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In-Depth Review and Analysis for the Applications and Manufacturing of NFRPCs

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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Review Article

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ABSTRACT

NFRCs have shown to be highly useful across various industries, providing numerous advantages over synthetic fiber composites such as friendly to the environment, low cost, weight, availability and cost effective. The global research community has been encouraged to investigate the affordability, accessibility, and ease of fabrication of natural fibers to see if they meet the criteria for a useful reinforced polymer composite for both industrial and structural applications. This paper examines the incorporation of natural fiber-reinforced composites into different industrial applications and the effect of different material characteristics, such as fiber length, weight fraction of the fiber, fiber orientation, fiber surface treatment etc.. Nonetheless, some difficulties must be tackled, for instance, how to manufacture composites efficiently and bond the fibers and matrix effectively. Furthermore, the incompatibility between natural fiber and polymer matrices and high moisture absorption of natural fiber limits their use cases, thus restricting their applications. This review could present a summary of the technical difficulties, processing methods, analysis, features, and It is written to provide an insight into the research and development of natural fiber reinforced polymer composites and its applications.

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1. INTRODUCTION

The utilization of natural fibers as a reinforcement agent for composites is offering multiple benefits over man-made glass and carbon fibers. These composites are made up of diverse reinforcements, which can be either natural or synthetic. The categorization of composites is illustrated in Fig. 1. Synthetic fibers such as glass, Kevlar, and carbon are now widely utilized in reinforced polymer composites, having been greatly refined in recent years to fulfill the needs of engineering endeavors. Nevertheless, an increased focus on eco-friendly materials in product design due to enhanced environmental consciousness has created immense opportunities for the utilization of renewable sources [2-3]. An alternative to synthetic fibers in the production of polymer composites is the increasing utilization of natural fibers. This could substantially reduce the reliance on synthetics. This is called Natural fiber reinforced polymer composites (NFRPC) and those have recently gained much popularity as they are known as natural fiber composites (NFC). These materials are incredibly valuable. They can be derived from plant & animal sources [4]. In recent years, there has been a lot of focus on making composite materials from renewable and nonrenewable natural resources like flax, jute, oil palm, and sisal. These fibers, derived from plants, can be divided into bast fibers (ex. ramie, hemp, flax, kenaf, and jute), seed fibers (coir, kapok, and cotton), leaf fibers (pineapple, abaca, and sisal), grass and reed fibers (wheat, rice, and corn), core fibers (jute, hemp, and kenaf) and other sources (roots and wood) [5]. Table 1 displays the most common, commercially-available fibers in the world and the amount produced [5]. Composites can be used Leisure, construction, aerospace, packaging, sport, biomedical, surgical and automotive industries, mainly automotive [6-7]. Great interest has been shown in the use of fiber reinforced polymer matrix due to the beneficial properties and cost-effectiveness of natural fibers compared to synthetic fibers, particularly its low weight. Decreased wear on machinery, good tensile and flexural strength, smoother finish on molded products, derived from renewable sources, plentiful availability [8]. Ease of use, environmental friendliness, and no hazardous effects on well-being. Natural fibers can be blended with various polymers (thermoplastic and thermoset) to produce NFPCs that are lightweight and strong with high specific stiffness [9]. In contrast, natural fibers possess some drawbacks in terms of their properties and are not exempt from issues. The composition of natural fibers includes (lignin, cellulose, pectin, waxy and hemicelluloses substances) and permits them to take in moisture from the environment, leading to weaker bonds between the fiber and polymer [10]. Natural fiber

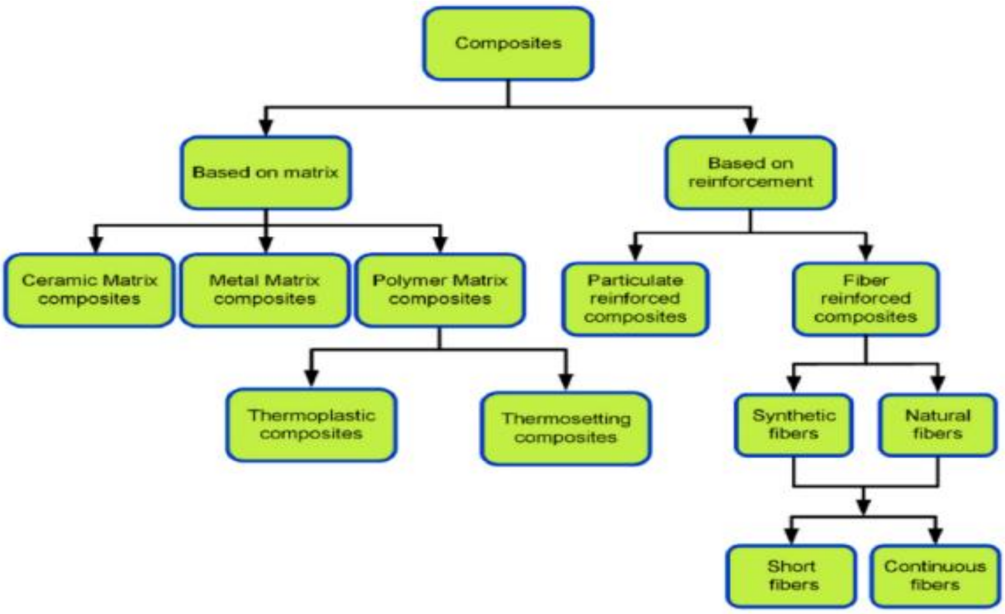

Fig. 1. The categorization of composites [1]

Table 1. the most common, commercially-available fibers in the world and the amount produced [13]

Fiber source	World production(ton)
Abaca	70
Coir	100
Hemp	214
Kenaf	970
Grass	700
Flax	830
Sisal	375
Jute	2300
Sugar cane bagasse	75.000
Ramie	100
Bamboo	30.000

composites don't have the same mechanical strength as synthetic fiber composites because they are less structurally dense [11]. Furthermore, the hydroxyl groups in lignocellulosic fibers result in high hydrophilicity, leading to weak bonding with matrices [12]. This causes a decrease in mechanical, physical, and thermal performance.

The following is the structure of this comprehensive paper: Section 2 provides the general characteristics of NFRPCs and it includes mechanical, chemical, thermal, water absorption, energy absorption, flame retardant, viscoelastic behaviors, as well as the tribology of NFRPCs. Section 3 expresses NFRPCs manufacturing techniques, how NFRPCs is behaving under various conditions in section 4. The application of NFRPCs is explained in section 5. Section 6 expresses the current challenges of NFRPCs and the future expectations. Finally, section 7 concludes this paper.

2. NFRPCs CHARACTERIZATION

A composite material consists of distinct elements that are not able to dissolve in one another and are blended together on a large scale [14]. The reinforcing phase is one element, and the other into which it is included is referred to as the matrix as illustrated in Fig. 2. The reinforcing phase materials come in flake, fiber or particle forms with diverse textures [15]. The performance of NFRPCs is highly dependent on a variety of elements, such as structure [16], mechanical composition [17], chemical [18] and physical properties [5], cell dimensions [19], microfibrillar angle [20] and the fiber/matrix relationship [21]. Studies in the literature have shown that these materials possess great mechanical characteristics as well as certain restrictions in their use. Studies show that NFs can significantly reduce the weight of composites [22]. [23] examined mechanical characteristics by altering fiber length and determined that composites with 15 mm length had the highest flexural and tensile strength. Research indicates NFs used as reinforcement can minimize tool wear in machining. Incorporating two components (wood flour and shell) in the polymer, the composites gain positive advantages like reducing shrinkage and increasing strength after molding [24]. Generally, the main characterization of NFRPCs is having high specific strength, with weight and cost and equally mechanical properties as well. It is important to obtain a better understanding of the effluence of mechanical properties (yield stress, hardness, tensile modulus and strength) on the utilization the different layers of NFRPCs as reinforcements in composites.

2.1 Mechanical behavior of NFRPCs

Some enhancements and suggestions of NFRPCs can be implemented in order to improve the mechanical behavior of NFRPCs. For instance, creating a strong base structure allows for easier improvement and reinforcement of polymers [25]. The most important factors which effect the mechanical performance of NFRPCs are the fibers strength [26], the orientation of that fiber [27], with interfacial adhesion property of that fiber [28], stacking sequence [29-31], eventually, the physical behavior as well [32]. The mechanical properties of NFRPC are greatly affected by the inherent fiber characteristics [33]. In addition to this, it relies on the capacity for stress to move from the matrix to the fiber [34], volume fraction [35], impurities [36] and moisture absorption [37]. Table 2 explains the mechanical properties of NFRPCs [38].

Fig. 2. Different natural fibers are frequently included as reinforcements in polymer composites [13]

Table 2. Explains the mechanical properties of NFRPCs [38]

NF	Density (g/cm^3)	Tensile Strength (MPa)	Young's modulus (GPa)	Reference
Bamboo	1.2-1.5	500–575	27.0–40.0	[39]
Banana	0.5–1.5	711–789	4.0–32.7	[40]
Cotton	1.5–1.6	287–800	5.5–12.6	[39]
Hemp	1.1–1.6	285–1735	14.4–44.0	[41-42]
Flax	1.3–1.5	340–1600	25–81	[41,43]
Bagasse	0.8–1	250–300	17–20	[44]
Ramie	1.4–1.5	400–938	61–128	[41]
Oil Palm	0.7–1.6	50–400	0.6–9.0	[45]
Sisal	1.3–1.6	468–640	9.4–22	[39,46]
Coir	1.2–1.6	170–230	3.0–7.0	[47]
Sugarcane	1.1–1.6	170–350	5.1–6.2	[48]
Kenaf	0.6–1.5	223–1191	11–60	[41,49]
Jute	1.3–1.5	393–773	13–26.5	[39,50]

These fibers possess many advantageous qualities, like a good mechanical property, low density, high strength, it will lead for making them the perfect option for reinforcing FRPCs. The popularity of NFs, especially when used to reinforce composite materials, is well-known for its beneficial effects on a variety of industrial applications that promote sustainability [51]. Naturally sourced fiber-based composites are utilized in a variety of industries, from car components and buildings to furniture and packaging. They are doing their part to preserve the environment through the creation of sustainable materials that can be used instead of traditionally or synthetic made fibers [51]. NFRPC has many advantages that help reduce material expenses, weight and provide eco-friendly solutions. It has been increasingly used in the electronic items [52], packaging [53], automotive industries [54-56] and plastics as well. NFRPCs are used for making home furnishings like windows, wall panels and furniture [57-59]. These materials are ideal for aircraft interior and eco-friendly automotive.

2.2 Chemical behavior of NFRPCs

A substance's characteristics or behaviors when it is chemically changed or reacted to, can be revealed through its chemical property. Chemical properties can be observed once a reaction has occurred, since the arrangement of atoms must be changed in order to study them. The chemical composition plays a role in its performance [60]. Fibers with considerable amounts of cellulose, hemicellulose and lignin are principal chemical properties and having OH groups in their molecular structure, making them hydrophilic materials [60]. The use of hydrophilic and hydrophobic substances in composite production leads to weaker adhesion between the matrix and fibers, causing poor stress transfer and a decrease in the quality of the finished product [60]. Altering the surface chemistry of the fibers can promote bonding between the matrix and the fibers, adjusting its polar properties and making the fibers more receptive to the matrix [61].

The pectin, waxes, and ash found in essential fibers are found in very small quantities. The Cellulose fibers sector has seen a rapid rise in popularity in recent times due to the increased need from the textile industry. Creating eco-friendly and skin-safe products.

2.2.1 Cellulose

Cellulose is a major component of natural fibers. It is the most common organic compound found on our planet, has no flavor and no smell. Plant fibers are typically composed of up to 70% cellulose. The cellulose content of different fibers varies; see the Table 3 shows for details [69].

2.2.2 Hemi cellulose

It is a combination of various plant polysaccharides, with a molecular weight smaller than cellulose. Plants contain hemicelluloses in their cell walls. The amount of hemicellulose in different fibers can vary; see Table 4 shows for details [69].

Table 3. The cellulose content of different fibers varies

S. No	Name of fiber	Cellulose (Wt.%)	Reference
1	Ramie	68.6-91	[62]
2	Alfa	45.4	[63]
3	Coir	37	[64]
4	Curaua	70.7-73.6	[63]
5	Henequen	60-77.6	[63]
6	Banana	62-64	[65]
7	Jute	59-71.5	[66]
8	Betelnut	53.20	[67]
9	Cotton	82.7-90	[63]
10	Kenaf	45-57	[64]
11	Sisal	78	[68]
12	Abaca	56-63	[63]
13	Palm	60-65	[63]
14	Piassava	28.6	[63]
15	Flax	71	[62]
16	Bamboo	26-65	[66]
17	Hemp	57-77	[62]

Table 4. The amount of hemicellulose in different fibers

S.No	Name of fiber	Hemicellulose(Wt.%)	Reference
1	Bamboo	30	[66]
2	Kenaf	9-13	[64]
3	Coir	20	[63]
4	Palm	-	-
5	Banana	19	[65]
6	Jute	13.6-204	[66]
7	Sisal	25.7	[68]
8	Curaua	9.9	[63]
9	Flax	18.6-21.6	[62]
10	Hemp	14-22.4	[62]

2.2.3 Lignin

Organic polymers known as lignin form the backbone of vascular plants and certain algae, providing essential structural support. Lignin is a vital part of the structure of cell walls, especially in wood and bark, making them more rigid and resistant to decay. The amount of lignin differs between materials, the data is compiled here [69].

2.3 Thermal behavior of NFRPCs

The type of loading, fiber and matrix type, any added fillers, fiber content and arrangement, fiber processing, and method of fabrication can all influence the thermal qualities of natural and hybrid fiber composite materials. The highest temperature at which a natural fiber can endure before breaking down is its thermal stability [70]. Fiber components such as hemicellulose, cellulose and lignin all break down at different temperatures. Together, this causes the entire fiber to decompose [71]. It is known that lignin breaks down at around 200 ◦C, while cellulose and hemicelluloses need more heat to decompose [72]. At temperatures between 300-450◦C, lignin and cellulose typically break down [73]. The heat resistance of the natural fiber can be increased by eliminating some quantity of lignin and hemicelluloses materials. Fibers with less lignin can be damaged by heat and can weaken the secondary cell walls [74]. Apart from cellulose, other potentially unsteady or semi-stable elements, such as pectin, waxes and water-soluble elements, can also be present. Therefore, the thermal conductivity of natural fibers can be a problem when manufacturing natural fiber-reinforced thermoplastic composite materials. The warm weather can have an adverse effect on the auto interior component constructed of natural fiber reinforced composites. The heat resistance of these composites is a major concern when there is a fire due to their low thermal stability. The prolonged exposure to temperatures higher than 250◦C can cause natural fibers to combust, and consequently weaken the structural stability of the part [75]. In conclusion, the temperature used in the fabrication process of the composite is a key factor to consider when examining the thermal stability of natural fiber composites. Investigative work is ongoing and some of the weaknesses of NFRPCs have been dealt with through modern progressions in fiber treatment and alteration, the investigation of new natural fibers, and a mixture of materials.

2.4 Water Absorption behavior of NFRPCs

Moisture absorption in FRCs decreases the fiber-matrix bonding, resulting in a decrease in the efficiency of load transfer from the matrix to the fiber. For natural fibers, water uptake within the fiber can lead to the weakening of its physical, thermal and mechanical properties because of the extraction of water-soluble elements. Additionally, this can be a problem [76]. Three distinct processes regulate the diffusion of

Table 5. The amount of lignin in different fibers [69]

S.No	Name of the fiber	Lignin (Wt.%)	Reference
1	Flax	2.2	[62]
2	Banana	5	[65]
3	Coir	42	[64]
4	Palm	11-29	[63]
5	Jute	11.8-13	[66]
6	Hemp	3.7-131	[62]
7	Alfa	4.9	[63]
8	Bamboo	5-31	[66]
9	Piassava	45	[63]
10	Ramie	0.6-0.7	[62]
11	Cotton	< 2	[63]
12	Abaca	7-13	[63]
13	Betelnut	7.20	[67]
14	Sisal	12.1	[68]
15	Kenaf	21.5	[64]
16	Henequen	8-13.1	[63]
17	Curaua	7.5-11.1	[63]

moisture in polymeric composites [77]. Water molecules pass through the tiny gaps between the polymer strands by diffusion. Capillary action transports fluid into the crevices between the fiber and the matrix. This issue is caused by inadequate saturation and infiltration during the first production phase. Incorporating microcracks due to expansion of fibers, particularly in natural fiber composites, is the third factor [71], as explained in Fig. 3. Polymeric composites display three varieties of diffusion patterns: Fickian diffusion, anomalous non-Fickian, and a combination of the two. Studies have revealed that moisture diffusion in hybrid composites can be affected by several elements such as the amount of fibers, their direction, structure, temperature, filler content, how the fibers are treated and how long they are immersed. Prolonged exposure, more natural fibers and air pockets raise the composite's water absorption [78-80].

At elevated immersion temperatures, moisture is taken up faster and the time for full saturation is much shorter [81]. In contrast, stacking fibers in a particular order (e.g. facing hydrophobic fabrics outward) and orienting natural fibers to 0° was proven to reduce the composites' water absorption [82-83].

Examinations of moisture absorption properties of composites with natural-natural and natural-synthetic fibers have been conducted [78,82-99]. An effective way to lower the moisture content and lower the diffusion coefficient is to employ a mixture of natural and synthetic fibers, while picking the right fiber content, layering pattern, and fiber orientation. Consequently, lessening the effects of moisture damage and composite material characteristics. The water absorption of natural-natural hybrid composites is subject to great fluctuations depending on the reinforcement fibers used. Different natural fibers have varied amounts of hydrophilic groups, porosity, and crystallinity, thus affecting their water uptake. This method of hybridizing natural elements is a cost-effective way to achieve equilibrium in wet areas.

2.5 Energy Absorption behavior of NFRPCs

Composite materials are popular in automotive and motorsport because of their ability to reduce weight, while still providing energy absorption, high strength, and stiffness [100]. Energy absorption is notably greater when the velocity is low, such as 2.5 m/s, resulting in a higher volume fraction [101]. In contrast, when velocity is very high, like 300 m/s, flax, jute and hemp perform similarly, although jute exhibited brittleness and low fiber strength [102]. The potential of NFPCs for making sustainable energy absorption feasible is studied by [101]. Testing conical specimens of jute, flax, and hemp for their properties and features is done through Vacuum Assisted Resin Transfer Molding (VARTM) technique [103].

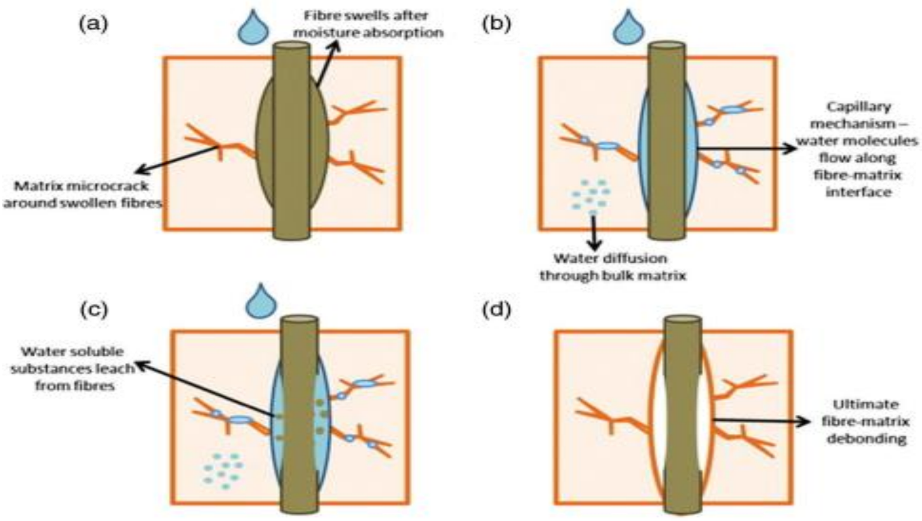

Fig. 3. Water's influence on fiber-matrix boundary: (a) Micro-fractures from fiber enlargement; (b) Water diffuses in the matrix and goes along fiber-matrix boundary; (c) Leaching of water-soluble compounds; (d) Separation of fiber-matrix interface. Get explicit consent from the creator to use their work [71]

2.6 Flame Retardant Behavior of the NFRPCs

Fire resistance is a key factor when creating composite materials made with natural fibers to ensure safety. When flame is present, five distinct steps occur in the combustion of composites: heating, decomposition, ignition, combustion and propagation]103]. A combination of char-developing cellulose material, which is one of the famous flame retardants for reinforced polymers (natural fibers), is often used [104]. The best way to decrease combustion in this situation is to maximize the stability and charring of the polymer. This will lead to a less flammable environment, minimize smoke production, and limit the level of materials produced from combustion [71]. Coating with a fire retardant is a way to boost the fire resistance of composites. This finishing or impregnation process includes a coating step. Manufacturing alters the fire resistance of fibers and cellulose particles [105]. The two most widely applied flame retardants are aluminum hydroxide [Al(OH3)] and magnesium hydroxide [Mg(OH)2], intentionally incorporated into plastic materials. Magnesium hydroxide is more thermally stable than aluminum hydroxide; it begins to break down at 300-320°C while aluminum hydroxide's decomposition starts at only 200°C. Hence, aluminum hydroxide is not suitable for the thermal stability of polypropylene, polyamides, and other materials due to its limited application, unlike magnesium hydroxide.

2.7 Viscoelastic Behavior of the NFRPCs

Investigation into temperature-dependent viscoelastic properties of natural fiber composite material can reveal information about its structure and the nature of its interfaces [106]. Storage modulus reveals the capacity to endure weight and the rigidity of natural fiber composite materials. Storage modulus is a measure of the energy a material can retain when it is subjected to repeated deformation. The ratio of the amount of energy lost to the amount stored gives us the mechanical damping coefficient, a measure of the molecules' ability to move in the polymer. Moreover, the quantity of energy that is converted to heat is linearly related to the loss modulus [107]. The elastic and viscous properties of polypropylene/jute yarn composites, as reported by [107], have been investigated. A combination of jute yarn and polypropylene resulted in commingled composites. The viscoelasticity of the combined composites was analyzed based on fiber content, as well as various chemical treatments including potassium permanganate, maleic anhydride modified polypropylene, toluene diisocyanate and stearic acid. This study established that greater amounts of fiber in the composite material resulted in a higher storage and loss modulus. In contrast, $KMnO_4$ treatment of the composites raise the storage and loss moduli of the materials when compared to untreated samples, irrespective of temperature.

2.8 Tribology Behavior of the NFRPCs

Almost all experiments have a failure rate due to the tribological loading conditions varying, which affects the frictional behavior and wear[108]. Strengthening the tribological properties of fibers or polymers through alteration [109]. Examinations of tribological properties of a variety of fibers have been done, such as kenaf/epoxy [110], betelnut fiber reinforced polyester [111], sisal/phenolic resin [112], cotton/polyester [113] and sugarcane fiber reinforced polyester (SCRP) [114]. The addition of natural fibers to PLA resulted in better wear performance, reducing the wear rate at higher loads compared to that of neat PLA [108]. Composites made with lamination were created using three natural fibers: optiva, sisal,grewia and nettle. Research was conducted on the link between natural fibers and their properties [108]. Investigation of the frictional behaviour and deterioration of composite materials in dry contact conditions with different operating parameters was conducted. The operating parameters could be altered, allowing applied load to be adjusted from 10 to 30 N and speed of 1 to 3 m/s and covering a span of 1,000 to 3,000 meters. The outcome of the investigation demonstrated that blending of natural fiber mats into PLA matrix can bolster the frictional and wear properties of pure polymers. There is an impressive drop in friction coefficient of up to 44%, with even more significant reductions (up to 70%) of wear rate seen in composites compared to pure PLA [108].

3. NFRPCs MANUFACTURING TECHNIQUES

Different raw materials such as fabrics, mats, fibers, resins, fillers, prepregs, etc. can be used to manufacture natural fiber-reinforced polymer composites (NFRPCs).Typically, natural fiber polymer composites are produced through the same methods used to make traditional reinforced plastic and fiber polymer composites.

These processes are utilized: hand lay-up, compression molding, resin transfer molding, vacuum infusion, injection molding, direct extrusion and compounding. The processes chosen are based on what is needed and will affect the characteristics of the finished item. Resin transfer molding exhibits better tensile and flexural properties than injection compression molding. The tensile strength using resin transfer molding for a banana/sisal hybrid fiber-reinforced polyester, as per research, is 1621 MPa, greater than that of compression molding which is 1347 MPa. Resin transfer molding has a greater flexural strength when compared to compression molding which yields 2276 and 2247 MPa respectively. The strength of polymer composites created using resin transfer molding isn't as high as those made by compression molding [115-116]. Some particulars of the processing are outlined in the following section.

3.1 Compression Molding

The popular way to manufacture strong, reinforced composite materials is Compression Molding, commonly used in the auto industry. This method is ideal for blending two or more polymers together. The composite materials are laid out in the cavity of the lower mold, then the core side of the mold is used to compress, shape and fill the cavity, and it is explained in Fig. 4. The component keeps the pressure high until the material is hardened. The form is taken out, and the item is obtained. Molds are made from a tough metal, like tool steel, and can be buffed and chrome-plated for a fine finish. The mold needs to be heated up to the desired temperature for 10-15 minutes before compression molding is done to ensure the pressure and temperature are appropriate for curing the materials [117-118].

The subsequent crucial elements when utilizing compression molding are the viscosity and polymer matrix sheets sandwiched between the fibers. To ensure a strong adhesion and infiltration of fibers and matrix, this is essential. Temperature and pressure must be closely monitored to guarantee that fibres do not suffer deterioration or fracture throughout the procedure [116,119]. The resin used in the process is fluid when heated and sticks well to the mold, giving the composites formed a great microstructure and strength. Laminated carbon fiber reinforced matrix composites may suffer from displacement defects and isolation of the fibers when the resin is exposed to high temperatures, weakening the bonding force between the layers. This would have a major impact on the microstructure and mechanical characteristics of laminated composite material [120-121].

3.2 Resin Transfer Molding

A preformed stack of fibers or fabric is encapsulated in a mold, sealed and then put through the resin transfer molding process for composite manufacturing. The polymers created can also be employed in carbon fiber-filled composites, epoxy laminates, and nanoparticle-incorporated polymeric materials. RTM has been carried out with reduced heat and pressure. By carefully controlling resin, monomer, activator and catalyst rates, cycle time can be shortened significantly, achieving a dramatic increase in output [122-123]. Fig. 5 explains the mechanical process of resin transfer molding (RTM). fiber sheets are put in the mold, and the mix of epoxy resin and hardener is pumped in and pressurized, all while a consistent gap is maintained. Reinforcement is frequently achieved through the use of carbon fibers. The cavity is filled with the resin at 200°C and 160 bar using a mixing head and pressurizing it. Consequently, resin infiltration is oriented vertically, meaning against the vertical plane, not horizontally, it is more resistant. Thermosetting

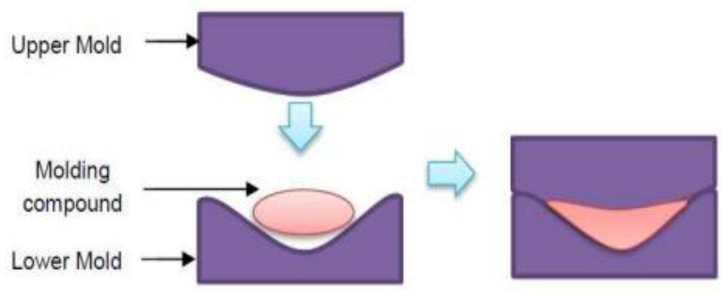

Fig. 4. Shaping a compound into a desired form with pressing and heat

resins like epoxy and polyester offer superior impact resistance, higher fracture strength, and greater fiber saturation than other types of resins [122,124-126]. The resin permeates the mold, saturating the fibers in the process. The resin penetrates the shape, saturating the fibers in the process. In order to achieve the desired result, it's important to manage certain factors when utilizing RTM, i.e. fluid viscosity, injection pressure, temperature, and fiber volume fraction.

Other benefits are fine finish of product, minimal empty space and cost-effective tooling [115]. This method, however, has its drawbacks: the size of the part is limited by the size of the mold cavity, tooling costs are high, and it is hard to reinforce the material due to the flow and resin saturation of the fiber [127]. Additionally, RTM finds usage in a variety of production markets, including aviation, defense, motoring, and sporting wares.

3.3 Injection Compression Molding

Injection molding is a technique used to form plastic parts in which molten resin is injected into a pre-formed mold and then cooled to create the desired shape. This method guarantees an even spread of adhesive, allows for accurate detailing on the exterior, and gives the finished piece increased durability. The feedstocks must be dried and in granule shape prior to being processed in the machine in order for injection compression molding to work effectively. This is because natural fibers tend to absorb moisture and create short fiber bundles. The granules are sifted through the chamber. The granules are fed into an extruder, pressed into a mold, and heated to form the desired shape. When the right amount of material has been obtained, the hot liquid is injected into the preheated mould to shape the composite part via the nozzle. The hot material will flow into the contours of the mold as explained in Fig. 6. Maintain heat and pressure in the mold until the item has hardened and cooled off. The items are cut back before performing an examination. This task must be completed for each product, taking 3-5 minutes. In order to achieve a perfect outcome, the first three attempts are discarded. This is because the initial three items usually don't completely fill the space, leaving a few pockets of air visible on top of the product. To keep the other products free from contaminants, the screw extruder must be cleaned with a purging compound like PP before and after injection molding. Subsequently, adjustments to the melt temperature, screw speed, and pressure must be made during injection compression molding. Advantages of injection molding include a smooth finish, reliable accuracy, and minimal material waste [119]. Injection molding has lower tensile strength than other thermoset fabrication techniques, Molding with injection has weaker tensile strength than other thermoset systems. In spite of the cost, a sealant must be applied to the most costly molds and some injection molded plastics to avoid oxidation.

3.4 Sheet Molding Compound

SMC is a highly adaptable composite material widely used in many sectors, such as automotive, aerospace, telecommunications, oil, leisure and industrial/consumer. SMC is a layered material consisting of a reinforced thermosetting resin and fiberglass, usually rolled into a coil with plastic film between layers to stop it from sticking. The components of SMC include a maturing agent, filler, activator, combined resin and release agent, which are put on two plastic films moving in succession [128-129]. Glass fibers and carbon fibers are commonly employed as materials for strengthening [130]. Fibers can be arranged into strands, then interlaced or sewed to make materials. A wide selection of materials like polyester, epoxy, vinyl ester, nylon and other thermosets and thermoplastics are utilized as matrixes. The production of continuous fiberglass strands, commonly referred to as 'roving', is the start of the SMC process; these strands are then cut to size. The bottom layer of the resin-filler paste is where the strands are placed. The paste and the fiberglass filament are being transported through the device, onto the backing material. The stuffing of the resin and the goop encapsulates the fiber to the lowest level of the goop, while the peak layer of the film is concealed. The rollers then press the fiber and paste combination together to form a single sheet of molding material. SMC paste is a mixture of cross-linked resin, fibers, filler, and various additives. This paste is comprised of a resin that is polymerized and cross-linked, along with fibers, filler, and other components. A consistent flow of resin and fiber is blended together to make pre-preg, which is carefully sandwiched between plastic sheets for molded part production and SMC is explained in Fig. 7. The paste is manipulated carefully while forming to create the finished solid shape [131-132].

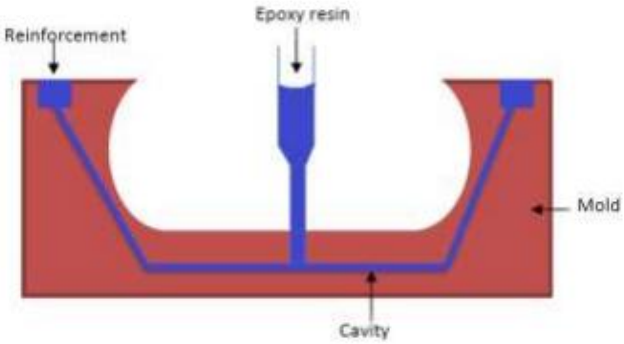

Fig. 5. Manufacturing process of RTM

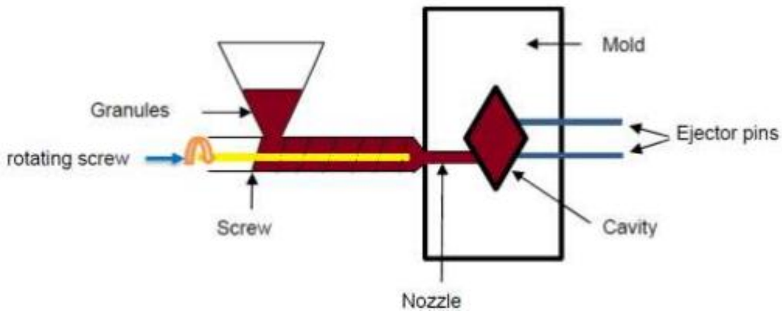

Fig. 6. Manufacturing process of ICM

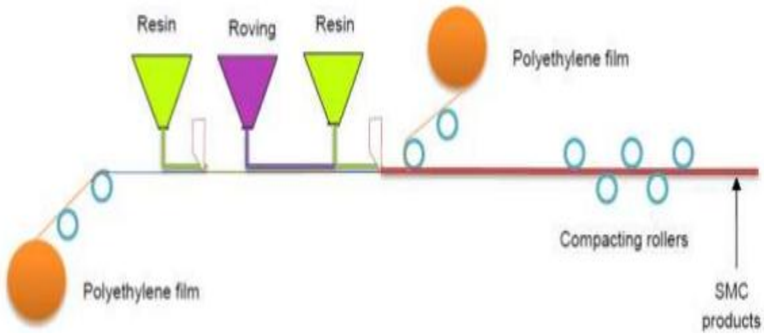

Fig. 7. Manufacturing process of SMC

SMC offers advantages such as superior mechanical characteristics, environmental friendliness, and heat-enduring capability over injection molding. SMC is a cost-effective method of creating a smooth finish on finished products, as well as having the ability to produce intricate shapes quickly. There is a downside though: the paste will thicken constantly and styrene is released, which affects the curing reaction [131,133].

4. NFRPCs BEHAVIOR UNDER VARIOUS CONDITIONS

Most of the utilization of NFRPCs is focused on interior uses. The use of NFRPCs outside is hampered due to their water attraction. The fiber volume fraction, temperature, permeability of the fiber, orientation of the reinforcement, protective surface coverings, surface geometry, and diffusivity all contribute to the behavior of NFRPCs [134]. For successful production of NFRPCs, due care must be taken while handling them pre- and post-manufacturing. NFRPCs could be utilized for an outdoor liquid storage container. These tanks may be subjected to various environmental conditions and stresses [135]. So, an investigation of these tanks in terms of structural physical, morphological, mechanical, etc. characteristics must be done mandatory. Wood flake composites deteriorate quickly when exposed to UV light and heat [136]. Conditioning for 205 days caused a drop in strength to half, and toughness to two-thirds of the original. [134] studied how UV light could be used to measure the aging process of sisal fiber composites. The higher fiber-loaded composite took in more water due to its high cellulose concentration. Fiber-reinforced composites with chemical treatment had reduced water absorption. The more water absorbed, the longer the immersion time, and the more fibers used, the weaker the composite material became. [137] conducted an investigation into the performance of hemp-reinforced composite material when submerged in water. Composite made with a larger portion of hemp fiber has better water absorption. The composite's water uptake was monitored at both room temperature and higher temperature of the water it was submerged in, displaying both Fickian and non-Fickian behavior. The strength and resistance to bending weakened when exposed to either water type. [135] investigated the possibility of utilizing coir fiber polymer for fabricating liquid storage tanks. Absorption of water in salt water was higher than for other liquids because of its low viscosity [138] and examined nettle composite's resistance to tension while exposed to varying conditions for 512 hours. The tensile strength of the composite decreased in each situation. The composite's tensile strength was diminished in all circumstances. Sunlight and river water caused the greatest decrease in tensile strength. No significant decrease in soil was evident. The weight of all the composites increased, except when exposed to sunlight. Significant growth in weight was observed in river water. [139] experimented with varied combinations of composites using jute and coir for reinforcement. Mixture of coir and nothing else exhibited highest water uptake and thickness of swelling in comparison to only jute blend. It was established that the hybrid composite with an exterior layer of jute displayed greater dimensional stability when evaluated with water absorption and mechanical tests. The blocking of water by jute could be the reason for this. [140] explored the impact of atmospheric exposure on kenaf polyester composite's physical and mechanical characteristics. The study found that conditioning led to a loss of mechanical properties because the fiber had inadequate wetting and moisture absorption. The high moisture absorption led to the gap forming between the fiber and matrix. This caused a decrease in the mechanical properties. Synthetic hemp, jute, and sisal-strengthened polypropylene blends were assessed for their performance in various conditions [141]. All composite materials have had an increase in weight, plus deterioration, after being exposed to certain conditions. All conditioned composites experienced a decline in tensile strength. A considerable decrease was recorded for the composite treated with 5% NaOH. The jute and flax fiber were treated with sodium bicarbonate and then exposed to the elements of the sea [142]. Results showed that post-treatment, jute fibres had higher water absorption. Flax's water absorption was lessened in comparison. Absorption of water was reduced when dealing with flax fiber. The flexural

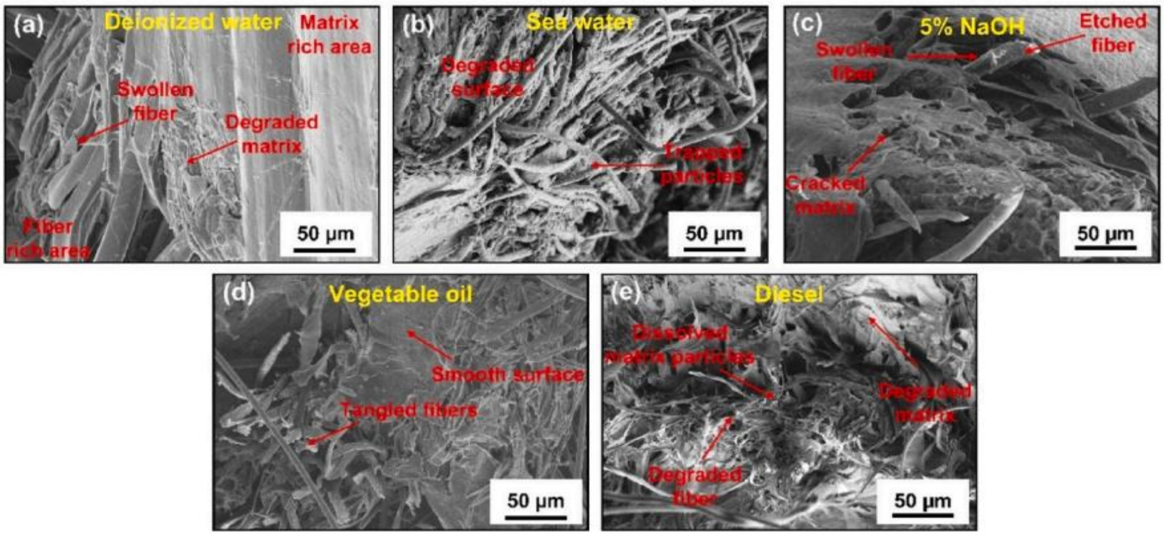

Fig. 8. Examined the long-term stability of kenaf fiber-reinforced polymer composite under various conditions over the course of six months using SEM micrographs [143]

properties were decreased in jute composite which had been treated. The researchers created a combination of kenaf and high-density polyethylene and exposed it to different conditions, including deionized water, seawater, 5% sodium hydroxide, vegetable oil, and diesel, for a period of six months [143]. The SEM analysis showed that 5% NaOH has the greatest environmental impact on the composite, but vegetable oil had the least impact s shown in Fig. 8.

It was investigated how water absorption affects the mechanical properties of various combinations of corn husk polyesters [144]. The composite was observed to absorb less water, comprised of a smaller amount of corn husk. Excellent characteristics obtained for composite with 20% of corn fiber by weight.

5. NFRPCS APPLICATIONS

The utilization of NFPCs is expanding rapidly in numerous engineering areas. Various types of natural fibers, such as kenaf, hemp, jute, oil palm, and bamboo incorporated with polymer composite, are becoming increasingly important for industrial applications [8]. NFPCs are being used in a variety of applications, such as electrical and electronic industries, aerospace,

Table 5. The summary of NFRPCs uses in industry [4,147-149]

Fiber	Application in building, construction, and others
Flax fiber	Objects such as window frames, panels, decking, railing systems, fencing, tennis rackets, bicycle frames, forks, seat posts, snowboards, and laptop cases.
Wood fiber	Frame for windows, panels, shutters, deck structures, railings, and barriers.
Oil palm fiber	Constructing components like windowpanes, door frames, insulated boards, siding, fencing, roofing, decking, etc. [146]
Hemp fiber	Manufactured items such as building materials, fabrics, rope, soil-stabilizing fabrics, and paper.
Jute fiber	Putting together wall boards, tiles for the ceiling, door structures, door covers, transfer, encasing, soil textiles, and sawdust boards.
Ramie fiber	Employ in industrial projects, e.g. for stitching, wrapping, netting, and filtration. Fabrics from hemp are used to make items such as furniture upholstery and clothing, as well as paper.
Coir fibers	Manufacturing a wide variety of items: wall cladding, door frames, roofing, tanks, packing, helmets, mailboxes, mirror surrounds, paperweights, projector casings, voltage stabilizers, seating upholstery, brushes, ropes, bags, mats, and mattress fillings.
Cotton fiber	Manufacturers of chairs, sofas, carpets, fabric, apparel, and rope products.
Kenaf fiber	Supplies for packing, phone covers, sacks, thermal insulation, fabric suitable for clothing, soil-free planting mixes, bedding for animals, and material that soaks up oil and liquids.
Stalk fiber	Constructing furniture, assembling walls, laying bricks, and installing pipes and drains.
Sisal fiber	The construction industry utilizes products like panels, doors, shutting plate, and roofing sheets; as well as the production of paper and pulp.
Bagasse fiber	Framework for windows, boards, terrace construction, barriers, and fences.
Rice husk fiber	Constructing supplies like wall boards, blocks, window jambs, cladding, verandas, balustrades, and barriers.

boats, machinery, sports equipment, office products, and more. The incorporation of NFPCs into polymer composites is popular due to its light weight, good strength, corrosion and fatigue resistance and economical manufacturing. Biodegradable, resulting in a better finish on composites, good mechanical qualities, derived from renewable and accessible sources rather than synthetic fibers [8]. The downside of NFPCs includes water absorption, processing temperature limits, and fluctuating quality, all of which have hindered their performance [145].

6. CHALLENGES AND FUTURE PERSPECTIVES OF NFRPCs

The review demonstrates that using NFRPC for sustainable industrial purposes is reasonable since the materials possess similar strength to synthetic fibers and leave a lighter footprint on the environment. It is extremely challenging to improve and control the mechanical performance of NFRPCs. Further exploration is needed from the research world to encourage and back the use of new NFs and chemical strategies in the progression of NFRPCs. Employing composites in outdoor projects can cause problems with longevity if they are exposed to the elements, like moisture and organisms. Reusable materials can be recycled from natural fiber composites. Technical issues like breakdown of polymers and fibers, high humidity, ignitability, difference in natural fiber composition, and inadequate bonding of hydrophilic fibers and hydrophobic polymers are the primary hindrances to recycling and employing NFRPCs that need to be tackled. Learning how to better the properties of NFRPCs both during and after their reuse is essential for heightened utilization. It appears that NFRPC is advancing quickly and may become a reliable resource for new uses. Or The progress of NFRPC is evident and can be seen as a possible sustainable material for various applications. Further investigation is necessary to triumph over the obstacles in creating NFRPC for ecological industrial use, which includes reducing expenditure on machines and materials, and making it easier to adapt the technology. The properties of NFRPC are poor because of the lack of compatibility between the fibres and binder, and because of the natural fibres' weaker properties in comparison to synthetic fibres. This issue can be remedied by adjusting the combination of the natural fibers and the polymer. Additionally, exploring new methods to process the materials could improve the interaction. Modifying natural fibres through NFRPCs. The alteration of the fiber structure through alkalisation drastically reduces the ability of natural fibers to retain moisture. This leads to better bonding of the fiber with the polymer layer. Composites are ideal for construction due to the combination of wood and plastic they contain. NFRPC have already proven their worth in electrical products and athletics, paving the way for them to become a dominant presence in the market. Investigation needs to be conducted to overcome the difficulties of NFRPC, like water uptake, in order to ensure lasting stability of outdoor projects and to ensure these materials have maximum service life, mitigation strategies such as recycling can be employed to guarantee maximum performance and recyclability.

7. CONCLUSION

This research conducted an extensive analysis of the features and advantages of natural fiber and national fibers reinforced polymer composites for sustainable industrial purposes. NFRPCs resources can be dealt with more effectively by implementing the circular economy to develop eco-friendly products and technology. NFRPC’s sustainability makes possible the implementation of innovative industrial applications. This survey covered an array of NFRPC studies on the processing methods and applications. It included a comprehensive overview of the field. It provides the general characteristics of NFRPCs and it includes mechanical, chemical, thermal, water absorption, energy absorption, flame retardant, viscoelastic behaviors, as well as the tribology of NFRPCs. With its manufacturing techniques, and behavior under various conditions. It summarized the application and challenges of NFRPCs. The characteristics of sustainable composites determined their selection, based on such qualities as different aspects such as physical qualities, chemical characterization, crystalline cellulose size, microfibrillar angle, flaws, construction, and extraction methods can all affect the characteristics of natural fiber. The arrangement, imperfections, wetness uptake, arrangement, ratio, material characteristics, microfibril angle, blemishes, chemical composition, cell size, and fiber-matrix alliance all have an effect on NFRPC properties. Natural fibers used in sustainable industrial applications have clear benefits, such as being eco-friendly, low cost, biodegradable, releasing less carbon, recyclable, abundant and energy efficient for disposal. The demand for sustainable materials has triggered a revolution in NFRPCs. Further research must be conducted to discover more ways to utilize NFRPC.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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