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REVIEW ARTICLE

Sustainable reclamation of synthetic materials as automotive parts replacement: effects of environmental response on natural fiber vulnerabilities

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Abstract
Sustaining the resilience of the environment against climate change volatilities is fast becoming a herculean task considering the vulnerabilities of the ecosystem and disruption of the global value chain. Environmental crisis emanating from improper containment of synthetic materials is a major impediment facing the world today, and the situation could get worse if urgent measures are not devised to mitigate the quantity of waste synthetic materials that find its ways to the environment. These wastes are released in the form of toxins, posing danger to the environments, causing biodiversity loss and the degradation of already battered-climate. In this paper, the authors apprise existing containment measures of synthetic waste materials taking a preliminary and on-the-spot assessment of their impacts and effectiveness of their application leading to their operation. The prospect of waste glass fiber in automotive part replacement is given utmost interest in this paper, in which, a significant quantity of glass fiber could be used as part of automotive materials to reduce their overbearing environmental carnage. By this approach, the emerging automotive parts may have their strength and durability enhanced against impact and corrosion. Mindful of the non-biodegradable properties of glass fibers, the paper captures how effective these fibers could be used as automotive parts against the traditional materials. This paper also reflects on the response of the natural fiber in terms of their sustainability, as natural forest faces severe extinction occasioned by anthropogenic activities.

Keywords Environments · Glass fiber · Reclamation options · Climate change · Biodiversity

Introduction

Fiber-reinforced materials have gained significant interest in automotive industries and are increasingly used as a potential replacement for metals in area where priority is placed on energy saving and environmental consideration. In many published works and as identified by industrial players, one of the concerns posed by fiber materials is their biodegradability and developing appropriate measures for their reclamation. There are also concerns on variation of environmental legislation in nations of the world, where in most cases, there is no clear-cut legislation guiding synthetic material deployment in many applications. This may also lead to worsening environmental impact in which the waste materials are disposed in landfills. The automotive industry all over the world was sourcing for sustainable materials, in which its overall composition could not poise challenges in term of weight saving and energy consumption; however, as research intensifies, it was concluded that decreasing the payload of vehicle bodies has positive impacts on vehicle performance, and its overall fuel consumption is significantly reduced which is a direct crucial factor in material selection for automotive part replacement alongside rigidity and strength of such materials. Further research works have established a correlation between weight reduction and impressive increase in vehicle mileage. It was further shown that the steering stiffness could also be controlled for longer periods of time if the materials display reasonable lightness

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in its composition. Having considered these attributes alongside the vehicle performance, it was established that in order to obtain improved automotive vehicle parts and to reduce pollution and disposal problems, the main factor that was to be considered in automotive industry is how to enhance the natural fiber properties for optimal efficiency. This may also lead to solving moribund and existing materials and providing comparatively lighter and easier to recycle than the material that was being used at that time. Climate change poses enormous danger in the structure and composition of materials, going by the volume of synthetic materials constituting environmental risks (Soundrapandian et al. 2021). The use of fiber-reinforced composite for varying applications was borne of their peculiarities to save the mankind of environmental calamities (Egbedina et al. 2022). Materials and their applications are the major contributors to environmental waste. These wastes are now becoming unbearable in terms of management, as a result of non-biodegradable plastic materials sourced from fossil fuel. The use of synthetic plastics remains a challenge amid their reclamation effects. Despite criticism against synthetic materials, it is still considered of utmost importance in several modern cities and industries (Estanqueiro et al. 2018). This may not be unconnected with their superior properties that have evolved over time like competitive market, availability, and their resilience. A significant advantage of synthetic materials is their tendency to withstand moisture or humidity due to their hydrophobic properties (George et al. 1998). Several industrial players continue to use synthetic plastic, being the most suitable polymeric characteristics that conform to their specifications. These standpoints, on the part of the players, remain a rallying point where synthetic materials enjoy significant patronage. However, the need to reduce the weight of products amid environmental concerns has made plastic materials so rampant and complex and most importantly, recalcitrant to biodegradation (Rozman et al. 2000). Several containment measures have been deployed in the management of non-biodegradable materials, and most popular of such methods is landfilling and incineration of waste materials (Nguyen et al. 2020). These disposal options, though majorly used in the developing countries, have continued to attract criticism, going by their effects and hazards reportedly noticed in other places, where it had previously been used. Landfilling is largely preferable in third world countries because of its simplistic approach. In places where landfilling is being done, there were concerns on haphazard pre-requirement procedure in many literatures leading to erosion of filled sites and a follow-up crisis. Incineration of fiber-reinforced waste materials has been used as a last resort to reduce huge environmental risk posed by synthetic materials amid growing concerns regarding their ineffective delivery. However, reports have it that unquantifiable toxic pollutants are released into the atmosphere at every application of incineration. The use of mechanical sorting and recycling has attracted interest in most of thermoplastic wastes. However, findings have shown that the physicochemical properties of most plastic materials are always altered and compromised after recycling, and as a result, the benefits of recycled polymers are controversial and often subjected to debate (Bourmaud et al. 2020). Reports have also shown that chemical recycling tends to recover monomers and other valuable components from plastic wastes, which mostly depends on the efficiency of catalysts and the economic reliability of process. Prior to 1950s, metallic materials have dominated the automotive and aviation industries, most importantly, their component parts. The awareness on climate change and the complication encountered in the management of waste metals have given a paradigm shift where research now favors lightweight materials to replace convectional automotive parts. The application of synthetic materials remains a sustainable component part in automotive industries with high records of compatibility to other materials in the production process (Kamble & Behera 2021). It should also be on record that several technological progresses were reported in some of the applications using synthetic fibers, necessitating their involvement in other engineering works (Mechtcherine et al. 2020). In terms of market share, polypropylene and polyester fibers have been on sharp decline in patronage since1970s, following reported cases of failure reported in their use (Pernica et al. 2010). With the adaptation of green materials in production formation, communities involved in the production of fiber composite have reduced the environmental load bearing by evolving plant-based raw materials together with synthetic material part formations (Adekomaya & Majozi 2023). This unique method has resulted in cars with excellent mechanical properties such as low density, biodegradability, and renewability against vehicles produced with synthetic materials (Schneider et al. 2019). With barrage of long delay experienced in the degradation of synthetic materials, natural fiber composites (NFCs) became a point of attraction which was used in aircraft seat to experiment their comparative lightness against synthetic fiber. This followed several other attempts in construction and larger automotive sectors where further findings confer superior advantage on natural fiber ahead synthetic materials. Natural fibers attracted global interest, following the European Commission directive, on "End of Life Vehicles" program, which made it mandatory for automotive manufacturers to use 95% recyclable materials by 2015. This strategic approach, regarding the use of NFCs, has promoted green economy in developed countries, reducing the quantity of fossil fuel consumption in articulated vehicles. To further shore-up support for NFCs and to strengthen the demand and raise the awareness on the technical and economic attributes of natural fibers, the United Nation General Assembly declared 2009 as the International

Year of Natural Fibers. Natural fiber–reinforced composites (NFRCs) are the brainchild of multidisciplinary research involving characterization of raw materials and designing and fabrication of sustainable materials, requiring thorough performance evaluation, to ascertain their suitability for the intended application (Silva et al. 2020). To complement the use of synthetic materials in automotive industries, natural fibers appear to be the only materials which derive its strength from the inclusion of synthetic materials as reinforcing fiber. While natural fiber is reportedly offering significant weight reduction, leading to energy saving in automotive part formation, this may not be said for other materials. The automobile ecosystem has continued to patronize synthetic material and natural fiber in considerable quantity. Figure 1 shows the projection of natural fiber production globally taking into consideration their level of demand in respective region of cultivation. In composite formation, and depending upon the application upon which a material is to be used, it is established that natural fibers and glass fiber could be used interchangeably to improve the mechanical, thermal, and electrical properties of emerging composite. The reason may not be unconnected with some of the deficiencies highlighted in Table 1. In order to minimize the quantum of natural fibers in some applications, the use of synthetic fibers such as glass, aramid, and carbon fibers are also used as reinforcing materials in construction works and few other interests in automotive industry (Nor Arman et al. 2021). There is also the concept of thermosetting polymers in material formation which utilizes polymer matrix composites like polyester, phenolics, and epoxy. This is a clear departure from thermoplastic family where polypropylene, polyethylene, and polystyrene are often deplored as thermoplastic matrix polymer. These crosslinking among the classes of materials are meant to reinforce and bridge notable deficiencies inherent in other materials resulting in better performance (Wang et al. 2006).

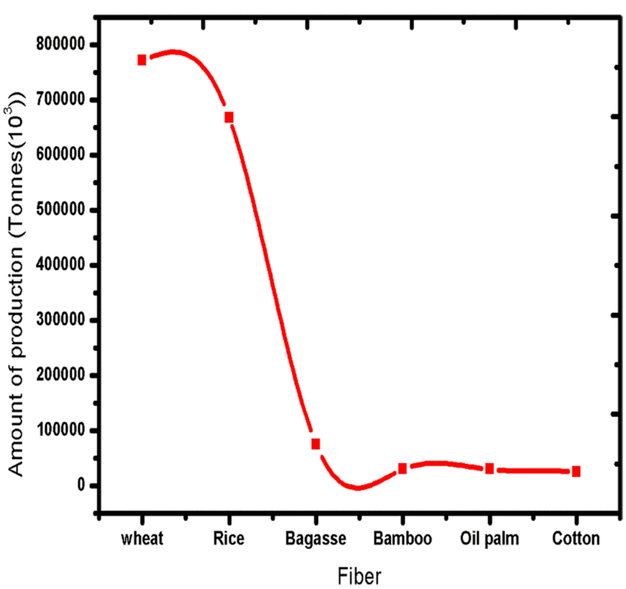

Fig. 1 Projection of global natural fiber production (Adekomaya & Majozi 2020b)

The involvement of conventional fibers, and by extension glass fibers, has remained the only dominance force in automotive part formation since their introduction to the industry in 1953 (Adekomaya & Majozi 2021). General Motors became the first maker to set the precedence by using these materials m Chevrolet Corvette where multiple glass fiber–reinforced materials were produced in open molds by hand rolling polyester resins into glass fiber mats. This production method led to the assembly of a prototype car; in which several batches spanning hundreds of cars were made. The reason as reported is to evolve glass composite materials with an improved weight reduction, better mechanical properties, and processing efficiency. The emerging products produced from some of these processes have been shown to be suitable in terms of desired results. Part of the positive attributes that have propelled these materials into point of reckoning is their great abundance, low cost, good mechanical properties, and reliable performance (Adekomaya et al. 2016). From manufacturing of automotive parts, findings have shown that the proportion of steel in car body is up to 15% of the entire body weight, utilizing about 25% of the world's glass, and responsible for 40% of the annual global oil demand. Despite spirited efforts to reduce the car body weight, findings have shown gradual increase with Audi

Table 1 Comparative advantages of natural fibers

S/N	Advantages	Disadvantages
1	Lightweight materials could reduce carbon footprint	Mechanical strength is lower compared with synthetic fiber
2	Operational energy requirements are low and enhance insulation and electrical and acoustic properties	Environmental factors are instrumental to their properties
3	They are biodegradable and reinforce the environment against climate vulnerability	They are hydrophilic in nature and could be susceptible to moisture penetration
4	They could be re-claimed in an eco-friendly manner	Interfacial bonding between matrix and fiber requires surface treatment
5	Natural fibers could also be reclaimed through thermal operation	Flame retardant of natural fibers is not reliable in most cases

product increasing by 460 kg in weight. These have led to the harmonization of social desire in terms of comfort and better driving performances, taking into consideration the environmental security. Reports have also shown that automotive industries account for about 23% of the total global carbon emissions followed by other pollutions during the vehicle's active time in which the environment is further subjected to heavy greenhouse gas pollution (Adekomaya et al. 2017b). The projection of 10% vehicle's total weight to be reduced leads to improving the fuel efficiency by up to 7%, and for every 1 kg saved on vehicle payload amount to about 20 kg of carbon dioxide prevented from being emitted into the atmosphere. The use of lightweight materials could offer twofold benefit: reducing the total bodyweight, which would result in increased fuel efficiency (Rajeshkumar et al. 2021). As referenced in published works (Sadhukhan et al. 2021), 100-kg body weight reduction in articulated vehicles could achieve about 0.3–0.5 dm^3/100 km fossil fuel reduction and a corresponding 7.5–12.5 g/km emission decline. In the works of other authors, findings have indicated that for the automobile industry to be globally relevant, there is pressing need to reduce the environmental burden in the entire value chain system. This captures the total life cycle of the automobiles starting from development, production, use, disposal, and recycling. Going by the lifespan of vehicles, as they approach their end-of-life cycle annually, the industry could generate between millions of tons of waste in which only 65% of these wastes is successfully recycled or disposed of. The implication is that the cumulative effect of these wastes that are unsuccessfully recycled could hamper sustainable and safe environment (Yibowei et al. 2021). Various efforts have been put forward by governments and environmental bodies toward the use of sustainable and eco-efficient materials in the wake of rising waste generation and recycling difficulties and amid carbon emission targets. Part of the efforts to reduce carbon footprint continues to enjoy accolades among member nations. These were part of the European Union decision as contained in their parliamentary decision targeting 2000 unrecycled automobile parts amounting to about 85% by weight by the year 2006 and 95% by 2015. This was also followed by combined efforts on the part of the European Commission and the European Automobiles Manufactures' Association, to evolve an encompassing legislation aimed at curbing CO_2 emission by setting standard for light vehicles in new vehicles sold, with a caveat of maintaining 130 g/km carbon dioxide emission mark by 2012, targeting 95 g/km by the year 2020. This effort was also replicated by the Japan Automobile Manufacturers Association (JAMA) and Korea Automobile Manufacturers Association (KAMA) by setting CO_2 emission target in order of the specification outlined by EU. In the USA, the government also implemented a policy to have a progressive increase in the fuel economy in the range of 54.5 miles per gallon (mpg) as per cars and light-duty trucks having model year 2025. Besides, a provision of pump gas is made for car users saving billions of dollars and reducing 12 billion barrel of oil consumption (Adekomaya et al. 2017a). The US automobile industry is estimated to be around $370 billion, and 75% of the vehicle's energy demand is reportedly associated with its payload (Adekomaya et al. 2017a), and use of glass and natural fiber will reduce automotive weight and benefit the entire ecosystem (Adekomaya 2020) (Figs. 2 and 3).

Prospective materials in the automotive industry: overview assessment

Various conventional and fiber-reinforced composite materials have been used to make vehicle parts (Andrady 2015). These materials were used in the first instance, to enhance the strength and durability of the material parts and majorly sourced from steel, aluminum, magnesium, copper, plastics, and carbon fiber (Easton et al. 2008). There have been several underlying factors guiding the selection of material, especially for the automobile body, which could range from thermal, chemical or mechanical resistance, easy manufacturing, and durability. They are also the issue of affordability in terms of cost and availability of production methods in which vehicle manufacturing parts are to be produced. These include the costs associated with a vehicle's complete lifecycle and capturing manufacturing, operating, and disposal costs. Reports have shown that composite materials provide a big advantage over metallic materials in automobile production in the future. Composites are reputed to have gained attention due to their lightness and safety and possibly evolve to a fuel-efficient vehicle. Typical of the composite materials is their high-performance fiber (as demonstrated in carbon or glass) in a matrix form (epoxy polymer) that, when processed, gives enhanced properties against an individual material (Jacob 2014). Carbon fiber–reinforced composites have shown to display stiffness and strength, in several of the applications they feature. Findings have also corroborated their long resistance to humidity or corrode like steel or aluminum, and they could largely support the weight reduction campaign in which fuel economy could be achieved by reducing vehicle payload (Easton et al. 2008). Part of the challenge in today's composites is that substantial components of these products were developed for aerospace applications in which their energy-saving measures may not primarily be critical. Preliminary reports on the cost of procurement of carbon fiber composites are reportedly 20 times higher than convectional steel, and by implication, the automotive may consider these materials lesser than others of considerably lower price (Lyu & Choi 2015). Therefore, metallic materials appear not to have been irrelevant in this application and may be considered in the

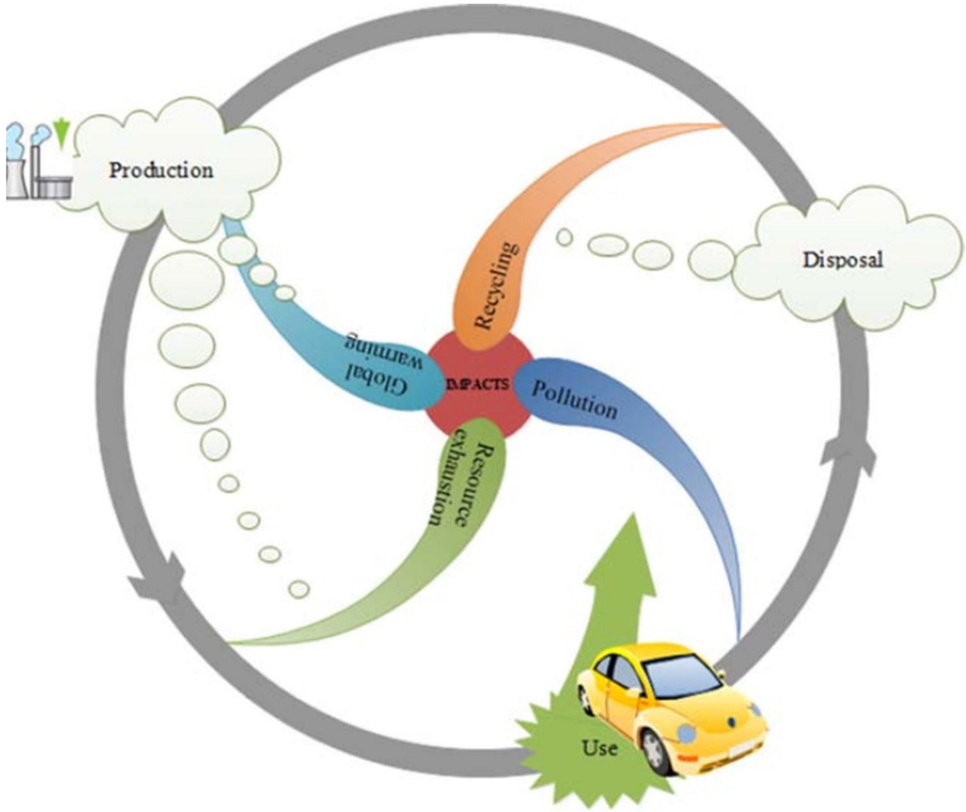

Fig. 2 Schematic diagram establishing symbiotic link between the automotive production chain and environment (Akampumuza et al. 2016)

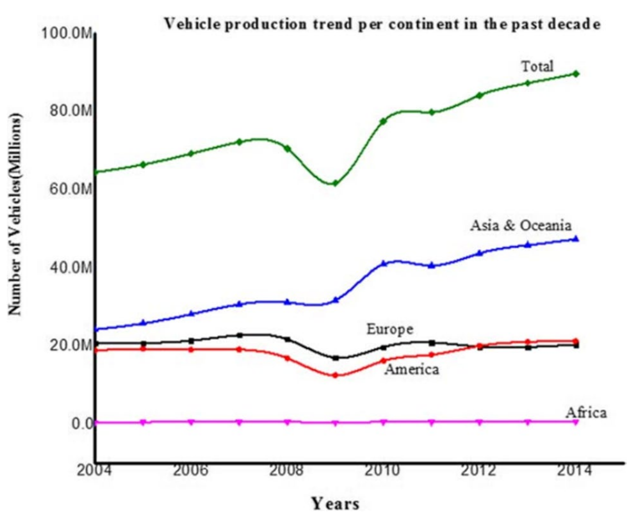

Fig. 3 Pattern of automobile output in terms of vehicle production by continent in the last decade (OICA World Motor Vehicle Production, n.d)

foreseeable future. In the scheme of metallic materials in relation with these characteristics, steel is considered as port of call. Research findings (Das 2000; Taub 2006) have also x-rayed recent developments around iron and steel in which steel have undergone several modification making them more lightweight, stronger, and stiffer and improved other performance characteristics. These features have extended the applications to include not only vehicle bodies, but also engine, chassis, wheels, and many other component parts that can reduce the payload of vehicle. In years back, iron and steel form enjoy critical patronage and serve as a replacement element of the vehicular structure, and are low-cost materials. Part of the reason making steel attractive in the body structure of automobile industry is its salient capability to absorb impact energy in the event of crash situation. This attribute is also traceable to aluminum making it suitable in automotive industry due to its low density and high specific energy absorption performance with comparative specific strength. Findings have shown that the use of aluminum can also offer weight reduction in vehicle body. The concerns around these metallic materials remain unresolved in the wake of these successes making them the last resort for automobile part replacement. Alternative materials have resonated in the evolution of glass materials, and 50%weight saving vehicle payload could be achieved by the substitution of metallic materials by glass fiber (Boland et al. 2016; Duflou et al. 2009). It is established that glass materials are often used for body structures, chassis parts, and exterior attachments. Magnesium could also serve as a light metal in which the automotive industry can benefit. Studies have shown that it is 33% lighter than aluminum and almost 75% lighter than steel/cast iron parts. In other reports, magnesium alloys could confer features rarely found in other metals upon automotive parts like better manufacturability, longer die life, and faster solidification. In addition, magnesium components have higher machinability. Fiber-reinforced composites as reported for glass fiber offer a wide range of advantages to the automotive industry (Rezaei et al. 2008). It is mainly due to the fact that the composite structures are of high strength/low weight ratio. Carbon fiber–reinforced materials or fiber glass–reinforced composites are also offering numerous new design possibilities for structural components in cars. These materials have significantly reduced the weight of automotive parts and also offer stiffness and durability on automotive parts. The future of automotive parts is lightweight materials and will continue to attract attention in automobile industry. In recent times, carbon fiber which used to be expensive is being reprocessed and reclaimed in order to evolve an affordable carbon fiber, which can complement automotive parts.

Based on the aforementioned discussion, it can be established that the automotive industry largely depends on a systematic approach leading to a more sustainable material selection. The process at which a suitable material is selected for a vehicle component part is the first and most important factor required for automotive design. There are several materials that can be used for automotive body and chassis as shown in Fig. 4, but the nitty–gritty required in the design formation is the main challenge here. In order for the automobile manufacturers to fully explore appropriate materials suitable for their body parts, the following requirements must be met:

Lightweight properties, this appears to be the most important consideration in the automotive company considering the weight reduction that would be achieved leading to improving fuel efficiency and greenhouse gas reductions

Economic consideration, the materials of interest having satisfied the weight saving measures must also be relatively viable and affordable in order to lower the overall production cost. This goes a long way to determine whether a particular material is suitable for vehicle component

Resilience, the ability of the materials to absorb impact energy through in-built strength as reinforced with appropriate fiber materials

Recyclability and reclamation of products after their end-of-life cycle is of primary concern in automotive industry. The entire value chain is dependent on the sustainability of the ecosystem

By 2030, the challenge with the automotive industry and society may be compounded in terms of proliferation of materials and the attendant reclamation options. Plastics and polymer composites provide weight savings, strength, and versatility in the automotive industry with new standards without sacrificing quality.

Emerging concerns amid upsurge in natural fiber patronage

There has been an upsurge in the use of natural fiber in several applications, ranging from household utilities, building, and automotive industries (Bourmaud et al. 2013). The industry is growing in leap and bound, no doubt, leading

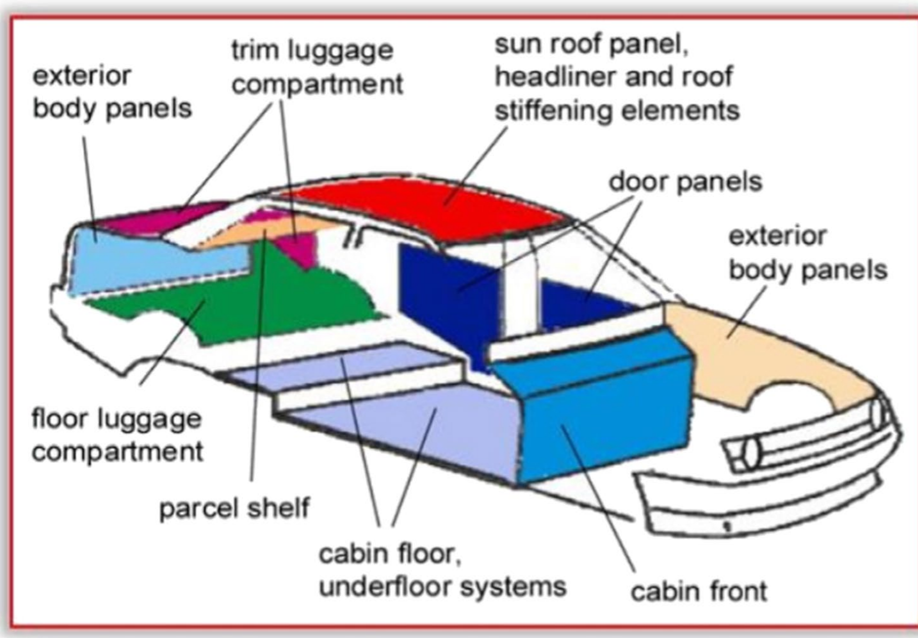

Fig. 4 Application of fiber-reinforced composite in automotive parts (Automotive Market Reports 2012)

to composite materials of natural fiber extraction that can limit ecological concerns. Involving natural fiber in several applications is taking toll on the environment considering the biodiversity loss amid dislocation of ecosystem that could trigger ecological disaster. These have exacerbated the environmental crisis being faced in many parts of the world as effects of climate change resonate with adverse impact. Though, findings (Rafieipour et al. 2021) have shown that one of the most promising ways of addressing the rising environmental vulnerability is the use of natural fibers in product formation, in order to reduce the non-biodegradability of materials in the neighborhood. This evolution has led to ripple effects on the replenishment process of natural fiber in the face of natural forest depletion. Though the production of natural fiber related polymer composites has increased significantly, this has not reduced the proliferation of synthetic materials and safe climate (Marcovich et al. 1999). Research has shown that by 2024, with estimated annual growth rate of 10%, natural fiber market could hit 4.8 billion USD, making natural fiber–reinforced composite materials the most sought-after materials globally (Chegdani et al. 2021). The use and demand of natural fiber-based polymer composite is rising, making synthetic composites unpopular in several applications where they had initially held sway. In addition to their biodegradation properties, and accessibility of their parent composites, another application promoting their use in car applications includes lightness and energy properties, enhanced acoustic isolation, and the ability to show CO_2 neutrality as a result of greenhouse gas consumption in production stages. In order to mitigate the impact of emission and rising global CO uptake globally, the automotive industry has evolved different mechanism aimed at achieving better environmental results by adapting natural fiber as alternative component parts. This approach has resulted in less energy use, and thus, promotion of cleaner manufacturing processes and highly recyclable material, in which disposal phase is hitch-free and sustainable. Part of the benefit also enables the entire value chain to develop a product with improved marketing strategy. As depicted in Fig. 2, three major properties of natural fiber were studied on the scale of tenacity, elongation, and moisture content, and the projection was illustrated. We could see that the elongation of natural fibers across divides is consistent along all the fibers displayed in the study, which made them suitable for several applications. The tenacity of natural fiber is also shown which is in line with published papers (Alomayri et al. 2013). Natural fiber tends to maintain equilibrium position before treatment and may have informed their high moisture content for all the natural fibers reported in this study. It is also important to study the cellulose and non-cellulosic features of natural fiber in order to predict the structure and properties inherent in its crystallinity and moisture absorption properties. Findings (Maracchini & D'Orazio 2022) have shown that physical properties such as density, tensile strength, moisture tendency, and crystallinity could influence the composition and internal structure of the natural fibers. Though, researches have shown that the strength of fibers cannot be based on quantity of cellulose content and microfibrillar angle, as noted in several published papers (Jawaid et al. 2021). In many cases (Mawardi et al. 2022; Yanou et al. 2021), it was established that fibers with reasonable cellulose content, moderate degree of polymerization of cellulose, and lower microfibrillar angle could produce composite with better mechanical properties. In other papers (Benmansour et al. 2014; Claramunt et al. 2016), natural fibers are often reinforced with higher lignin content and higher microfibrillar angle in order to demonstrate lower strength and modulus as their formative properties. There are also natural fibers with higher amount of cellulose and lower spiral angle as shown in banana fibers. Findings have also shown that these features could induce natural fibers with higher modulus and tensile strength. Some drawbacks to these properties could promote lower breaking elongation as demonstrated in some coir fiber applications. In order to reinforce the mechanical properties of natural fibers for applications, it is important to conduct salient tests on their specimen to ascertain the composition, structure, and number of defects such natural fiber exhibits. In several applications and under severe stress, findings (Khalid et al. 2021) have shown tensile failure in many natural fiber composites, by intercellular or intracellular forms. In cases where fibers are embedded with higher cellulose content as shown in many banana- and pineapple-reinforced composites, crack propagation often occurs along the vulnerable bonding between cells, thereby resulting into intercellular fracture. Contrary to expectation, cracks are mostly initiated through the cells in a region with lower cellulose content, resulting in the weakening of the intracellular fracture and microfibrillar pullout. Some papers (Chen et al. 2014; Silva et al. 2017) have shown that the elongation of natural fibers largely depends on the degree of crystallinity, orientation, and the angle of the microfibrils to the fiber axis. This was also affirmed in Fig. 5, with coir fiber demonstrating high degree of elongation as against other natural fibers of repute. Some authors have also attributed these unique properties of coir fiber as a result of their perfect helical spirals formed by the microfibrils around the fiber axis.

Replenishment strategy of natural fibers amid hybridization with synthetic fibers

There has been public outcry on the depletion of natural forest while no sustainable strategy was put in place to curtail the overbearing disappearances of nature. While natural fibers serve multifaceted approach in energy conservation

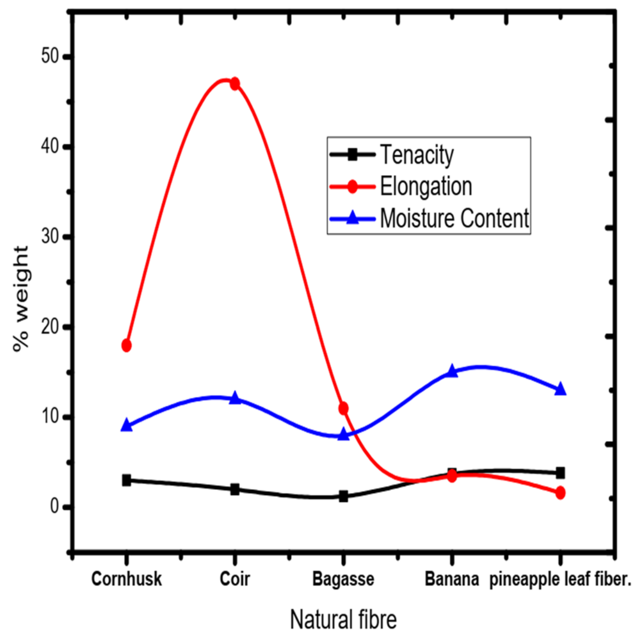

Fig. 5 Salient properties of natural fiber for environmental conservation (Adekomaya & Majozi 2019)

roadmap, it is equally important to devise a sustainable means of mitigating the natural fiber over-use to conserve biodiversity in a very sustainable and structured manner. In this paper, the authors x-ray the possibility of adopting hybridization of fibers in which natural fiber proportion in the composite formation is significantly reduced while the synthetic portion is polymerized to shed reasonable non-biodegradable components in them, in order not to constitute environmental crisis. In many published works (Sanivada et al. 2020), this approach of reinforcement, in which more than one type of fibers in the matrix forms a hybrid composite material, is becoming novel in engineering applications. In general principle, studies have shown that fiber-reinforced hybrid composites may be categorized into the following, depending on the production method:

- Two types in which a base material consists of a matrix and the other consists of more than one supporting fiber phase
- Two types of materials embedded in the composite, in which one consists of a reinforcing fiber and the other consists of more base matrix phase
- Manifold phases with several base matrixes and more than one reinforcing phase

To foster environmental sustainability and preserve nature, this paper appraises past works, most importantly, several papers on hybridization of matrix with respect to natural or synthetic fibers so as to be acquainted with inherent properties derivable from this approach. In this paper (Ahmed et al. 2018), it was affirmed the effectiveness of glass fiber and carbon fiber as reinforcement in the formation of composite with hybridized natural fibers. These authors established that with the enhanced volume proportion of glass fibers in the composite specimen, tensile strength and Young's modulus of the emerging materials were improved due to the better compatibility of the fractional glass fibers with the matrix. It was also noted that polymerized glass fibers degrade faster as against synthetic fiber not pre-treated prior to hybridization. In other findings (Mohanty et al. 2018), it was established that the polyester materials reinforced with natural fibers displayed frail properties against jute reinforced with epoxy materials. Further findings also indicate that upon integration of glass fiber into the composite materials, significant improvement in the properties was noted. It was concluded that glass fiber used in the reinforcement may have been responsible for spike in the composite properties. What was not reported is the degradation properties of the glass fiber used in that particular study. In another experimental study (Aliotta et al. 2019), researchers highlighted the prospect of hybrid reinforcement of natural fiber and glass fiber, in which the recycled glass fibers could be integrated into composites with improved mechanical properties. This was contrary to other composites, in which a particular jute or glass fiber was independently used as reinforcement in composite formation. In other works (Bharath & Basavarajappa 2016), hybridization was reported in the form of interlamination and intra-lamination. Interlaminate process is achieved by basically overlaying of fiber or by placing layers over fiber, made of various strands. In the case of intra-laminates, the two filaments are usually entrapped inside a uniform layer. Part of the features of this production is that the emerging composite could be biodegradative with less environmental effects. Similar findings were also reported in the works of other workers (Zini & Scandola 2011). In another paper, this author (Dong 2018) x-rayed the hybridization effects on emerging composite, as it relates their degradation over 5 years on the environment. The findings showed that the manufacturing process devised for the composite formation (vacuum bagging method) may have influenced the properties of the composite to degrade naturally. This unique production of composite was also reported to have reduced the intensity of the glass fibers to degrade naturally, having degraded the components in the friendliest manner. Some findings (Tokiwa et al. 2009) also show that hybridization of fibers could be most viable option, in reclamation of synthetic materials, and these are evident in many published works (Reichert et al. 2020; Sohn et al. 2020). While the process of hybridization may have prevented, thousands of synthetic materials to have constituted waste burden on the environment, further consequences of hybridization in terms of enhancing the structural, thermal, and mechanical properties of many natural fiber–reinforced composites are also identified (Babu et al. 2013; Henke et al. 2017). Hybridization also serves to expand the reclamation strategy of synthetic fiber by providing better approach in reducing the moisture content of natural fiber along with nobler mechanical properties. In a related papers (Chiellini et al. 2003; Iwata 2015), glass or carbon fiber was shown to be impervious to moisture penetration and with relatively higher mechanical strength as compared to natural fibers. This referenced paper further affirmed that hybridization through the synthetic fibers reinforces the mechanical properties of natural fiber–reinforced composite while reducing the quantity of non-biodegradable fiber on the environmental space. In other research papers (Park et al. 2019; Vaia et al. 1993), dampness and rising moisture content of composite materials were attributed to hybridization process, thereby dashing hope of earlier findings. Table 2 x-trays specific synthetic fibers and natural fibers as studied by researchers under the guise of reclamation of non-biodegradable materials in which synthetic fibers belong. These studies considered hybridization technique as viable option.

Fiber hybridization is designed to balance the deficiency of one specific fiber to achieve sustainability, low cost, and improved performance of fiber-reinforced composites. Hybridization was long introduced as one of the best reclamations of fiber composite in which in many cases provide flexibility in fiber selection for engineering material properties according to the application requirements. In many hybrid composites, the emerging fiber is typically produced by hybridizing natural fibers with synthetic fiber(s) with superior and resilient properties, such as mechanical strength, chemical stability, nontoxicity, noncombustible, resistance to high temperatures, and thermal or acoustic insulation. Fiber hybridization is usually produced when there is intermingling of different types of fibers as a mixture or interlaminating layers of different fibers before their addition to the matrix.

This approach has made hybridization more popular mostly when the natural fibers and the synthetic fibers, such as glass, carbon, Kevlar, basalt fibers, and carbon nanotubes, can enhance the mechanical performance of emerging composite materials. In many cases, studies have shown that the hybridization of jute fiber with glass fiber fabric (1:1 wt ratio) has resulted in the enhanced tensile and impact strengths of jute fabric–reinforced polyester as also confirmed in other notable published works by three-fold and six-fold, respectively. In other similar works, studies have shown that almost ten-fold of tensile strength and five-fold of the impact strength improvement are obtained by hybridizing jute fabric with carbon fibers. There are also reports of shrinkage and warpage in some of the emerging composites in which findings shows that the flow and cross-flow shrinkage values of these emerging composites can be optimized by controlling the injection molding process parameters, thereby meeting the material's maximum shrinkage requirements for under-the-hood parts used in automotive part replacement industry. Studies have also established the possibility of hybrid composites of natural fiber with other natural fibers, and the reports equally show comparable mechanical improvements to those hybridized with synthetic fibers, but this approach has been criticized in many reports in terms of sustainability of such applications.

The overall performance of hybrid composite is determined by inherent factors as reported in notable works. Some of the factors include fiber content, hybrid ratio, fiber orientation, stacking sequences, and innate fiber features. Findings have also shown that the tensile strength and failure strain of the hybrid composite is

Table 2 Hybridization as a reclamation process of synthetic fibers

Synthetic fiber	Natural fiber	Merits	Ref
Glass	Jute	Improvement in the mechanical properties of the emerging composite and enhancing the biodegradable properties of the glass fiber	(Boland et al. 2014; Bourmaud et al. 2013; Rezaei et al. 2008)
Glass	Sisal	Tensile strength and overall performance are improved, most importantly, with the addition of jute fibers	(Babu et al. 2013; Manjula et al. 2017; Nor Arman et al. 2021)
Carbon	Palm/sugar	Several hybridization results showed that these hybrid composites with 60% of sugar/palm fibers and 40% carbon fibers improve their flexural strength as well as environmental risks	(Das & Chaudhary 2021; Liang & Hota 2013)
Glass	Banana	Banana fiber is noted for the optimum flexural properties when reinforced with glass fiber. These composites biodegrade in a friendly manner	(Ali et al. 2021; Madurwar et al. 2013)
Carbon	Jute	Hybridization improves the impact and flexural properties of these materials with increasing the jute fiber percentage in carbon/jute hybrid composites	(Fan et al. 2019; Rajeshkumar et al. 2021)

mostly increased from ~ 200 MPa to 0.9% for flax-alone reinforced composites to ~ 700 MPa and 1.4% for glass fiber–alone reinforced composites. With the inclusion of higher glass fiber hybrid volume fraction, the hybrid composite maintained its integrity to a significant level until the failure dominated by the bigger elongation of glass fiber. In many cases, the hybrid composite had a higher interlaminar shear strength when compared with the composites reinforced with either natural or glass fiber alone. This was evident in the increase in interlaminar fracture toughness from the twisted flax yarn structures and rough surface that led to the bridging and entangling of interfaces.

Part of the advantages of hybridization is that it can compensate for the inherent disadvantages of the individual bioresources. For example, it was observed in literature that the different stacking configurations of the hybrid PLA composite with kenaf(K)/bamboo(B)/coir(C) showed a diverse range of mechanical properties results. With the same proportion of fiber content (60 wt %), the stacking sequence of KBCCBK increased the neat resin tensile strength from 25 to 187 MPa and the modulus from 1.7 to 7.5 GPa as evidenced in the product formation of such materials. The same findings showed that the increased tensile strength was in the range of 20 and 78% higher than composite sequences of KCCK and BCCB, whereas modulus only reported 2 and 25% higher than those of KCCK and BCCB, respectively. It was also stated that the high Young's modulus of kenaf and bamboo fibers contributed better in resisting loads at the outer layers of composites, while the high ductile coir fiber offset the low elongation of the kenaf and bamboo fibers in the composites. In case of the flexural properties, the PLA/BCCB and PLA/KBCCBK composites had in the range of 20% higher flexural strength but 70% lower flexural modulus than the PLA/KCCK composite. This higher content of flexural modulus as seen in the PLA/KCCK composite was explained by the lumen connected to the secondary layer of the kenaf and coir fibers, which promoted cohesion by interlocking the fiber cell walls with the PLA matrix. The results further suggested that high-strength and modulus fibers in the outer portion of the layers and effective matrix impregnation into lumen are key factors responsible for hybridization configuration in which the superior mechanical performance is expected from the composites. Another recent study of the fiber aspect ratios in kenaf/corn husk for hybrid composites showed that hybrid fillers with similar dimensions were effective in external force transfer and modulus enhancement, which also corroborated previous indicator in the enhancement of mechanical properties of a hybrid composite.

Salient properties of natural fiber for environmental conservation

Natural fiber composites are notable for features which made them suitable for environmental conservation. The use of natural fiber has resulted in lower environmental impacts than glass- or carbon-fiber composites as they were reflected in many of their production impacts in which the performances of tier products are sufficiently low in terms of environmental performance of the product. There were many life cycle assessments (LCA) undertaken on natural fiber composite in which significant energy savings and greenhouse gas reduction were reported when they were deployed to reduce the weight of aircraft, trucks, automobiles, and other vehicles. These significant energy savings from light-weighting materials are larger in quantity than the impacts of fiber production. Even so, there was public outcry on the impact of natural fiber production in an area where climate change is already taking toll on such practices, making it necessary to embark on further research because agricultural processes used to produce fibers can reduce feedstock availability in other applicable needs. Another LCA research study on environmental impact assessment of fiber reinforced composite was evident by comparing 3 kg of 30% glass-fiber composite component with a 30% cellulose-fiber component and a 40% kenaf-fiber component in automotive applications, and the study showed that the environmental benefits of NFRCs are mainly because NFRCs are lighter than glass-fiber composites and contributed to the energy efficiency of automobiles. Across all strata of natural fibers, it was further shown that the 3-kg part had a life-cycle energy consumption of approximately 20 MJ for fiber production, with possible 150 MJ for resin production, and contributed to about 80 MJ for part manufacturing, leading to 20 MJ for energy sourcing, in which 1200 MJ is dedicated for use, and 1 MJ alone desired for end of life, and 1450 MJ would be required for total life-cycle energy consumption. Life-cycle energy consumption on its own appears to be the largest for the use-phase because most of its application requires considerable composite part in automobile formation, which makes the use-phase energy consumption proportional to the weight of the component. In many published works (Adekomaya & Majozi 2020a; Sadiku et al. 2017), cellulose- and kenaf-fiber components often weigh less than the glass-fiber component; as a result, the use-phase energy is lower. All other recovery options had approximately the same life-cycle energy as noted previously by other workers. It is also noted in other findings that kenaf and the cellulose composite provided almost 7% reduction in life-cycle energy use of the component, compared with the glass-fiber composites, with potential as high as 19% with resizing of the power train. The findings were also criticized as one of the isolated reports as this may not be consensus for other publication with similar natural fiber components.

There are also several life cycle assessments that can be undertaken to boost the energy recovery and reclamation process of fiber-reinforced materials. Such approaches have been undertaken by other workers ranging from landfilling, incineration with energy recovery, and recycling. Landing of fiber-reinforced polymers, like carbon and glass fibers as well as natural fibers, is being done globally in line with best practices which makes biomass sequester carbon, to reduce its greenhouse gas reduction to a considerable level, while the incineration with energy recovery tends to release the carbon in the biomass but can also displace the use of fossil fuels as feedstock materials, thereby making alternative route to greenhouse gas reduction. The quantity of energy recovered from the incineration of NFRCs ranged from 12 to 34 MJ/kg of the composite, which is much better than for glass fiber composites, which are often in the range of 7.5 MJ/kg. Several reports have found the end of life of polymer composites and also affirm the environmental benefits both for recycling of the flax/PP composite materials and for incineration for energy recovery if the process would replace coal combustion. The approach in which the pellets from the waste fiber composite and combusting were used as alternative fuel was also considered but found to be much more expensive as compared with waste incineration option. The overall objective of adopting life cycle assessment in fiber composites, which have been mostly focused on automotive applications, is to measure its energy-saving measures in terms of its recovery as compared to glass fiber materials. Also, it was discovered that fiber-reinforced materials can display inferior environmental impacts than existing ones when certain factors are considered. For example, flax is superior in most environmental impact assessments compared with glass fiber, except for eutrophication, in which the use of fertilizers for flax production can accelerate its degradation. Several other studies were also carried out to examine the potential for eutrophication, and it shows the correlation from fibers produced with fertilizers and the environmental impact assessment. In the regenerative process involving LCA, it was suggested that the use of the banana fiber required could change composite to achieve the same functional characteristics, which could also reduce the production advantage of natural fiber. Different adaptation of fiber treatment played a vital role in the analysis of the environmental impact of fiber composite. Deployment of fiber-reinforced materials for automotive industries requires treatment of these fibers using physical and chemical methods. Green methods provide a sustainable approach in which the fibers are coated with bacterial nanocellulose, fungal, enzyme, and plasma and further treated for the surface modification of plant fibers as highlighted in Table 3. Part of the advantages of this process is that coating of bacterial nanocellulose enhances plant fibers to increase the hydrophobicity in which the bacterial cellulose forms the hydrogen bonding with the hydroxyl groups present on the surface of the plant fibers. Reports also show that fungal treatment often causes the removal of non-cellulosic material from the plant fibers and protect the cellulose and hemicellulose material against environmental vulnerability. Cellulose as they are embedded in plant fibers can be hydrolyzed by the bacterial cellulase. Plasma treatment often reinforced the surface boundaries of the plant fibers. All these approaches are embarked upon to change the morphology, thermal behavior, crystallinity, and mechanical properties of the plant fibers without using any harmful chemicals. They also help to maintain the biodegradability of the fibers and maintain their lightness in the event they are deployed for automotive parts. The prospective materials in the automotive industries are reported to be natural fiber inclined, to provide broad-based materials recyclable and sustainable for environmental reclamation. Automotive parts are now biodegradable and lighter in weight to offer energy reduction in diesel-driven cars. These have also provided a value chain in which materials for automotive parts are being sourced from natural fiber ecosystem. Materials for automotive parts must be degradable after its lifecycle. This approach reduces the volume of waste to be recycled which sometimes poses serious threat to mankind. The materials identified in this research provide a sustainable way of saving energy and also saving mother earth from serious environmental threat.

Replacement strategy for natural fibers has been accommodated in the reclamation options of natural fiber as contained in the body of this paper. By practice, fibers are sourced from nature making it naturally abundant and easily accessible for automotive application. The competitive demand of natural material for other needs have remained a stumbling block, limiting the application of these materials and also making it relatively abundant for automotive industries. Nevertheless, other options are being explored to bolster natural fiber availability through dedicated cultivation, and hybridization practice. In areas where natural fiber is relatively available, synthetic fibers are sometimes used as component fibers to provide mechanical properties of proportionate quantity, in a manner that biodegradable components are much higher than synthetic materials.

Conclusion

Fiber-reinforced composite has been widely applied in the automotive sector. It was also estimated that 75% of fuel consumption could be achieved with vehicle weight reduction, while with every 10% reduction in vehicle weight could

Table 3 Physical and chemical properties of natural fibers adaptable in automotive industries

S?N	Treatment methods	Effects on fibers	Merits	Demerits	References
1	Plasma	Reduces in surface layer wettability and helps to form a new functional group capable of enhancing mechanical properties and hydrophobicity and interfacial adhesion	Hazardous chemicals may not be needed which favors environmental resilience and low operating cost resulting in short treatment time and greater efficiency	Application of low-pressure plasma sometimes requires a well-structured plasma reactor system with expensive vacuum systems, which makes the entire process difficult	(MacArthur et al. 2016; Pernica et al. 2010)
2	Chemical treatment	Cleaned fiber interfacial surface, with possible effects on the modification of moisture absorption process, and helps to increased surface roughness, and interfacial adhesion, with improved fiber strength	Easy processability after treatment, and acceptable in diverse light weight applications, adaptable at industrial scale, flexible in production methods	Involve the use of hazardous chemicals with impact on ecosystem, require proper handling, solvent waste disposal is difficult in many cases, expensive in terms of final product	(Browne et al. 2011; Jawaid et al. 2021)
3	Fungi	The removal process works well in non-cellulosic and amorphous compounds, resulting in enhanced crystallinity index	Generally low in terms of cost, often efficient and ecofriendly with minimal biodiversity loss	Proper care in choosing the treatment time, long treatment time may affect the strength of the fibers	(Bousquet et al. 2006; Egbedina et al. 2022)
4	Nanocellulose coating	This approach provides new material on the fiber surface with possible interfacial adhesion	Environmental sustainability, low production cost	Bacterial cellulose are mostly hydrophilic, loss of fiber strength is often reported in some cases	(El Miri et al. 2015; Morsada et al. 2021)
5	Enzymes	Useful in the reinforcement of fibers and non-fiber components, interfacial adhesion is often reinforced, enhanced fiber surface, improved fibers appearance and outlook	Environmentally friendly, high quality fibers are often produced in the process, well-structured environmental treatment, low fermentation waste occurs	It is very expensive and mostly used as a pilot scale study	(Sun et al. 2017; Zhao et al. 2018)

also result in 6–8% increment in fuel economy and every 100 kg in terms of weight saving in automotive; there is also approximately 20 g/km reduction in CO_2 emission in power-trains. Weight reduction of automobile vehicles has the direct supports of the European Commission's and the European Automobiles Manufacturers Association's desire of reducing CO_2 emission. Several initiatives advanced by the European Union End-of-Life Vehicle has mainly targeted the reuse or recycling of 95 wt% of vehicles starting from 2015. In the USA alone, the Corporate Average Fuel Economy requires that automakers reduce the energy demand in terms of fuel economy of cars and light-duty trucks to 54.5 mpg by 2025. Similar regulations are being proposed in many other countries to increase the fuel economy and CO_2 reduction in the foreseeable future. In this review paper, we have highlighted the importance of lowering the harmful effects of non-biodegradable materials on the environment, taking into cognizance the complexity of degradation of the materials amid environmental vulnerability. For this singular reason, it is incumbent on researchers to consistently utilize materials that are completely biodegradable while complimenting these materials with polymerized synthetic fibers to reduce their stakes in the environment. Though it is clear that natural fibers are superior in specific properties, to the synthetic fiber-reinforced composites taking into consideration their certain peculiarities, efforts should be made in which the synthetic fibers are accommodated in future composite production against the backdrop of their improved mechanical properties. In order to broaden the use of natural fibers in engineering applications, it is now of essence to strengthen their mechanical strength with synthetic fibers, and in order to lower environmental effects of synthetic fibers in equal manner. While synthetic fibers serve dual purposes, there are tedious challenges in improving the mechanical properties of natural fiber–reinforced composites. This may involve further study from the research community to encourage the utilization glass fiber as hybrid component for reinforced composite materials. The inclusion of glass fiber in composite formation may be exempted in automotive industries, considering the energy-saving measures provided by natural fibers. With the giant strides being recorded in material formation, it is expected that in the future, these improvements would lead us towards environmental resilience and biodiversity preservation.

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Data availability All data generated or analyzed during this study are included in this article.

Declarations

Ethics approval and consent to participate Not applicable.

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