specific interaction. The effects of many chemical treatments, including ethylenediaminetetraacetic acid (EDTA), NaOH, polyethylene imine (PEI), CaCl2, and Ca(OH)2, were studied by Le Troedec et al. By using differential thermal analysis and testing, the impacts were on the mechanical characteristics of composite materials made from hemp fiber and lime mixes. Every treatment was discovered to have an effect on the fiber surface. While the 6% NaOH treatment caused the complex calcium ions connected with the pectins and the separation of the fibers, the EDTA treatment caused the separation of the fibers and an increase in the crystallinity index of the fiber bundles.

The effects of many chemical treatments, including ethylenediaminetetraacetic acid (EDTA), NaOH, polyethylene imine (PEI), $CaCl_2$, and $Ca(OH)_2$, were studied by Le Troedec et al. Researchers looked at how differential thermal analysis and testing affected the mechanical characteristics of composite materials made from hemp fiber and lime mixes. Every treatment, it was discovered, directly affected the fiber surface. While complex calcium ions linked to pectins and fibers were separated by the 6% NaOH treatment, fibers were also separated by the EDTA treatment, which also improved the crystallinity index of the fiber bundles.

Venkateshwaran et al. investigated the impact of different alkali (NaOH) treatments (0.5%, 1%, 2%, 5%, 10%, 15%, and 20%) on the mechanical characteristics of a banana/epoxy composite. [35]. According to the findings, 1% NaOH treated fibre reinforced composites outperform other treated and untreated fibre composites in terms of properties. The alkali content on the fibre surfaces improves the mechanical properties of the final composite. The increasing alkali content, on the other hand, may damage the fiber's surface and impair its mechanical properties. The impact of different chemical treatments on the mechanical properties of sisal-oil palm hybrid fibre reinforced natural rubber composites were examined by John et al. [56]. During chemical treatment, the torque values rose, which promoted cross linking. The maximum tensile strength was attained when the fibers were treated with 4% NaOH, much to how alkali treatment boosted the composites' tensile strength in comparison to untreated composites. However, the stronger interface that arises from the improved rubber-to-fiber adhesion in composites treated with 4% NaOH restricts solvent access and results in some swelling. Van van Weyenberg et al. [24] investigated the effects of flax processing variables and fiber treatment on the mechanical characteristics of flax fiber reinforced epoxy composites. It was demonstrated that producing composite materials with improved properties wasn't always the case when employing long flax slivers. Chemical treatments can be utilized to enhance flax fiber reinforced epoxy composites' flexural characteristics to the highest degree achievable. Transverse strength and modulus both increased by as much as 250% and 500%, respectively. Strength and modulus, two longitudinal parameters of the UD composites, shown 40% improvement.

The rubber wood fiber was treated with laccase enzymes, which resulted in modifications to the lignocellulosic fibers' chemical and physical properties. Natural materials' crystallinity changes as a result of these chemical processes, which also change the concentration of hemicellulose [57]. Additionally, they increase the amorphousness of the lignin. The fiber alters the EFB fiber's shape and single fiber tensile strength. Norul Izani et al. [13] evaluated the EFB fiber treated with boiling water, 2% sodium hydroxide (NaOH), and a combination of boiling water and NaOH. It was discovered that the treatment altered the fiber surface topography's properties. The thermal stability of treated EFB fibers over untreated EFB fiber was improved by the two various types of treatments. In contrast, the treated fibre exhibited a greater Young's modulus and tensile strength than the untreated fibre. Epoxy composites enriched with sugar palm fibre now have improved tensile characteristics as a result of alkaline treatment at greater alkaline concentrations and soaking times. A rise in alkaline content, on the other hand, might be harmful to fibres [58].

Investigated was how OPEFB fibers affected the coating of Acrylonitrile Butadiene Styrene (ABS). The coating method enhanced the fibers' mechanical, physical, and mechanical properties. Both the fiber's ability to disintegrate when in contact with soil and its capability to absorb water were decreased by the ABS treatment. In comparison to their initial state, the coating improved the tensile strength and elasticity moduli of OPEFB fibers. The metrics for the shear strength of the fiber reinforced soils were improved by coating the fiber to enhance the surface area between it and the soil particles. [66].

III. FLAME RETARDANT PROPERTIES OF THE NFPCs

Natural fiber composites are preferred over synthetic fiber-based composites because they are more environmentally friendly and long-lasting. They work in a range of sectors, including building materials [9, 18, 20, 38, 67], the aerospace industry [68], and the automobile industry [69]. Given that they are made of organic materials, natural fibers and polymers are especially susceptible to having their properties changed by flame. A different component, flame retardancy, has seen a sharp rise in importance as a result of the need to produce natural fiber composites that meet safety regulations. Composites burn in five stages when a flame is present: (a) Heating, (b) Decomposition, (c) Ignition, (d) Combustion, (e) Propagation [70]

Whether or whether the ignition stage has been accomplished, the process will end before an actual fire is started if flame retardancy has been reached in the aforementioned stages. Burning composites produces two distinct products, one with a high cellulose content and the other with a high lignin content. larger values of lignin signal a larger danger of char formation, whereas higher values of cellulose suggest a higher potential for flammability [71]. Flax fibers offer thermal resistance [72], and silica or ash is another crucial component that aids in putting out fires [73].

The fire resistance of different NFPCs was increased using a variety of approaches. Fire barriers can be utilized in addition to phenolics, ceramics, intumescents, glass mats, silicone, ablatives, and chemical additives. The intumescent system's coatings and materials have shown to be exceptionally efficient fire barrier solutions. When heated, these barriers expand, causing the surface of the cell wall to burn evenly. The burned surface, however, protects internal or below-the-surface components from flux and heat.

One of the well-known or efficient flame retardants for reinforced polymers (natural fibers) is employed when char-forming cellulose material is present [74]. Making the polymer more stable and using char-forming are the only ways to reduce combustion in this situation. As a result, the amount of products that may be produced during combustions will be limited, the flammability will be reduced, and there will likely be less smoke [72]. Fire retardant coating is another method for enhancing composites' fire resistance. During the impregnation or finishing process, this coating is applied. The fibers and lingo-cellulosic particles are changed throughout manufacture, which determines how fire resistant the end products are [75].

Aluminum hydroxide [$Al(OH_3)$] and magnesium hydroxide [$Mg(OH)_2$] are the two metal hydroxide flame retardants that are most frequently used, and they are added on purpose to polymers. The previously indicated chemical breakdown occurs to these two flame retardants:

$$2Al\,(OH)_3 \rightarrow Al_2O_3 + 3H_2O \quad \Delta H = 20 \text{ cal/g} \quad (1)$$
$$Mg\,(OH)_2 \rightarrow MgO + H_2O \quad \Delta H = 328 \text{ cal/g} \quad (2)$$

Among these two flame retardants, magnesium hydroxide has better thermal stability than aluminium hydroxide because the temperature range produced by the decomposition of magnesium hydroxide is nearly 300-320 degrees centigrade (C), which is significantly higher than the temperature range provided by aluminium hydroxide, which is only 200-C. Despite the fact that magnesium hydroxide can be utilised for polyamides, polypropylene, and other polymers, aluminium hydroxide is regarded to be more thermally stable. Furthermore, research has demonstrated that adding expandable graphite (EG) and ammonium polyphosphate (APP) to composite polymers as FR sources improves the fire resistance of PP composites with flax fibre reinforcement. Furthermore, it was demonstrated that a composite addition of expandable graphite (25 wt%) and flax fibre (30 wt%) decreased heat generation.

Zhan et al. [77] conducted research on SPDPM (spirocyclic pentaerythritol bisphosphorate disphosphoryl melamine), an intumescent flame retardant for PLA. PLA's antidripping properties and flame retardancy are improved with the addition of 25 weight percent of SPDPM (Spirocyclic Pentaerythritol Bisphosphorate Disphosphoryl Melamine), an active flame retardant. It is difficult to include flame retardancy, and it can only be done with a significant high loading of inorganic filler. Research on how to construct a natural fiber composite with increased fire or flame retardancy was done by Hapuarachchi and Peijs [78].

This natural fiber composite was created by mixing two different kinds of nanofillers with PLA polymers produced from agricultural sources in order to create a synergy related to flame retardancy. Analysis will demonstrate that the peak heat release (PHRR) was reduced when the hemp fiber mat was added to the PLA resin.The capacity of NFPCs to biodegrade. Natural fiber reinforcement in polymers enables the creation of high strength composites. These composites are also less costly, lighter, and have better mechanical qualities than previous versions or additions [29].

While other fiber components, such as cellulose, lignin, and others, deteriorate at different temperatures, natural fibers breakdown at 240 degrees Celsius. For instance, lignin begins to break down beyond 200°C, but other components will also begin to break down at higher temperatures [9].

Since lignin and hemicelluloses, two structural components of fibers, regulate the fibers' thermal stability, their contents can be increased or fully decreased. This can be achieved with the use of chemical procedures. The development of fibers and materials with functions are two crucial factors for the deterioration of natural fibers [9]. Natural fibers have a shorter lifespan and are less hazardous to the environment than synthetic fibers, which deteriorate over time and produce pollution. The quantities or makeup of cellulose, hemicelluloses, and lignin affect the characteristics of lignocellulosic materials' thermal breakdown [13]. After exactly 1500 days of burial, more than half of the weight of jute or Biopol composite is lost [21].

The NFPCs' Absorption of Energy: Due to their excellent strength, energy absorption, and stiffness, composite materials are often used in the automotive and racing industries. This is mostly due to their bulk reduction property [79].A greater volume percentage is only possible at low speeds, such 2.5 m/s, which suggests improved energy absorption [80]. Jute showed brittleness and weak fibers, although flax, hemp, and hemp all performed similarly at high speeds, such as 300 m/s [81]. The potential of NFPCs was examined by Meredith et al.; this is necessary for the application of providing sustainable energy absorption. recollections of motorsports [80]. Conical samples of hemp, jute, and flax are tested using vacuum assisted resin transfer molding (VARTM) to determine their properties. To examine a specific energy absorption (SEA), different values produced by different kinds of materials were recorded.

IV. TRIBOLOGY PROPERTIES OF NFPCs

It is critical to consider tribological loadings when designing mechanical parts since each material has wear and friction properties that worsen with time [5]. 90% of failures are caused by differences in tribological loading conditions, which modify the wear and friction characteristics [82]. Reinforcement can change the tribological properties of fibres or polymers in either a positive or negative way [83]. Numerous fibres have been studied in various types of tribological investigations, including kenaf/epoxy [84], betelnut fibre reinforced polyester [85], sisal/phenolic resin [86], sugarcane fibre reinforced polyester (SCRP) [87], and cotton/polyester [88].

For a particular type of bearing application, Chin and Yousif [84] used kenaf fibers reinforced with epoxy composite, and they showed an 85% increase in wear performance and normal orientation in composites. El-Tayeb used a variety of variables, such as speed, test length, and load [87], to evaluate the wear and friction properties of glass fiber/polyester (GRP) and sugarcane fiber/polyester (SCRP). The results of the experiment showed that SCRP and GRP composite are competitors. Xin et al. [86] explored the same characteristics for sisal fiber reinforced resin brake composites and showed that sisal fiber might replace asbestos in brake pads [89, 90].

Laminate composites were produced using three various natural fibers, including grewia, nettle, optiva, and sisal. In their investigation of this connection of natural fibers, Bajpai et al. employed a hot compression approach to blend three separate components into a PLA polymer [82]. For a better understanding of the friction and wear properties of composite materials, a variety of settings have been researched, including dry contact under various operating situations. Due to the possibility of adjusting operating parameters, the applied force was changed between a range of 10 to 30 N, a speed between 1 and 3 m/s, and a sliding distance between 1000 and 3000 meters. According to the study's conclusions, adding natural fiber mats to a PLA matrix can reduce friction and wear in basic polymer. Produced composites for a given wear rate exhibit an estimated decrease in the coefficient of friction of 10–44%, with a higher decrease of 70% [82].

V. WATER ABSORPTION CHARACTERISTICS OF THE NFPCs

In polymers, natural fibers function well as reinforcement. Natural fibers' vulnerability to moisture, however, is their main drawback [91]. The interface adhesion between the fiber and the polymer matrix has a substantial impact on the mechanical characteristics of polymeric composites [15]. Since cellulose, hemicelluloses, lignin, and pectins all include hydroxyl 1 groups, natural fibers are typically hydrophilic sources and strong polar materials. Natural fibers also contain significant amounts of cellulose and hemicelluloses. As opposed to this, polymers have a high level of hydrophobicity. The area where matrices and natural fibers intersect is weakened because there are major suitability issues between the two [5]. Water absorption steadily reduces from the composite materials' outer layers into the matrix's main body. Composite materials often weigh more when wet, lose strength, deflect more, swell more, and put stress on neighboring structures because of their propensity to absorb a lot of water. These can cause bending, buckling, a greater likelihood of microbial inhabitation, and damage from freeze and unfreeze, which can reduce the mechanical characteristics of composite materials [92].

Due to the hydrophilicity of the fibers, oil palm fiber natural rubber (OPF-NR) composites exhibited an increase in the water absorption percentage that corresponded to an increase in fiber loading. With increased OPF, microcracks and the viscoelastic properties of the polymer led the NR absorption behavior to change from Fickian to non-Fickian [8].

Because they included more lignin and hemicellulose as well as flaws in the composite system, woven pandanus fabric composites performed better in trials using the two types of fabric in terms of water absorption than woven banana fabric composites [93]. The temperature can also affect how much water composites absorb. Table 4 [4] displays the equilibrium moisture content of a few natural fibers at 65% humidity and 21°C. It was discovered that the OPF-NR composite absorbed water at a lower rate than the OPF-sisal fiber-NR hybrid biocomposite. The inclusion of sisal fiber, which has a greater proportion of the very hydrophilic holocellulose (23%), resulted in the usage of more water. In comparison to sisal fiber, which only comprises 9%, OPF has 19% more lignin. Lignin doesn't absorb as much water since it is hydrophobic [8].

Numerous studies [8, 56] shown that coupling agents such maleic anhydride polyethylene and chemical treatments like bleaching, acetylation, and alkali treatment can reduce the amount of moisture that NFPCs absorb. To ensure there are no contaminants that might increase the fiber surface roughness and hinder moisture absorption by removing the fiber's coating of OH groups, the fiber surface is cleaned during the chemical treatments, as shown in the equation below [5, 9].:

$$\text{Fiber-OH} + \text{NaOH} \rightarrow \text{Fiber-O}^{-}\text{Na}^{+} + H_2O \qquad (3)$$

Sreekala and Thomas [91] investigated the OPEFB fiber's capacity to absorb moisture at various temperatures. They also examined the impact of additional treatments, such as silane treatment, gamma irradiation, latex coating, mercerization, acetylation, peroxide treatment, and isocyanate treatment, on the OPEFB fiber's capacity to absorb moisture. They found that every treatment had the ability to absorb moisture at any temperature. By enhancing the fiber surface's adhesive properties and increasing the surface area that encourages mechanical interlocking, mercerization of OPF-sisal fiber-NR hybrid composites reduced the composite's capacity to absorb water [94]. Before mixing them with a polymer matrix, agave fibers were chemically modified by Shinoj et al. [8] to improve moisture absorption.

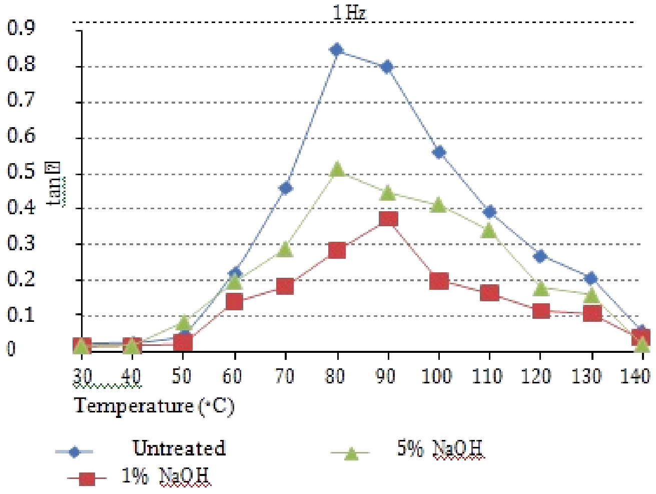


Figure 2: tan£ versus temperature curves of the alkali treated and untreated composites at 1 Hz frequency [35].

The chemical procedure utilizes four various kinds of reagents: acetic anhydride (Ac), maleic anhydride (MA), styrene (S), and acrylic acid (AA). The study discovers that chemical treatment lowers water's overall diffusivity and that water is more mobile in the fiber core than at the surface.

The NFPCs' viscoelastic characteristics. The structure, morphology, and determination of the interface characteristics of natural fiber composite materials may be understood via dynamic mechanical testing or the viscoelastic behavior across a wide temperature range [95]. The storage modulus of natural fiber composite materials provides details on their stiffness and load-bearing ability. The storage modulus is the maximum amount of energy that can be held inside a material during one oscillation cycle. The mechanical damping coefficient, which relates to the degree of molecular mobility in polymeric materials, is defined as the ratio of loss modulus to storage modulus. The rate of heat loss from the sample, however, directly affects the loss modulus variation [96].

Reports on novel blended biocomposites with viscoelastic properties created from yarns like jute and polypropylene. Jute yarn-reinforced polypropylene composites were created using the commingling process. A number of chemical treatments, such as potassium permanganate (KMnO4), maleic anhydride modified polypropylene (MAPP), toluene diisocyanate (TDI), and stearic acid (ST), were used to create the composite substances. These procedures were studied in relation to the fiber content and the composites' viscoelastic behavior or dynamic mechanical properties. The experiment shows that increasing the fiber content improves the composite's storage and loss modulus. However, the storage modulus and loss modulus of the appropriately treated composites are higher than those of the untreated ones at all temperatures as a result of the chemical treatment with KMnO4 and MAPP. Using a dynamic mechanical analyzer, Venkatesh-waran et al. [35] investigated how alkali treatments changed the viscoelastic behavior of natural fiber composites. The associated viscoelastic properties were determined as a function of temperature and frequency when the measurements were conducted in the tensile mode of the used equipment. Figures 2 and 3 [35] illustrate the graphs obtained by the experiments, which were plotted as storage modulus (E) vs temperature and tan versus temperature at frequencies of 0.1, 1, and 10 Hz, respectively.

VI. RELAXATION BEHAVIOR OF THE NFPCS

The body-calming properties of natural fiber are essential for helping NFPCs relax in stressful circumstances. As a result, a thorough analysis of the reinforcing fiber's tensile stress relaxation is required [38]. As an illustration, Sreekala et al. [29] a research of this kind was carried out, which concentrated on the properties of each individual OPEFB fiber and also explored the influence of fiber surface modification, age, and strain intensity on the fiber relaxation behavior. Surface changes, such as latex modification, which minimize the physical contact that would otherwise occur between the latex particles and fiber surface, significantly impair the fibers' ability to relax under stress. The OPEFB fiber's rate of stress relaxation was optimized at 10% strain level, as shown in Figure 4, and the relaxation modulus values for the fiber exhibit similar patterns as shown in Figure 5. Water and heat ageing also reduce the pace at which the oil palm fiber relaxes. In contrast, stress-relaxation rateOPF-sisal fiber-NR hybrid composites decreased as fibre% rose [97].

VII. THERMAL PROPERTIES OF NFPCs

OPF is projected to have greater thermal stability than flax and hemp fibers due to the superior thermal stability of untreated OPFs. Between 1.083 J/g/C1 and 3.317 J/g/C1, in particular, the heat capacity of OPFs rises between 20 and 150 degrees Celsius [98]. The thermal diffusivity, thermal conductivity, and specific heat of flax/HDPE composites all reduced as fiber content increased. The thermal conductivity and diffusivity, on the other hand, barely changed between 170 and 200 °C. The specific heat of the biocomposites rose with temperature [4]. Pineapple leaf fiber has been used as the base for the construction of practical polycarbonate composites. The composite made from modified pineapple leaf fibers and silane-treated showed the best tensile strength and impact resistance. The thermogravimetric research shows that the composites have worse thermal stability than pure polycarbonate resin. Additionally, when pineapple leaves' fiber content grew, so did their heat stability [4]. Enzymatic treatment can enhance the surface and thermal characteristics of some natural fibers, including flax and hemp [56]. Treatments with pectinase and hemicellulose can improve the thermal properties of the aforementioned fibers. The potential use of enzymes to improve natural fiber surfaces for natural fiber composites is fascinating [67]. Norul Izani et al. [13] looked at how chemical treatment affected the EFB fiber's tensile strength and form. Both 2% sodium hydroxide (NaOH) and a solution of NaOH and hot water were used as treatments. The chemical treatment with NaOH and boiling water increased the tensile strength, thermal stability, and surface topography of the EFB fibers while also giving them better thermal properties than untreated fibers.

Thermal Properties of NFPCs: OPF is more thermally stable than untreated OPF and is predicted to be more thermally stable than flax and hemp fibers. The heat capacity of OPFs rises with temperature, rising from 1.083 J g C1 to 3.317 J g C1 between 20°C and 150°C in particular [98]. Thermal diffusivity, thermal conductivity, and specific heat of flax/HDPE composites all fell as fiber content rose. Thermal conductivity and diffusivity, however, exhibited no discernible alterations in the 170-200 C range. The specific heat of the biocomposites increased steadily as the temperature increased [4]. We created practical polycarbonate composites utilizing pineapple leaf fiber.

VIII. NATURAL FIBER POLYMER COMPOSITES APPLICATION

Applications for NFPC are expanding rapidly across a range of technical disciplines. Jute, hemp, kenaf, oil palm, and bamboo are just a few examples of the natural fiber reinforced polymer composites that have gained popularity in a variety of automotive applications, structural components, packaging, and construction [5, 99]. A wide range of companies employ NFPCs, including those that produce office supplies, sports and recreation equipment, machinery, boats, and airplanes. NFPCs are frequently used in polymer composites because of their low specific weight, relatively high strength, low production cost, resistance to corrosion and fatigue, total biodegradability, improvement of the surface finish of moulded part composites, reasonably good mechanical properties, easily accessible and renewable sources, and low specific weight [5, 98]. The NFPCs' physical drawbacks, such as moisture absorption, a limited range of processing temperatures, and fluctuating quality, have, on the other hand, limited their performance [73].

1. **Natural Fiber Composites Applications in the Interior Car:** Companies have conducted substantial study to include NFPCs into their designs. Several research on the use of NFPCs in the automotive industry have been done by European manufacturers, notably in interior car parts such as seat backs, parcel shelves, boot liners, front and rear door liners, truck liners, and door-trim panels [89]. Fibre from nature has been blended into polymers for high demand applications such as external car body components as well as inside auto elements [18].

   As seen in Figure 6, cellulose fibre composites are used in a range of automotive components by German manufacturers (BMW, Audi Group, Ford, Opel, Volkswagen, Daimler Chrysler, and Mercedes), including the seats in the Mercedes Benz A-class model and the fax in the Mercedes Benz E-class model.Fibre sisal fibre reinforced epoxy door panels. The Audi corporation employs a flax/sisal mat reinforced polyurethane composite to make door trim panels [60]. Ford employs kenaf reinforced PP composites for the door panels of their "Mondeo" car and flax for the floor trays [61]. Bangladeshi kenaf fibers are used for the production of door panels on the Mondeo. Package trays and door panel inserts for Opel Vectra vehicles are now constructed of a kenaf and flax combination. Volkswagen used cellulose fiber to make the seatback, door panel, boot-lid finish panel, and boot-liner for the Passat Variant, Golf, A4, and Bora automobiles. Many NFPCs are used in the automobile manufactured by the BMW Group. The BMW Group employed more than 10,000 tons of natural fiber in 2004 [100]. A total of twenty-four kilograms of renewable raw materials, including sisal and flax for the interior lining of the door panels, are transported by each BMW 7 Series vehicle. Incorporate wool for the upholstery, cotton for soundproofing, and wood fiber for the seat backs. In order to replace glass fibers in premium polypropylene components, Daimler-Benz Germany is investigating sisal, jute, coconut, European hemp, and flax. Daimler-Benz produced the seat back panels, center armrest consoles, dashboards, and seat shells. Additionally, it increased certain cars' NFPC usage from prior models by nearly 98% by using natural fibers like abaca and flax. The Cambridge company, on the other hand, began employing a flax fiber/polypropylene composite to make the rear shelf trim panels for the Chevrolet Impala model in 2000. [8, 101]. Table 5 shows how Toyota, Proton, Volvo, and other automakers used cellulose fiber to make car components.

2. **Natural Fiber - Applications in the Industry:** NFPCs are used in a variety of industries besides the car industry, such as building and construction, aerospace, sports, and others. Boats, divider screens, office supplies, and ceilings are a few examples. Due to their susceptibility to environmental degradation, nonload bearing interior components in civil engineering get the majority of NFPC applications [72]. Achieving habitable, healthy, and ecologically responsible places is the goal of green building design. Currently, biocomposites are one of the main materials used to make environmentally friendly products. The two types of biocomposites utilized in the construction business are nonstructural biocomposites, which comprise window and exterior construction, and structural biocomposites, which include bridge and roof structure [2].

   Natural fiber reinforced composites were beneficial for a range of applications in building sectors due to their low weight, high stiffness to weight ratio, and biodegradability [102]. Sisal fiber reinforced composite thin walled components have a variety of uses, including structural building parts, long span roofing elements, tanks, facades, and piping strengthening of existing buildings, according to research by Van de

Weyenberg et al. [24]. Bamboo fiber may be utilized as reinforcement in structural concrete components, whilst sisal and coir fiber composites have been used to replace asbestos in roofing components [15]. Natural fiber reinforced concrete boards, ceiling tiles, and sheets (both plain and corrugated) are lightweight and ideal for application in roofs, ceilings, and walls. and walls when building affordable homes [103]. The numerous uses of cellulose fiber in manufacturingconstruction and other various sectors are displayed in Tab 6.

TABLE 6: Natural fiber composite applications in industry [3, 63–65].

Fiber	Application in building, construction, and others
Hemp fiber	Construction products, textiles, cordage, geotextiles, paper & packaging, furniture, electrical, manufacture bank notes, and manufacture of pipes
Oil palm fiber	Building materials such as windows, door frames, structural insulated panel building systems, siding, fencing, roofing, decking, and other building materials [14]
Wood fiber	Window frame, panels, door shutters, decking, railing systems, and fencing
Flax fiber	Window frame, panels, decking, railing systems, fencing, tennis racket, bicycle frame, fork, seat post, snowboarding, and laptop cases
Rice husk fiber	Building materials such as building panels, bricks, window frame, panels, decking, railing systems, and fencing
Bagasse fiber	Window frame, panels, decking, railing systems, and fencing
Sisal fiber	In construction industry such as panels, doors, shutting plate, and roofing sheets; also, manufacturing of paper and pulp
Stalk fiber	Building panel, furniture panels, bricks, and constructing drains and pipelines
Kenaf fiber	Packing material, mobile cases, bags, insulations, clothing-grade cloth, soilless potting mixes, animal bedding, and material that absorbs oil and liquids
Cotton fiber	Furniture industry, textile and yarn, goods, and cordage
Coir fibers	Building panels, flush door shutters, roofing sheets, storage tank, packing material, helmets and postboxes, mirror casing, paper weights, projector cover, voltage stabilizer cover, a filling material for the seat upholstery, brushes and brooms, ropes and yarns for nets, bags, and mats, as well as padding for mattresses, seat cushions
Ramie fiber	Use in products as industrial sewing thread, packing materials, fishing nets, and filter cloths. It is also made into fabrics for household furnishings (upholstery, canvas) and clothing, paper manufacture.
Jute fiber	Building panels, roofing sheets, door frames, door shutters, transport, packaging, geotextiles, and chip boards.

IX. CONCLUSIONS

Natural fiber reinforced polymer composites, which provide benefits for usage in commercial applications (the automobile industry, buildings, and structures) as compared to synthetic composite materials, have desirable qualities including low density, lower cost, and reduced solidity. When natural fibers are utilized as reinforcement in polymeric composites, the mechanical behavior of polymers is enhanced. This study evaluates the natural fiber reinforced polymer composites' mechanical, thermal, energy absorption, moisture absorption, biodegradability, flame retardancy, and tribology characteristics. On the relaxation and viscoelastic behavior of NFPCs, research is conducted. NFPCs are reportedly employed in the industrial and automotive industries as well. Also highlighted is how chemical processing affects the properties of natural fibers. These NFPCs may be chemically treated to further enhance their mechanical and physical properties, and coupling agents and alkalization of the fiber surfaces can stop the NFPCs from absorbing moisture.

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