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Review article

Potential of lignocellulosic fiber reinforced polymer composites for automobile parts production: Current knowledge, research needs, and future direction

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ABSTRACT

In recent years, there has been a notable surge in research focusing on the use of natural fiber-reinforced polymer composites (NFRPCs) in the automobile industry. These materials offer several advantages over their synthetic counterparts, including lightweight properties, renewability, cost-effectiveness, and environmental friendliness. This increasing research interest in NFRPCs within the automotive sector is primarily aimed at overcoming the challenges that have thus far limited their industrial applications when compared to conventional synthetic composites. This paper provides a comprehensive overview of the potential applications and sustainability of lignocellulosic-based NFRPCs in the automobile industry. It examines the current state of knowledge, identifies research needs and existing limitations, and provides insights into future perspectives. This review shows that, while lignocellulosic fibers hold great promise as sustainable, high-performance, and cost-effective alternatives to traditional reinforcing fibers, continuous research is needed to further address issues such as fiber-matrix compatibility, processing techniques, long-term durability concerns, and general property improvement. These advancements are essential to meet the increasing performance demand for eco-friendly, renewable, and energy-efficient materials in automotive design.

1. Introduction

Natural fibers are renewable organic materials produced from plants, animals, or minerals and are mainly used as sustainable sources of materials for both industrial and domestic purposes [1,2]. They are considered one of the largest sources of materials for sustainable energy generation and composite production because of their eco-friendly nature, renewability, biodegradability, and lower cost [3–5]. Reports have shown that over 998 million tons of agricultural-related by-products are produced annually from global agricultural activities. This is likely to increase significantly in the coming years as most developing countries continue to intensify their farming systems [6,7]. This large volume of waste materials can be converted into useful products for energy production and other applications [8]. Lignocellulosic-based agricultural resources are promising sources of raw materials with attractive attributes for large-scale industrial applications if properly harnessed, especially in areas requiring renewable materials for economic transformation and sustainability [9]. Recent awareness of environmental impact management and the increasing demand for lightweight

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and energy-efficient vehicles has led to the exploration of natural-based materials as integral components in automobile production [10]. The use of lignocellulosic fibers sometimes referred to as vegetable fibers or plant-based fibers in composite production for critical applications such as automotive, has displayed great potential for lowering greenhouse gas emissions and reducing fuel consumption, owing to their carbon dioxide neutrality and lightweight nature, respectively [11–13]. In response to the rapid growth of the world's population, new government regulations and policies on climate issues, fear of the future disappearance of petroleum-derived products and other non-renewable mineral resources due to their high rate of depletion, have generated intensive research efforts toward producing eco-friendly and cost-effective natural products for industrial applications [14,15].

Lignocellulosic fibers are extracted directly from either the primary plants (e.g., sisal, jute, hemp, bamboo, etc) or from the waste products of various agricultural processing of secondary plants (e.g., pineapple, banana, coconut, cotton, etc) [16]. They are the most widely studied by industries and research communities when compared to other types of natural fibers. This is due to their unique characteristics such as renewability, eco-friendliness, availability, low cost, and most importantly, acceptability [17–19]. Applications of fibers obtained from animal sources are often restricted by laws, whereas the use of mineral fibers such as asbestos is generally prohibited by many countries because of the high risks of exposure associated with human health [20,21]. Hence, both animal and mineral fibers are not covered in this overview.

Exploring the potential of natural fibers as reinforcing materials for biocomposite development has witnessed enormous research interest in recent times because of their attractive features and advantages over synthetic fiber-reinforced composites. However, despite all the attractive characteristics of natural fibers, they are still less competitive with synthetic fibers as reinforcement materials in the composite global market, owing to their limited properties, wide variation in fiber quality, poor fiber/polymer compatibility, and high-water absorption characteristics [22,23]. Several studies have been conducted to address these prevalent challenges of natural fibers to improve their properties as well as their applicability, particularly in composite production and utilization [24–27]. Some of the approaches that have been reported include developing a new fiber extraction and processing technique, identification and utilization of different fiber treatment methods, exploration of different natural fibers and fiber contents [28,29]. Studies have shown that fiber types, fiber treatment, and fiber extraction methods are the major parameters that are often considered during the production of natural fiber-reinforced polymer matrix composites for property enhancement, especially the mechanical properties and thermal stability of the products [30–32]. Singh et al. [31] found that the surface treatment of natural fibers leads to a considerable increase in the tensile and flexural strength of a polymer-based composite reinforced with jute, banana, and sisal fibers. Maya et al. [33] investigated the effects of chemical treatment on sisal/oil palm-reinforced natural rubber hybrid composites using both alkaline and silane treatment processes and concluded that composites containing chemically treated fibers possess better mechanical properties than untreated fibers. Bezazi et al. [34] used two novel extraction techniques for agave fiber extraction. In the first technique, the Agave leaves were buried in the soil at a depth of 30–40 cm for 90 days, whereas in the second method, the leaves were completely immersed in an air-tight container for approximately 2 weeks, after which they were removed and gently scraped off the outer non-fibrous parts to separate the fibers. The mechanical properties and performance of the fibers obtained using both extraction methods were then studied. The outcome of the study shows that there was a strong correlation between the mechanical properties and extraction techniques, as the fibers produced by burying the agave leaves in the ground generally exhibited higher tensile modulus and strength than water-based extracted fibers. Ghosh et al. [35] studied the influence of different volume fractions of banana fiber-reinforced vinyl ester resin composite and reported a significant increase in the specific tensile strength of the composite by 65 % at a fiber volume fraction of 38.6 %. Sreekumar et al. [36] conducted a similar study on the effect of banana fiber volume fraction in polyester matrix composites and reported 40 % as the optimum volume fraction of the fiber that gave the maximum tensile strength.

Some of the commonly used natural lignocellulosic fibers in biocomposite production include flax, abaca, agave, hemp, sisal, jute, pineapple leaves, banana stem, oil palm, rice husks, coir, and bamboo [37–39]. Extensive commercialization of natural fiber-based composite products in the automotive sector is still underdeveloped, particularly in the production of exterior parts [40,41]. Hence, it is necessary to critically assess some of the various drawbacks that limit their full-scale commercialization in the industry and to identify the way forward for new research and development in this field. Although several review articles on natural fibers and their composites are available in the literature, they have not been able to address and provide permanent solutions to all the above-mentioned challenges. Therefore, this critical appraisal brings forth the much-awaited development in the use of NFRPCs, and the current knowledge in exploring NFRPCs as sustainable automotive materials, while considering their physical and chemical characteristics, properties, and availability. The prospects and limitations of NFRPCs in the automotive sector, research needs, and future direction are summarized.

2. Lignocellulosic fiber and its composite

Fibers derived from plants are naturally occurring materials with excellent specific properties owing to their lower densities [18,42]. They are tough and stiff with moderate mechanical properties and thermal stability. The total volume of plant-based natural fibers produced yearly across the world is approximately 30 million tons and has been used for various applications, including textile products, food packaging, paper making, biocomposite development for automobile and aerospace components, building materials, and sports equipment [43–46]. The properties of plant-based natural fiber-reinforced composites largely depend on various factors, including the plant part from which the fibers are extracted, the age of the plant, the method of extraction, the geographical location of the plant, and growing conditions such as soil composition, temperature, humidity, and frost. The density of these fibers also varies greatly with the method of fiber harvesting and extraction process [47–49]. Plant fibers can be extracted from the stem, leaf, or seeds. The extraction method of fibers from the stem and leaf is very similar but differs from seed fiber extraction [50,51]. Table 1 highlights the world's annual production of different plant fibers, their volumes, and the part of the plant where they were extracted.

Plant fiber-reinforced polymer matrix composites have shown adequate potential as alternative materials to synthetic fiber-reinforced composites for commercial and domestic purposes [54,55]. Thermoplastic and thermoset polymers are commonly used matrix materials for the production of natural-based fiber-reinforced composites [56–58]. Examples of thermoplastic materials used for this purpose include polyethylene (PE), polyvinyl chloride (PVC), polypropylene (PP), and polystyrene (PS). Thermoset materials such as polyurethane, epoxy, phenolic, silicone, and polyester are also very popular as matrix materials for plant fiber-based composite development. Most thermoplastic polymers require lower processing temperatures usually below 200 °C, which is suitable for these types of fibers to prevent thermal degradation that could weaken their reinforcing potentials. They can also be easily recycled [59]. On the other hand, some thermoset polymers can withstand higher processing temperatures and longer curing durations but have low recyclability because of their unique characteristics of forming three-dimensional crosslinked networks during curing. Common composite processing methods, such as hand lay-up, filament winding, compression molding, injection molding, vacuum-assisted transfer molding, autoclave processing, and additive manufacturing, can be employed for processing natural fiber-based polymer matrix composites [60–62]. For biocomposite development, polyester, and epoxy are the most widely studied among researchers. Because of the unique characteristics of thermoset polymers, special processing techniques such as vacuum-assisted transfer molding and autoclave curing are often employed in the processing of thermoset-based natural fiber-reinforced composites, especially for critical applications such as transportation and marine sectors [63,64]. Compared to other conventional processing techniques, the two methods mentioned above prevent the emissions of volatile organic materials during composite curing and manufacturing, however, they are relatively more expensive than other processing techniques [65].

2.1. *Natural fibers versus synthetic fibers*

Reports have shown that petroleum-derived products will be limited as their future availability is uncertain because of increasing human activities on natural resources which lead to their rapid depletion rate [66]. Hence, the need to source renewable and inexpensive materials that are environmentally friendly and abundantly available has become imperative. Natural fibers mainly originate from either plants or animals, whereas synthetic fibers are man-made materials derived from the synthesis of different chemical compounds. Natural fibers are cheap, lightweight, renewable, biodegradable, and non-toxic, but they have lower properties [67,68]. Synthetic fibers, on the other hand, exhibit advantageous properties such as thermal stability, superior mechanical and electrical characteristics, lower susceptibility to water absorption, and increased durability. Nevertheless, synthetic fibers come with drawbacks as they tend to be costly, pose toxicity risks, are non-renewable, non-biodegradable, and are not considered environmentally friendly [69–71]. Synthetic fibers such as glass fibers can cause lung cancers if inhaled, especially during production operations [72]. Table 2 compares some of the important characteristics of natural and synthetic fibers.

2.2. *Extraction of natural lignocellulosic fibers*

The extraction of natural fibers involves sequential procedures to separate the fibers from various plants and prepare them into useful products. These procedures, which may vary depending on the specific fiber types and plant source, include harvesting of the plants, cleaning, retting, decortication, separation, drying, and finishing. Some fibers, depending on the desired end product, may require additional modification such as fiber spinning, which is mainly common with cotton, flax, and jute fibers. Natural fibers can be

Table 1
Annual world production of natural fiber from different plants [52,53].

Types of fibers	World production (10^3 tons)	Origin
Abaca	70	Stem
Bamboo	10,000	Stem
Flax	815	Fruit
Ramie	100	Stem
Coir	100	Stem
Broom	abundant	stem
Banana	200	Fruit
Elephant grass	abundant	Stem
Cotton lint	18,500	Stem
Hemp	215	Stem
Kenaf	770	Stem
Pineapple	abundant	Leaf
Linseed	abundant	Fruit
Oil palm fruit	abundant	Fruit
Jute	2500	Stem
Nettles	abundant	Stem
Caroa	–	Leaf
Rice husk	abundant	Fruit/grain
Rice straw	abundant	Stem
Sisal	380	Leaf
Sugarcane bagasse	75,000	Stem
wood	1,750,000	Stem

Table 2
Comparison between synthetic and natural fibers [73].

Natural fiber	Synthetic fiber
Lightweight	Relatively heavier
Low cost	Very expensive
Renewable	Non-renewable
Limited mechanical properties	High mechanical properties
Recyclable	Non-recyclable
Low energy consumption during manufacturing	High energy consumption during manufacturing
CO_2 neutral	Generate CO_2 and other harmful substances
Good insulation properties	Poor insulation properties
Low health risk	High health risk
Biodegradable	Non-biodegradable
Good dielectric properties	Poor dielectric properties
Low thermal properties	Good thermal properties
Non-toxic	Toxic
Low tool wear	High tool wear
Low electrical properties	High electrical properties
Abundantly available	Less available

extracted from the stems, bark, leaves, fruits, and roots, which serve as the basis for their sub-classifications.

Generally, mechanical and retting processes are the two methods that are often used for natural fiber extraction, as reported in the literature [30,74,75]. For the mechanical extraction process, the fibers are separated from the plants using either a manually or mechanically assisted machine, as shown in Fig. 1. The part of the plant to be separated is inserted into the machine, which consists of two grinding gears that are driven by either human or machine power to obtain the fibers. Retting involves submerging the plants completely into a suitable liquid solution for several days to enable the action of moisture and bacteria to dissolve the cellular tissues and gummy substances surrounding the plants and facilitate easy separation of the fibers from their plants. Retting can be accomplished through different methods, including water retting, dew retting, or microbial retting. The common goal is to promote the natural breakdown or decomposition of the non-fibrous binding substances that hold the fibers together.

2.3. Classification of natural fibers

Natural fibers are generally obtained from different types of renewable resources and are classified based on their origin, i.e., animals, plants, and minerals. Plant fibers, which are the most commonly used natural reinforcing materials in polymer-based composites, are mainly composed of cellulose, hemicelluloses, lignin, pectin, and traces of other compounds [17,73,77]. These

Fig. 1. Natural fiber extraction processes: (a) mechanical method (b) manual method (c) retting method [75,76].

fibers can be extracted from different parts of the plant, which serves as their basis of classifications: bast fibers (hemp, kenaf), leaf fiber (sisal, pineapple), fruit fiber (coir), seed fiber (cotton), stalk fiber (rice husk), and reed/grass fiber (canary). Over the years, researchers have intensified their efforts in exploring more vegetable plants for the possibility of extracting their fibers for composite development with improved properties. These efforts have led to the discovery of some new plants with attractive fiber qualities. One of these newly reported natural plants is sea purslane which has enhanced mechanical and thermal properties [78]. Fig. 2 shows the general classification of natural fibers.

2.4. Natural fiber-based biocomposites

Concerted efforts have been made to produce natural fibers from agro-based materials for composite development [80]. Natural fiber-reinforced polymer matrix composites, sometimes referred to as 'biocomposites' can either be considered as fully or partially degradable materials, depending on the choice of polymeric resin used, as summarized in Fig. 3. A large percentage of most countries' agricultural processes have been utilized to produce useful materials for industrial development. In recent years, many countries have ventured into trading natural lignocellulosic fibers to enhance the living standard of the people by using natural materials in manufacturing NFRPCs for both economic development and industrial transformation [81–84]. The newly developed idea of employing lignocellulosic fibers as reinforcement materials in composite production has been a focal point in the literature due to their great potential for replacing the existing synthetic fiber-reinforced composites that are not only very expensive but also pose many environmental challenges [13,85–88]. Some of the attractive features of biocomposite materials are lightweight, biodegradable, cheap, and environmentally friendly compared to traditional composites made from synthetic materials [88].

2.5. Manufacturing processes of NFRPC materials

Several manufacturing techniques have been used to produce composites with lignocellulosic fibers as reinforcement materials. The selection of a particular processing method for any type of composite relies on the materials used for producing the composite, the production volume, the desired properties of the final composite product, and the intended application area [89,90]. Diverse techniques were developed to address specific challenges encountered during composite processing, particularly delicate fiber-based composites such as those found in lignocellulosic fiber materials. Research has shown that all traditional composite manufacturing techniques can be employed to fabricate lignocellulosic fiber-reinforced polymer matrix composites [90]. However, the advantages and limitations of each of these manufacturing techniques must be considered to ensure a suitable choice of processing method. The manufacturing of composite materials typically involves some forms of shaping, and molding to properly blend the fiber and resin. The

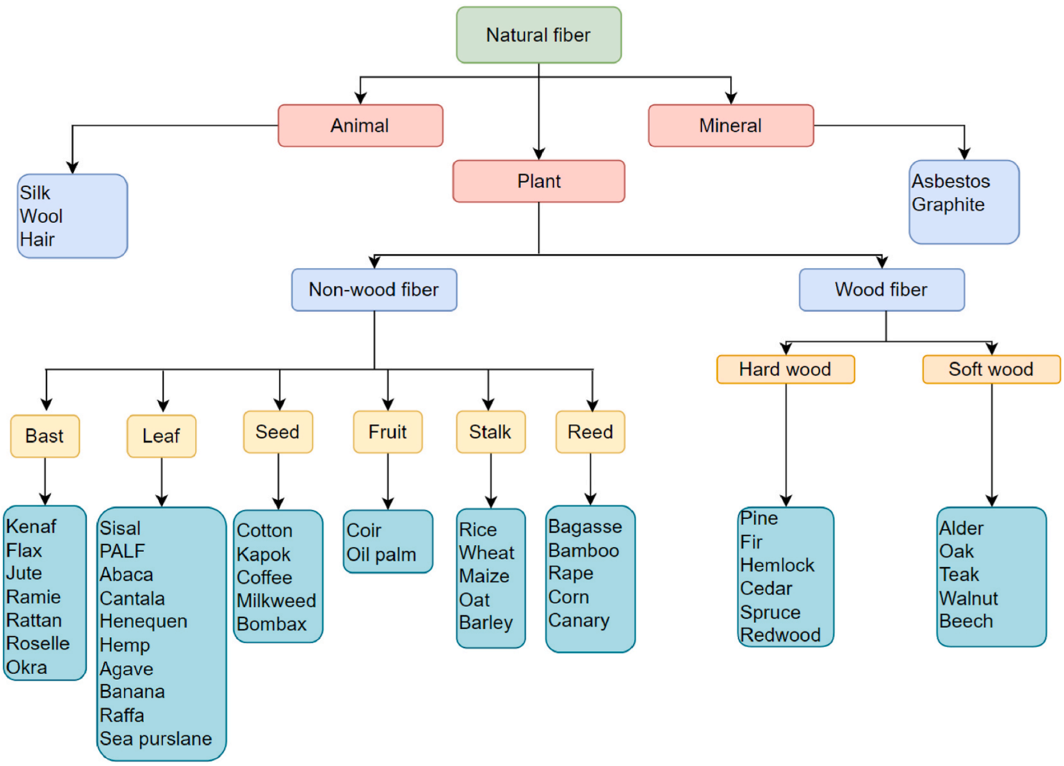

Fig. 2. General classification of fibers [13,78,79].

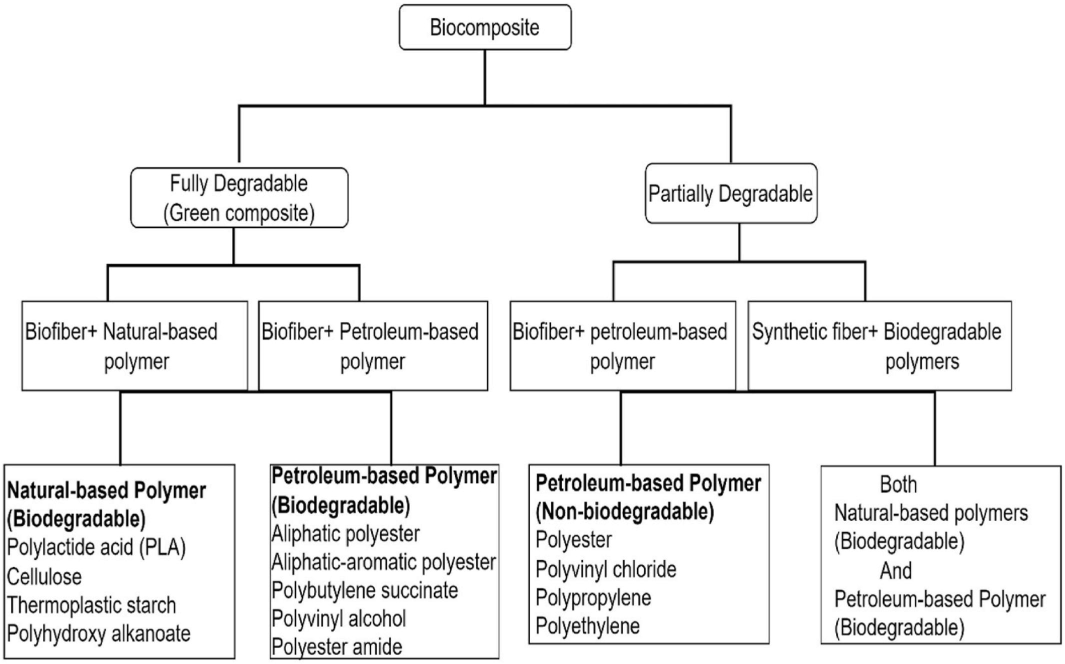

Fig. 3. Classification of the biocomposites.

creation of a mold tool is crucial in the composite development process, to ensure the necessary uniformity of fiber and resin before the curing stage [91]. This step is fundamental to achieving the desired structural integrity and performance characteristics of the final composite material. A comprehensive understanding of the manufacturing methods, properties, and characteristics of natural fibers and their composites will widen their acceptability and applications in critical sectors such as automobile, aerospace, and electronics.

Some of the commonly used composite manufacturing techniques for natural fiber-based composite, along with their associated benefits and limitations are summarized, as presented in Fig. 4.

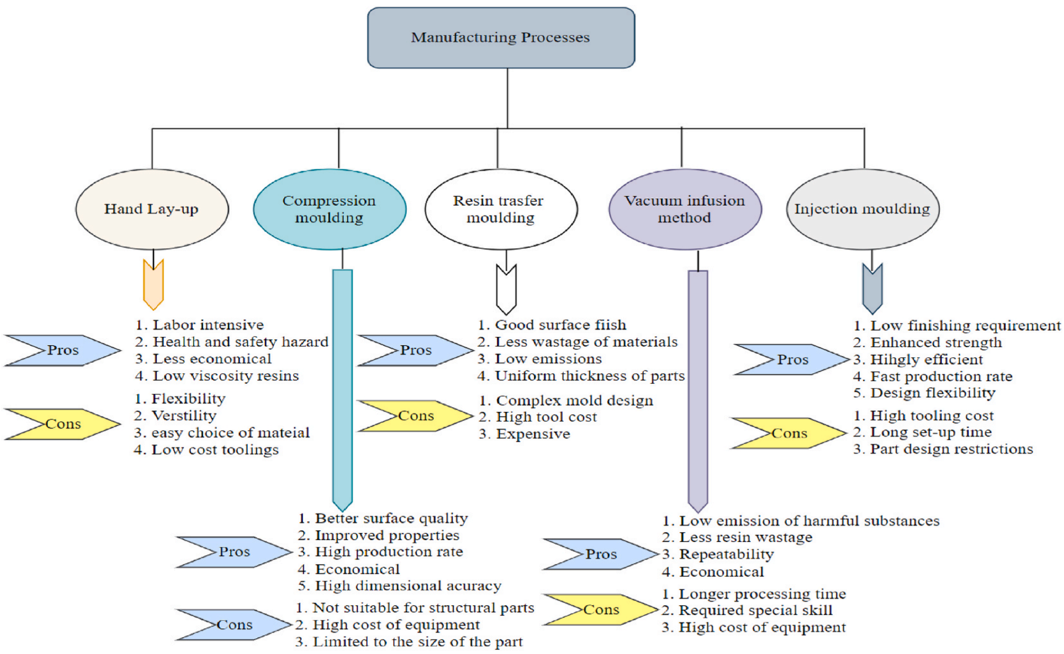

Fig. 4. Common manufacturing processes for natural fiber-based composites.

3. Properties of lignocellulosic fiber and its composites

Natural fibers obtained from plant sources exhibit considerable variation in properties, which makes their selection as reinforcing materials in composite development very difficult because they affect the quality of the resulting composites. The properties of natural fibers depend largely on different factors including the chemical compositions of the fibers, fiber types, methods of fiber extraction, fiber maturity, and growing conditions [92,93].

3.1. Physical properties

Table 3 shows the physical properties of some specific plant fibers. The average density of plant-based natural fibers ranges from 0.5 to 1.7 g/cm^3. The physical attributes of natural fibers are crucial factors in determining their application in various sectors such as the aerospace and automobile industries [94]. The lower densities of natural fibers are advantageous in the production of lightweight materials, which are essential in the manufacturing of automobile and aircraft parts to improve fuel efficiency. The main drawbacks of natural fibers are their shorter length and high water absorption characteristics, which significantly affect the mechanical properties and long-term durability of the fiber and its composites [11,95,96]. Most natural lignocellulosic fibers such as coir, abaca, kenaf are often classified as short fibers, as can be observed in Table 3.

3.2. Chemical properties

The main chemical constituents of lignocellulosic fibers are cellulose, hemicellulose, and lignin, with other traces of constituents such as pectin, wax, moisture, and ash, as shown in Table 4. Cellulose is a straight-chain polymer of carbohydrates that consists of several microfibrils bound together by both lignin and hemicellulose, which makes them flexible with a mechanical load-bearing function [102]. It has a crystalline structure present in the primary cell wall of a green plant. It contains glucose ($C_6H_{11}O_5$) repeating units linked together by beta 1,4-D-glycosidic bonds at C_1 and C_4 positions with a very high degree of polymerization ranging from several hundred to over ten thousand [103]. The choice of any natural fiber for composite development depends on the chemical characteristics of the fibers, such as the cellulose content, moisture content, microfibril angle, and several other constituents that are considered less important but have some negative influences on the properties of the produced composite materials [99,102]. The low moisture resistance behavior of lignocellulosic fibers is due to their hydrophilic nature, which makes them less compatible with hydrophobic polymers during composite processing [104].

3.3. Mechanical properties

Natural fibers have gained significant attention in several sectors owing to their exceptional characteristics, including environmental and economic sustainability as well as acceptable strength-to-weight ratio. Understanding the mechanical behavior of natural lignocellulosic fibers is crucial for their successful utilization in various applications ranging from textiles to composite productions. These fibers exhibit a wide range of mechanical properties which largely depend on the chemical compositions of the fiber, types of the fiber, age, and the history of the fiber plant. The presence of non-cellulosic components in lignocellulosic fibers, such as hemicellulose, lignin, ashes, waxes, and pectin plays a major role in altering the mechanical behavior of the fibers. It affects the interfacial bonding strength between the fiber and the matrix during composite processing. Hence, reducing the presence of these components in the fibers, mostly achieved through fiber treatment, directly enhances the reinforcing potential, leading to improved mechanical properties and thermal stability of the fiber [53,111]. The mechanical properties of certain lignocellulosic fibers, extensively documented in the literature, encompass parameters such as tensile strength, Young's modulus, and elongation at break (refer to Table 5).

Table 3
Physical properties of some natural fibers [97–101].

Fiber	Density (g/cm^3)	Diameter (μm)	Length (mm)
Cotton	1.2–1.6	14.5	42
Jute	1.3–1.46	18.4	2.55
Flax	1.4–1.5	20	31.75
Hemp	1.48	19.9	11.2
Ramie	1.5	31.55	160
Sisal	1.2–1.5	21	2.5
Coir	1.2	17.5	1.25
Softwood kraft	1.5	–	–
Abaca	1.5	18.2	4.9
Kenaf	1.52–1.63	19.8	2.35
Henequen	1.2–1.6	–	–
Pineapple	1.52	50	–
Banana	1.3	–	2.9
Bamboo	0.6–1.1	25	2

Table 4
Chemical composition of some natural fibers [52,100,105–110].

Fiber type	Cellulose (%)	Lignin (%)	Moisture content (%)	Hemicellulose (%)	Pectin (%)	Ash (%)	Waxes (%)
Fiber flax	71	2.2	7	18.6–20.6	2.3	–	1.7
Seed flax	43–47	21–23	–	24–26	–	5	–
Jute	45–71.5	12–26	12	13.6–21	0.2	0.5–2	0.5
Hemp	57–77	3.7–13	8	14–22.4	0.9	0.8	0.8
Ramie	68–91	0.6–0.7	12–17	5–16.7	1.9	–	0.3
Kenaf	37–49	15–21	6–12	18–24	–	2–4	–
Abaca	56–63	7–9	–	15–17	–	3	–
Sisal	47–78	7–11	11	10–24	10	0.6–1	2
Henequen	77.6	13.1	–	4–8	–	–	0.5
Pineapple	70–82	5–12	11.8		1–2	1.1	–
Coir	37	42	10	20	2–4	–	10.6
Bamboo	26–65	5–31	9–10	30	–	–	–
Banana	62–64	5–7.5	10–11	19	4	–	–

Table 5
Mechanical properties of natural fibers [45,68,106,112,113].

Fiber	Elongation (%)	Tensile strength (MPa)	Young's modulus (GPa)
Cotton	3.0–10.0	287–597	5.5–12.6
Jute	1.5–1.8	393–800	10–30
Flax	1.2–3.2	345–1500	27.6–80
Hemp	1.6	550–900	70
Ramie	2.0–3.8	220–938	44–128
Sisal	2.0–14	400–700	9.0–38.0
Coir	15.0–30.0	175–220	4.0–6.0
Softwood kraft	–	1000	40.0
PALF	1.6	413–1627	34.5–82.51
Bagasse	1.1	20–290	19.7–27.1
Henequen	3–4.7	430–580	–
Banana	53	355	33.8
Kenaf (bast)	2.7–6.9	295	–
Okra	4–8	184–557.3	8.9–11.8
Abaca	2.9	430–813	31.1–33.6
Kapok	2–4	45–64	1.73–2.55
Elephant grass	2.5	185	7.4

3.4. *Thermal properties*

The thermal characteristics of lignocellulosic fibers are of great importance because they determine how the fibers respond to heat, particularly during the composite manufacturing process. Some of the thermal characteristics of natural fibers include thermal conductivity, thermal stability, flame resistance, and ignition temperature. The specific thermal properties of natural fibers vary widely depending on the fiber type, extraction or processing methods, fiber treatment, and growing conditions of the fiber plants. Generally, natural lignocellulosic fibers possess lower thermal properties, which may be advantageous in some applications such as textile industries, but limit their usage in other areas, such as composite production. Some of the effective testing methods that have been utilized to assess the thermal behavior of these fibers and their composites include thermogravimetric analysis (TGA), derivative thermogravimetry (DTG), and differential scanning calorimetry (DSC). The thermal disintegration of natural fibers is usually caused by the breakdown of their chemical components due to heat or ultraviolet energy [114,115]. Natural fibers have a limited processing temperature range, typically between 180 and 200 °C, which primarily affects the mass production and application of natural fiber-reinforced polymer matrix composites [116].

3.5. *Acoustic properties*

Rapid growth has been observed in the use of natural fiber-based composite materials due to their improved acoustic properties for various applications, particularly in the building and automotive sectors. Natural fiber-based composites have good acoustic properties because of their inherent damping properties, porous structures, and lower densities. This enables the absorption of sound energy within the pores of the cell walls, thereby improving the sound absorption coefficient (SAC) and reducing noise and vibration levels in automotive components. The sound absorption coefficient is typically calculated by measuring the fraction of incident sound absorbed by materials. The range of SAC falls between 0 and 1, where a value of 1 signifies maximum absorption, and 0 indicates no absorption. Many factors affect the acoustic properties of natural fiber-based composites, including the type and size of the fiber, types and volume of the matrix material, fiber thickness, method of composite manufacturing, and aspect ratio of the fibers. Natural fibers with high aspect ratios, such as jute and hemp, have been reported to possess better sound absorption coefficients than other fibers with low aspect ratios [117]. Lee and Joo [118] investigated the effect of fiber diameter on the acoustic properties of natural fiber-reinforced composites using polyester with different fiber diameters and found that the sound absorption coefficient of the developed composite material increases as the fiber diameter decreases. A similar study conducted by Koizumi et al. [119] showed that reducing the diameter of natural fiber enhances the sound absorption coefficient of NFRPCs. Reports have also shown that the types of fibers have a significant influence on the sound absorption coefficient of both natural and synthetic fibers [120].

Abdullah et al. [121] studied the effect of fiber types on the sound absorption coefficient of natural fiber-based composites with a fiber thickness of 1 cm. The study was performed using banana and sugarcane bagasse fibers with polyester resin as the matrix. The hybridization effects of the two natural fiber-reinforced composites on the SAC were also evaluated. The results showed that the sound absorption coefficients of both the sugarcane fiber-reinforced composites and banana fiber-reinforced composites were 0.6338 and 0.6635, respectively, while the hybridized composite with the two fibers combined gave 0.733 at a frequency of 2325 Hz. The study also varied the fiber volumes and concluded that the sound absorption of both fibers increases with increasing fiber volume fraction.

3.6. Tribological properties

The tribological characteristics of natural fibers are a crucial consideration factor for choosing the best reinforcing materials for the production of both structural and non-structural composites. The specific tribological properties of natural fibers vary significantly among different types of fibers (e.g., hemp, pineapple, cotton, banana, jute, flax, etc.) and can be further influenced by fiber processing and treatment methods [122,123]. Tribology is the study of interacting surfaces that move relative to one another as well as their effects, which include wear, friction, and lubrication. This property plays an important role in various mechanical and structural systems or components, as it helps engineers and researchers understand and control the behavior of different surfaces in contact with each other. The tribological behavior of natural fibers is of great interest among researchers and manufacturers, especially in applications involving composite reinforcement, as the fiber and matrix material form a single interface that can easily wear off or tear during its service life when subjected to either mechanical loading or chemical attack [124]. Natural fibers and their composites have been widely used in designing several automobile parts that are directly in contact with other surfaces. Ali et al. [125] developed a coconut fiber-reinforced polymer composite with fiber content varying between 2 and 8 wt%, as an alternative brake pad material and compared the results with a similar volume fraction of a standard brake pad material made of Kevlar. The reports showed that the newly developed green composites can be sufficiently used to develop a brake pad material with acceptable properties. This study further indicates that the thermal stability of the composite material can be enhanced by increasing the coconut fiber weight fraction in the composite. Yashwhanth et al. [126] conducted a comprehensive survey on the potential applications of natural fiber-based

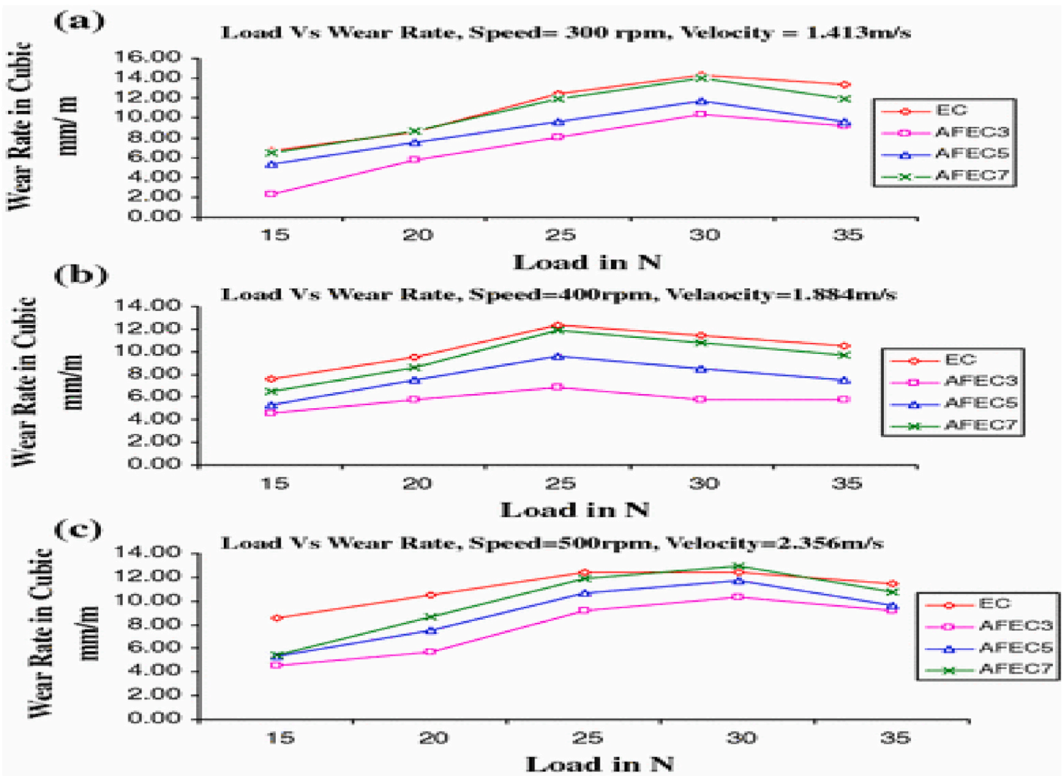

Fig. 5. Effect of fiber length on the wear behavior of agave fiber reinforced epoxy composite under different wear testing conditions: (a) 300 rpm, 1.413 m/s velocity; (b) 400 rpm, 1.884 m/s velocity; and (c) 500 rpm, 2.356 m/s velocity [132].

composites as an alternative material to asbestos in vehicle brake pad designs. The study concluded that although natural fiber-based composites have great potential in the design of brake pads, their properties, such as thermal stability and wear rate, need to be improved through material selection and fiber surface treatment for optimal performance. Interfacial adhesion between natural fibers and polymer resin appears to be the most dominant factor affecting both the tribological and mechanical properties of NFRPCs [127]. Therefore, improving the interfacial bonding between the matrix material and the fiber will directly enhance the tribological characteristics of the composite material. The coefficients of friction, wear resistance, lubrication, and moisture absorption behavior of natural fibers and their composites have been extensively investigated and documented in the literature by numerous researchers [128,129]. These studies have provided a better understanding of the relationships between these material properties and the performance characteristics of natural fibers and their composites in various conditions. The comprehensive exploration of these factors provides valuable insights for researchers, engineers, and manufacturers involved in the field of natural fiber-based composite designs. Most natural fibers are hydrophilic and can easily absorb moisture from the surrounding environment or through contact with other materials. Reports have shown both positive and negative effects of moisture absorption on the tribological properties of natural fibers. For instance, moisture absorption can act as a lubricant to natural fibers, thereby enhancing wear resistance and reducing friction. On the contrary, when natural fiber absorbs excess moisture from the surroundings, it swells up, thereby causing the surrounding matrix component to undergo some microcracks, which negatively weaken the stress transfer efficiency between the fiber and the matrix, thereby reducing the overall strength of the composite material [130]. The tribological properties of natural fibers depend on several factors, including the fiber type, processing or extraction method, surface finish, fiber treatment, environmental conditions, length, and diameter of the fiber [131]. Studies have shown that longer and thinner fibers may have different friction and wear characteristics than shorter and thicker fibers. Mylsamy and Rajendran [132], investigated the effect of three different fiber lengths (3 mm, 5 mm, and 7 mm) on the wear behavior of chopped agave fiber-reinforced epoxy composites. The results of their study showed that the wear rates of the composite decrease with a decrease in the fiber length, as 7 mm fiber length showed the highest wear rate (refer to Fig. 5). This report indicated that the critical fiber length of the composite may be within the range of 3 mm, leading to a more effective reinforcement potential of the fibers with improved wear resistance Mylsamy et al. [123] investigated the impact of surface modification on Coccinia indica (CI) and its ensuing effects on the tribological properties of Coccinia indica-reinforced epoxy matrix composites. This modification was carried out using both sodium hydroxide and silane treatments at concentrations of 5 wt% and 3 wt%, respectively. The results of the study showed that both treatments improved the wear resistance of the composites with 15 % and 39 % weight loss for NaOH and silane-treated composites, respectively.

4. Application of NFRPCs in the automotive sector

The use of lignocellulosic fiber-reinforced composites in automotive industries has been increasing in recent years because of the great demand for synthesized materials from renewable sources with excellent structural and non-structural properties for automobile parts production [60,133]. The viability of NFRPC materials in the automotive industry has experienced significant growth within the research community. This surge in interest is attributed to their potential as an alternative to synthetic fiber-based composites, with a particular emphasis on substituting glass fiber-reinforced composites [134–136]. Plant-based natural fibers are classified into two primary types, determined by their applications and corresponding global market demands: wood fibers and non-wood fibers [137,138]. Wood fibers are commonly used for construction purposes and are very popular in North America. Non-wood natural fibers thrive mostly in the automotive industry in Europe using both thermoplastic and thermoset resins as matrix materials for their composite production. Non-wood fibers have been successfully used as reinforcement materials in polymer matrices for different automobile parts manufacturing, including door trims, seat backs, dashboards, and headliners [134,135,139,140]. These renewable or partially renewable composite materials offer lower energy consumption during production, reductions in weight and fuel consumption, improved recyclability, high specific strength, and low cost. These characteristics align with the sustainability goals of the automotive industry [141]. These goals encompass the development of materials that are not only durable and renewable but also exhibit enhanced properties, including mechanical, acoustic, and thermal stability. This pursuit is undertaken without compromising the important factors of lightweight construction and energy efficiency, which are frequently demanded in the sector [142]. Reports have indicated that the existing automotive materials are unable to meet the current demand for material performance. Consequently, recent advancements in materials processing technology have revealed that composites synthesized with natural lignocellulosic fibers as reinforcement could serve as an ideal solution to address the evolving requirements for advanced materials in the automotive sector [54,143–145]. Over the last few decades, there has been a consistent interest in the field of renewable materials among researchers and academia. This increasing research interest is usually aimed at improving the performance of NFRPCs to make them a suitable alternative to conventional engineering materials in the automotive sector. However, despite all these research efforts, the use of NFRPC has not yet been fully translated into a large-scale application in the automotive industry due to some of its limitations [146,147].

One of the significant limitations of NFRPCs in the design of automobile parts is their inferior mechanical characteristics. This drawback poses a considerable challenge, as it undermines their structural integrity and long-term application when compared with traditional materials like metals or synthetic fiber-reinforced composites [148]. To address this issue, researchers are actively engaged in developing hybrid composites that integrate both natural and synthetic fibers. Additionally, they are optimizing composite processing methods to enhance the mechanical performance of these materials. This innovative approach seeks to bridge the gap in mechanical properties and pave the way for the broader and more effective use of NFRPCs in automotive applications. Thus, the use of NFRPCs as eco-friendly automotive materials is a developing field of inquiry, and the continuous attempt to enhance their functionality and processing techniques will probably broaden the use of these materials in the sector, particularly for the production of structural automobile parts such as external body panels and structural body reinforcements.

4.1. Automobile parts made from lignocellulosic-based NFRPCs

Composites reinforced with natural lignocellulosic fibers are commonly used for non-structural purposes, particularly the interior parts of automobiles, because of their excellent thermal insulation characteristics. These include car door interior panels, trunk liners, seatbacks, cabin liners, parcel shelves, dashboards, seat cushions, door trim panels, and more [149–152]. Nonetheless, these composites have minimal usage in the exterior design of automobiles owing to their limited load-bearing capacity. However, some particular components such as transmission covers and bumper beam covers have been reported to be produced using natural fibers reinforced with polyester [153,154]. Fig. 6 illustrates the specific automobile parts that can be manufactured using NFRPCs.

4.2. Prospect for lignocellulosic-based NFRPCs in the automotive sector

Previously, synthetic fibers were extensively used as the sole reinforcing materials in composite development owing to their enhanced mechanical properties and lightweightness compared to metals and ceramics. Nonetheless, various research studies have indicated that despite their aforementioned advantages, artificial fibers pose certain ecological concerns and are comparatively more costly than fibers derived from nature. In addition, the continued expansion in the use and depletion of finite traditional energy sources has compelled researchers to look for alternatives that are not only ecologically responsible but also replenishable for the development of new composite materials. Furthermore, the automotive industry's sustainability objectives have led researchers in this domain to focus on developing more appropriate materials that are eco-friendly and financially viable. The features of natural fibers make them a crucial component in the automobile sector, as there is a consistent effort to reduce vehicle weight to improve fuel efficiency, enhance vehicle functionality, and adhere to emission regulations [135,156].

Plant-based fiber-reinforced composites have been employed in the production of various automobile parts as far back as the 1940s. During this period, Henry Ford pioneered the use of fiber-based composites, utilizing hemp fiber as the reinforcement material. This marked a significant milestone as it led to the creation of the first components made of plant-based natural fiber composites in a car [17,19,157]. This historic development not only showcased the feasibility of plant-based composites in automotive applications but also laid the foundation for ongoing research and advancements in the field of sustainable and eco-friendly materials for the automotive industry. This led to the production of the East German Trabant body in the early 1950s, Daimler–Benz in 1994, and Mercedes in 1996, using natural fiber-reinforced polymer matrix composites [158]. Awareness of NFRPCs for automotive applications has been substantial, driven by the growing demand for materials with high-specific properties, lightweight characteristics, and environmentally friendly attributes in the industry. This reflects a keen interest in exploring alternative materials that not only meet performance requirements but also align with the industry's increasing emphasis on sustainability and renewable resources [159]. The economic sustainability of NFRPCs in the automotive sector can be attributed to many other advantages of natural fibers over synthetic fibers, which are critical in the manufacturing of automobile components. These include high design flexibility, non-toxicity, ease of processing, reduced greenhouse emissions, low energy consumption, carbon dioxide (CO_2) neutrality, and better specific properties [146,160,161]. The appealing qualities of natural fibers and their composites, along with their promising potential in critical sectors such as

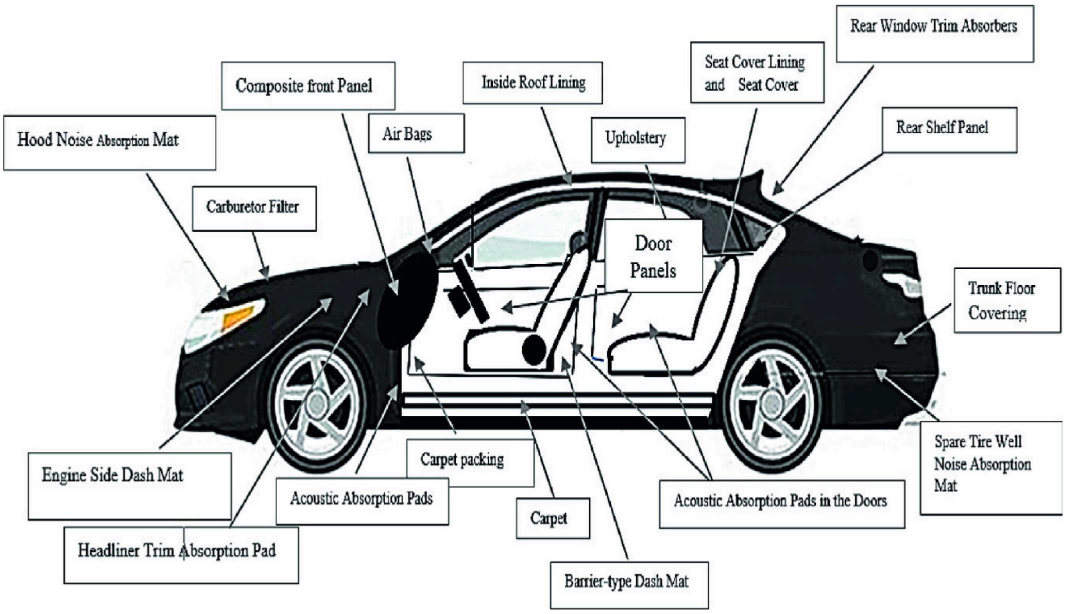

Fig. 6. Specific application areas of NFRPCs in automobile parts [155].

the sports and automotive industries, have progressively redirected research focus toward the development of sustainable composite materials. In this context, lignocellulosic fibers are gaining prominence as key reinforcing components. Studies have shown that these composite materials can significantly reduce the cost of automobile production by 20 % and weight reduction by 30 %, which will directly reduce fuel consumption significantly [146,162]. As research and development in this field continue, it is expected to see more widespread use of these composite materials in other critical sectors in the future.

4.3. NFRPCs as sustainable auto materials: Research needs

The use of NFRPCs as a sustainable and potential alternative to traditional automotive materials such as steel and aluminum has attracted serious research attention. NFRPCs are made using natural fibers as reinforcement, such as jute, bamboo, kenaf, flax, abaca, sisal, and hemp, which are embedded in a polymer matrix. Despite the tremendous growing research on NFRPCs for sustainable automotive materials, there are still many areas that require further investigation to either minimize the efforts required to manufacture the composites or maximize the desired benefits. In the past few years, European automotive industries have intensified efforts in developing natural-fiber-based biocomposites using conventional thermoplastics and thermosets as matrix materials for the manufacturing of different automobile components such as seatbacks, package trays, door panels, headliners, dashboards, and other interior parts [41,163]. This was further accelerated in 2006 immediately after the establishment of the European Union legislation to regulate excesses from these critical industries [12]. According to the legislation, manufacturers of vehicles must use materials in the design of the parts that can be reused or recycled to a minimum of 85 % by mass after the end-of-life of the vehicles [164]. The legislation also sets rules to ensure that reused components do not pose any health risks to the environment. A similar approach was also adopted by the Japanese government to produce vehicles such that 88 % of the components could be recycled after their useful life by 2005 and up to 92 % and 95 % by 2010 and 2015, respectively [165]. To achieve this industrial revolution in this sector, researchers have ventured into developing materials that can meet all these demands and other requirements. Although NFRPCs have a few issues, studies have shown that they are still the best candidate materials. This is due to their renewable nature, lightweight, recyclability, affordable, and ability to absorb more energy during impact [166]. NFRPCs exhibit excellent acoustic properties and high specific strength, rendering them highly appealing for applications that demand lightweight materials with superior sound absorption characteristics and high strength. These qualities make NFRPCs particularly well-suited for a range of industries, including automotive, aerospace, and applications requiring bulletproof and ballistic features [167,168]. Weight reduction in the automotive sector is an important factor every automaker considers in designing and manufacturing vehicles because it reduces fuel consumption, thereby minimizing the emission of greenhouse gasses. In addition, the automotive industry has determined to reduce the cost of vehicle production by using more economical and inexpensive materials in the manufacturing of the major components [137,169]. Fig. 7(a) illustrates that, in the year 2016, the automotive industry emerged as the second-largest sector, following construction, to extensively utilize NFRPCs. Meanwhile, Fig. 7(b) depicts the research progress in NFRPCs from 1990 to 2021. It can be observed from Fig. 7 (b) that the number of studies on NFRPCs has risen exponentially in the last three decades because of their promising potential in many sectors, especially in the transportation industries.

Owing to their many advantages over the more often used glass and carbon fiber-based composites, NFRPCs have seen a significant surge in research over the past three decades [171]. As shown in Fig. 8, these benefits can be divided into three categories: economic, property, and environmental, which are the major factors that influence the popularity of NFRPCs in the automotive industry.

4.4. Limitations of NFRPCs in the automotive sector

Despite the appealing characteristics of lignocellulosic NFRPCs, some significant challenges must be addressed, including compatibility issues, low durability, limited properties, poor moisture and fire resistance, and the need to develop cost-effective manufacturing techniques to produce large-scale and complex NFRPC components. Most natural fibers are hydrophilic, which makes them less compatible with hydrophobic polymer resins [29,172–174]. The lack of compatibility between the natural fibers and

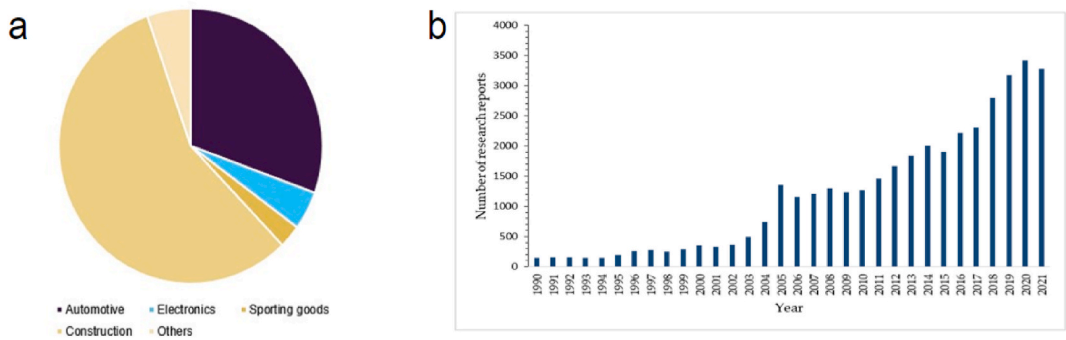

Fig. 7. Progress in NFRPCs: (a) global utilization of natural fiber-based composites in different applications in 2016 (b) the number of research publications on NFRPCs from 1990 to 2021 [170].

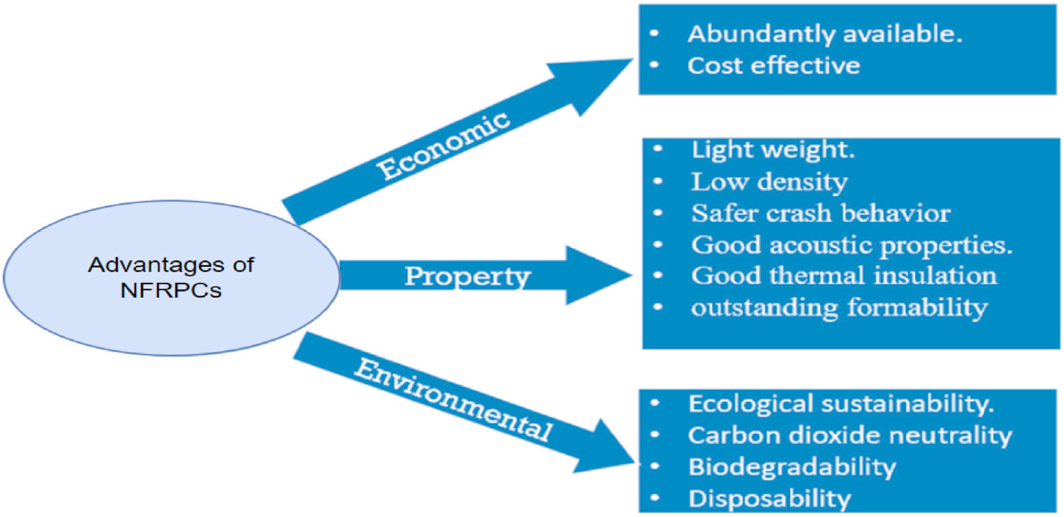

Fig. 8. Factors influencing the steady rise of research in NFRPCs for automotive applications.

the resin materials reduces the interfacial adhesion of the two components, thereby reducing the general properties and durability of the developed composite materials, as well as their dimensional stability [175]. Poor thermal stability, low fire resistance, and limited processing temperature negatively affect the long-term durability of NFRPCs, thereby restricting their application to specific parts in automobile component production [176].

To address these challenges, researchers have made efforts to improve the compatibility and wettability between fibers and matrix materials at the fiber-matrix interface. This is achieved by adopting various physical and chemical treatments for fibers and, in some cases, treating the resins before the composite processing stage. Choice of fibers and resin materials, fiber orientations, fiber volume fraction, and fiber hybridization are some of the other approaches that have been employed by these researchers to enhance the physio-mechanical properties of NFRPCs [177–179]. The reports from all these studies showed tremendous achievements in the resulting properties, particularly the mechanical properties of the produced composites. Furthermore, investing in training, research, and other educational programs for engineers, manufacturers, and researchers will ensure a better understanding of the unique properties and processing requirements of natural fiber-based composites, for optimal properties and materials control. This investment in R&D could result in the discovery of cutting-edge techniques and new technologies that will further improve the performance of natural fiber composites and broaden their acceptability in the automobile sector.

5. Future direction

The growing environmental awareness from the use of synthetic-based composite products in the automotive sector, as well as continued governmental and environmental bodies' involvement in enforcing the adoption of more sustainable materials in vehicle production, will help to achieve more innovations and increase development in the automotive industry. This is expected to provide a lasting solution to the challenges associated with the current materials that are being used in this sector. The use of NFRPCs in automobile parts production presents a promising opportunity for the automotive industry. In addition to the automotive sector, NFRPCs have been used for several critical applications. Fig. 9 highlights past, present, and future uses of NFRPCs in different sectors of the economy. It can be projected that the present problems of NFRPCs that limit their popularity toward advanced applications will be overcome through extensive research and development in this important field of study.

First, the development and use of NFRPCs will open up new market opportunities for automobile manufacturers, such as electric vehicle manufacturing and the external parts of automobile production, including bumpers, hat racks, bumper beams, roof covers, door protective covers, headlight covers, and general auto bodies. Achieving this expansion necessitates a concerted effort to explore and identify additional lignocellulosic fibers with superior properties as potential reinforcement materials in composite development when compared to existing fibers.

Secondly, developing new manufacturing techniques that are more energy efficient and cost-effective, as NFRPCs require specific and robust processing techniques to achieve optimum performance. For example, the use of 3D printing and other additive manufacturing techniques could allow for the production of complex shapes and structures with NFRPCs, making their integration into automotive designs easier. In addition, optimizing these processing techniques and enhancing the composite performance is essential to meet the growing demand for eco-friendly and energy-efficient vehicles. Further research is needed to develop advanced testing methods and techniques to accurately and reliably evaluate the durability and long-term performance of the resulting composites. This requires comprehensive material characterization to determine whether the developed composites meet the properties requirements of the automotive sector.

Finally, as consumer demand for sustainable and eco-friendly products continues to rise, vehicles incorporating natural fiber

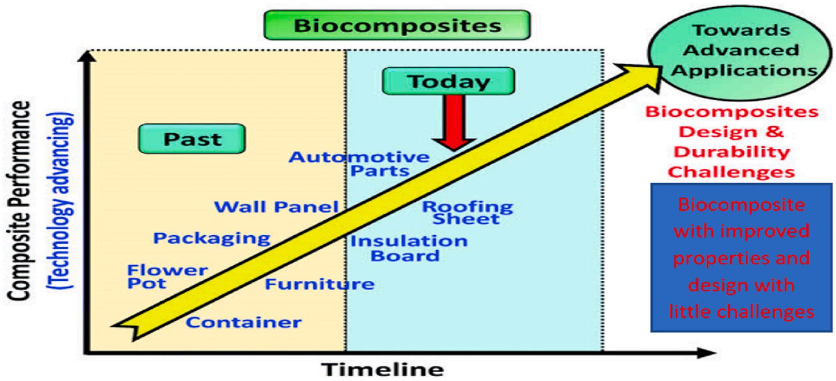

Fig. 9. Future projection of NFRPCs toward advanced application [180].

composites may appeal to environmentally conscious consumers. Therefore, there is a need for more studies on the environmental impact of using these composite materials in the automotive industry concerning their recyclability and end-of-life disposability.

6. Conclusion

The adoption of natural-based materials in the automotive industry as a way of reducing the environmental challenges facing the sector and improving economic sustainability has been gradually increasing over the last few years. This approach to sourcing environmentally friendly and renewable materials as integral parts of automobile bodies has become necessary due to global and various governmental regulations on the safety environment, consumer choices, and, in some cases, cost reduction in vehicle production. The current research and development efforts in NFRPCs with improved properties have revolutionized the automotive industry, considering the significant advantages of NFRPCs and the current global challenges stemming from fossil-based resources in the sector. Therefore, it is expected that increasing investment in the R&D of NFRPCs as sustainable automotive materials can potentially minimize the problem of harmful gas emissions, reduce the cost of automobile production, and minimize the dependency of the sector on scarce and non-renewable petroleum-based resources. This general overview has shown that NFRPCs offer several advantages over traditional materials, such as increased specific strength, eco-friendliness, and cost-effectiveness. However, more research is needed to optimize the use of these materials in the automotive industry, such as improving their mechanical properties, developing appropriate processing techniques, and assessing their long-term durability. Nevertheless, the future direction of lignocellulosic fiber-reinforced polymer matrix composites in the automotive industry is optimistic, and with continued R&D in this field, these materials are expected to play a major role in the production of lightweight and high-performance vehicles with minimal environmental impacts.

Data availability

No data were used for the research described in this article.

CRediT authorship contribution statement

Abdulrahman Adeiza Musa: Writing – original draft, Methodology, Investigation, Data curation. **Azikiwe Peter Onwualu:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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