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Natural fibre-reinforced thermoplastic composites: A bibliometric analysis and review of eco-friendly solutions in exterior automotive components

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ABSTRACT

The automotive industries are consistently working towards the advancement of lightweight components to enhance fuel efficiency. Thermoplastic matrix composites have been found to provide several notable benefits, including potential weight reduction, recyclability, specific strength, corrosion resistance, cost-efficiency, and design versatility. The variety of material forms and combinations in fibre-reinforced thermoplastic polymers has expanded, opening new possibilities for their use in the automotive sector and beyond. Natural fibres, due to their biodegradability, widespread availability in nature, and cost-effectiveness, offer an opportunity to broaden the range of materials used while reducing reliance on petroleum-based products. Moreover, various modifications are employed to enhance the properties of natural fibres, making them more competitive with synthetic fibres for these applications. This review provides a thorough bibliometric and technical overview of the use of natural fibres as reinforcement fibres in the thermoplastic composites. A particular focus is placed on plant fibres and their potential applications as composite reinforcement for automotive applications, especially exterior components. The review also provides an overview of the properties of commonly available thermoplastic matrices and the various composite fabrication techniques. This information can assist in making informed decisions when selecting the most suitable material and process for specific product development. Furthermore, this review examines the mechanical properties of natural fibre reinforced thermoplastic composites and sheds light on the important challenges that must be addressed.

1. Introduction

Currently, natural fibre polymer composites (NFPCs) have been used as a material for automotive exterior components. A few examples are brake pad, door panel, and car spoiler. Manufacturers use natural fibres like kenaf, hemp, flax, jute, and sisal reinforced with polymer composite to reinforce exterior automotive parts due to factors like decreased weight, cost, and carbon dioxide emissions, less dependency on foreign

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oil supplies, recyclable nature, and additional benefit theof being "green" or environmentally friendly [1–3]. The utilization of natural fibre has become pivotal for the development of sustainable automotive applications. The major automotive industries have successfully used natural fibre polymer composites for different automobile parts, which mainly describe the crashworthiness of the interiors and exteriors [4]. For example, Lau et al. [5] examined the applications of natural fibre-reinforced composites in automotive structural applications. Various properties of natural fibre-reinforced composites are discussed, including fibre–matrix adhesion, fibre mechanical properties, moisture, impact and fatigue [6]. A number of automotive companies have increasingly used polymer composites reinforced with natural fillers, especially in the internal parts of the car, such as door panels, trim parts in dashboards, parcel shelves, etc. [7,8].

The side mirror is a pertinent case study for exterior components, as it exemplifies key design challenges such as achieving aerodynamic shapes to reduce drag force and mitigating wind noise. These challenges are universal across exterior parts and have spurred significant research into material solutions that offer improved acoustic and mechanical performance. For example, Hariprasad et al. [9] investigated acoustic characterization of polypropylene composites reinforced by natural fibres for automotive applications. The result has shown that an increase in thickness is not effective at higher acoustic absorption frequencies. This drive for performance and sustainability is leading the automotive industry to extend the use of natural fibre composites from established interior applications into more demanding exterior parts, such as bumper beams, trunk panels, roof covers, and side mirrors, in addition to interior components like door panels, parcel shelves, and instrument panel supports. This shift is driven by the excellent mechanical properties, relatively low cost, low density, and recyclability offered by natural fibre based composites [10].

Commonly manufactured from plastics or aluminium for lightweighting, components like side mirrors represent a significant opportunity for material substitution with natural fibre composites. Research indicates that the properties of commercial side mirrors can be comparable to those of hybrid natural fibre-reinforced composites. However, due to the poor characteristics of natural fibre like wettability, inconsistent properties and lower heat resistance, natural fibre is not being seen as the main option for these components. Although there are a few solutions to improve the natural characteristics of the natural fibre like fibre treatment, stacking sequences and hybridization, the major concerns of the manufacturers are the cost for the solutions. Hence, manufacturers will still use commercial plastic and aluminium as the material for exterior components of cars. However, there are lots of researchers who have tried to determine the hybrid natural fibre reinforced composite, which had the potential to replace the commercial materials with lower costs [11,12]. For example, Ramasubbu et al. [13] studied the mechanical properties of hybrid natural fibre reinforced polymer composite of automotive components. It is shown that hybrid composite has better mechanical properties than sisal fibre composite and kenaf fibre composite, which is suitable for light weight automotive applications. The applications of NFPCs are growing rapidly in numerous engineering fields. The different kinds of natural fibres reinforced polymer composite have received a great importance in different automotive applications by many automotive companies such as German auto companies (BMW, Audi Group, Ford, Opel, Volkswagen, Daimler Chrysler, and Mercedes), Proton company (Malaysian national carmaker), and Cambridge industry (an auto industry in USA). Besides the auto industry, the applications of natural fibre composites have also been found in building and construction industry, sports, aerospace, and others, for example, panels, window frame, decking, and bicycle frame [14].

This review paper is organized into two primary segments to systematically explore this field. First, a bibliometric analysis maps the evolving research landscape of natural fibre reinforced thermoplastic composites for automotive applications, identifying key trends, leading contributors, and emerging focus areas. Subsequently, a detailed technical review examines the fundamental properties of natural fibres, advanced modification techniques to enhance their performance, and the characteristics of suitable thermoplastic matrices. This leads to a focused discussion on manufacturing processes and the mechanical performance of these composites, evaluating their potential to meet the high demands of exterior automotive components, with this potential demonstrated through specific case studies on spoilers, brake pads, and side mirrors.

2. Scientometric analysis methodology

One of the most extensive databases for indexing citations in academic and scientific research is the Web of Science (WoS). It includes more than 20,000 excellent journals from a variety of fields, such as the humanities, social sciences, engineering, and natural sciences. The creation of WoS has greatly made it easier for academics to analyse research trends at three different scales: micro (individual researchers), meso (institutions and journals), and macro (disciplinary scope) [15]. The systematic indexing of papers published in journals recognized by WoS allows academics to efficiently follow the development of concepts across various institutions, time periods, regions, and topic areas [16]. An advanced search query spanning the years 2000–2025 was carried out on March 7, 2025, inside the WoS database using the search string: TS = "((fiber OR fibre) reinforced thermoplastic* composite*))" AND "(automotive)". To guarantee that all versions of phrases with the same root were found in the search results, asterisks were added to specified keywords. Out of the 839 items this search produced, only 704 relevant publications, including journal articles, conference proceedings, and book chapters that were chosen for further examination in this investigation. The inclusion criteria were restricted to studies that explicitly examined natural fibre-reinforced thermoplastic composites within automotive applications. Publications focusing solely on synthetic fibres such as glass, carbon, or aramid were excluded, as were papers unrelated to thermoplastic matrices or vehicle components. This careful filtering ensured that only publications aligned with the scope of natural fibre-based thermoplastic composites for automotive applications were analysed in this investigation.

3. Result and discussion on scientometric analysis

The publication and citation patterns for studies on natural fibre reinforced thermoplastic composites for the automotive industry throughout time are shown in Fig. 1. Since the early 2000s, the number

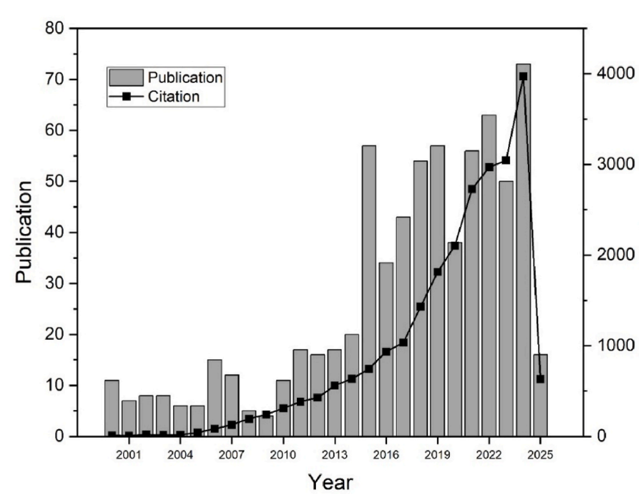

Fig. 1. Annual number of studies on natural fibre reinforced thermoplastic composites in the automotive sector from 2000 to 2025.

of publications has gradually increased, indicating a rise in interest in this topic. The research output was initially rather modest, with less than 20 papers per year. Nonetheless, the number of published research increased significantly after 2010, suggesting that the subject received more attention from the scientific community. This rise could be explained by the automobile industry's increased focus on sustainable materials as researchers looked toward greener substitutes for traditional composites [17].

The publishing tendency became even more noticeable after 2015, as the number of papers generated steadily increased. The number of articles published peaked in 2024, surpassing 70 in a single year. This implies that the sector has accelerated significantly, maybe because of material science breakthroughs and the growing use of natural fibre composites in automotive applications. However, the quantity of articles noticeably declines in 2025. This decrease is probably due to incomplete data rather than a reduction in interest in the topic, since new papers may not have been completely indexed in databases yet.

A similar rising trajectory is shown in the citation trend, which indicates the growing importance of this field of study. Citations were initially few, but as the number of publications increased, more scholars started citing prior studies. The consistent increase in citations implies that early research in this field became well-known and aided in the advancement of natural fibre-reinforced composites science. Citations peak around 2024, when they exceed 3500, which might be a sign of the release of extremely significant research or thorough review articles that consolidate the body of knowledge. Nevertheless, 2025 sees a notable drop in citations, which is to be anticipated given the delayed accumulation of citations for freshly published works. Citation counts seem to have decreased in recent years since it usually takes time for recently released research to be referenced.

Overall, research on natural fibre reinforced thermoplastic composites for automobiles seems to have accelerated significantly during the previous 20 years, based on trends in publication and citation. Sustainable composite materials are becoming more and more important in the automobile sector, as shown by the rising number of publications and citations. The most recent years have shown a brief reduction; however, this is probably due to missing data rather than a drop in research effort. The optimization of composite qualities for improved performance may be the focus of future research in this area, highlighting the contribution of materials derived from natural fibres to the achievement of global sustainability objectives.

The main funding agencies that have financed research on natural fibre reinforced thermoplastic composites for automotive are included in Table 1, together with information on the number and length of funded projects. With 38 projects funded between 2013 and 2025, the National Natural Science Foundation of China is the largest provider. This substantial financial support is in line with the growing research output reflected in the publication trend, especially after 2013, when there was a noticeable increase in the number of papers. A strong national emphasis on sustainable materials for automotive applications is shown by China's substantial expenditure in this area [18]. Another important source of financing for research is the European Union, which supports 26 projects, and the German Research Foundation, which supports 27. The effect of the German Research Foundation, which has been supporting since 2011, is seen in the steady rise in research production during that time. The European Union's assistance, which runs from 2013 to 2024, is also consistent with the current surge in publications and citations. The formation of important research teams and partnerships that have advanced the area was probably made possible by the financing from these organizations. The German Federal Ministry of Education and Research has shown its strong commitment to the advancement of natural fibre-reinforced thermoplastic composites by funding 16 projects between 2011 and 2024. Research has also been supported by the Natural Sciences and Engineering Research Council of Canada, but via fewer funded projects (11) between 2014 and 2025. Even though there were fewer projects awarded, the financial support shows that there is still interest in creating environmentally friendly composite materials. A definite association is shown when this financing data is contrasted with the trends in publications and citations. Research funding has increased in tandem with the rise in publications and citations, particularly after 2011. Financial assistance from these organizations has been crucial in advancing research in this field, as seen by the largest funding contributions coinciding with the peak in publications and citations seen around 2023. Additionally, funding for this sector is expected to remain until 2025, which might maintain or even boost research output in the years to come. Citation patterns demonstrate that the robust financial support has not only enhanced the quantity of research but also their effect. It is anticipated that future advancements and uses of sustainable composite materials in the automotive sector will be fuelled by sustained investment in this area.

Table 1
Top funding agencies for natural fibre reinforced thermoplastic composites in automotive research.

Funding agencies	Year	No. of funded project
National Natural Science Foundation of China	2013–2025	38
German Research Foundation	2011–2023	27
European Union	2013–2024	26
Federal Ministry of Education Research	2011–2024	16
Natural Sciences and Engineering Research Council of Canada	2014–2025	11

3.1. Journal analysis

The top five most prolific journals in the area of natural fibre-reinforced thermoplastic composites for automotive applications between 2000 and 2025 are thoroughly examined in Table 2. Since it identifies the most significant sources advancing composite materials, this data is essential for researchers hoping to publish in high-impact journals. These journals were chosen based on their impact factor, research category, and overall proportion of articles, indicating their function in sharing important discoveries in this niche field.

A prominent source for interdisciplinary engineering research, especially in composite materials, Composites Part B: Engineering

Table 2
Top five productive journals on natural fiber reinforced thermoplastic composites in automotive in 2000–2025.

Journal	Impact Factor	Category	Total percentage (%)	Total cumulative percentage (%)
Polymer composites	4.8	Materials Science Composites (Q2/10/35) Polymer Science (Q1/17/95)	6.325	6.325
Polymers	4.7	Polymer Science (Q1/19/95)	4.654	10.979
Composites part B engineering	12.7	Engineering, Multidisciplinary (Q1/1/181) Materials science, Composites (Q1/2/35)	4.296	15.275
Journal of thermoplastic composite materials	3.6	Materials science, Composites (Q2/13/35)	3.222	18.497
Composite structures	6.3	Materials science, Composites (Q1/8/35) Mechanics (Q1/9/170)	2.745	21.242

stands out among the listed journals with the greatest impact factor (12.7). The fact that polymer composites and polymers are available further emphasizes how crucial polymer science is to the creation of thermoplastic composites reinforced with natural fibres. These journals are ranked highly in the scientific community because they are in the Q1 and Q2 quartiles. Composites Part B: Engineering is ranked at Q1/1/181, which indicates that it is one of the best engineering and materials science journals. Polymer science, materials science, composites, and mechanics are the main study areas addressed in these publications, demonstrating the field's interdisciplinary character. To improve their appropriateness for automotive applications, the incorporation of natural fibres into thermoplastic composites necessitates a thorough investigation of the material's mechanical performance, thermal stability, and manufacturing methods. The presence of publications in materials science and polymer science on this list indicates that the main goals of this field's research are to improve mechanical characteristics, optimize fibre-matrix interactions, and create high-performance, environmentally friendly composites. Their respective contributions to the discipline are shown by the overall proportion of articles across various journals. Composites Part B: Engineering comes in at 4.296 %, Polymers at 4.654 %, and Polymer Composites at 6.325 %. A considerable amount of research on natural fibre-reinforced thermoplastic composites for automotive applications is published in these five journals, as seen by the cumulative proportion of 21.242 %. This directs researchers to the most appropriate publication platforms by highlighting the concentration of significant findings in a small number of excellent journals. The importance of materials science and polymer engineering in developing sustainable composite materials for automotive applications is highlighted by this research. Natural fibre-reinforced thermoplastics are becoming more popular as businesses seek lightweight, environmentally responsible substitutes for traditional composites because of their advantageous mechanical qualities, affordability, and renewability. The growing significance of this field of study is shown by the strong impact factors and Q1 rankings of a number of the journals in this table, which make them perfect venues for sharing fresh research on composite performance, processing advancements, and sustainability approaches.

3.2. Contribution and collaboration between countries

The contributions and partnerships made by nations worldwide in the area of natural fibre-reinforced thermoplastic composites for automotive applications between 2000 and 2025 are highlighted in Table 3 and Fig. 2. While the collaboration network offers insights into the interconnection of research activities across various countries, the number of total publications for each country shows the amount of interest and commitment in this field of study.

In this category, Germany leads with 154 publications. Extensive research on lightweight, high-performance composite materials has been fuelled by the nation's robust automotive sector, which is represented by firms like BMW, Mercedes-Benz, and Volkswagen [19]. The size of Germany's node on the map in Fig. 2 emphasizes how crucial it is to international cooperation, particularly with France, Italy, Switzerland, and Spain. These collaborations probably focus on industrial-scale composite manufacturing, thermoplastic resin compatibility, and fibre treatment techniques to ensure that natural fibre-reinforced thermoplastic composites meet the demanding requirements of automotive applications. The German study falls into the following areas: Materials Science, Composite Engineering, Polymer Science, and Sustainable Materials study. Collaborations with France and England, among other European countries, indicate a determined attempt to create thermoplastic composites that are strong and biodegradable, which will support the circular economy initiatives and environmental goals of the EU [20]. It is worth noting that funding and publication output are not always directly proportional. For example, although the NSFC funded the largest number of projects (38), Germany leads in publication count with 154 papers. This discrepancy reflects the maturity of Germany's research ecosystem, strong automotive sector, and well-established international collaborations that have enabled more rapid translation of research into publications. By contrast, China's significant funding is relatively recent and reflects an accelerating trajectory in natural fibre composite research, which is expected to further expand its publication output in the coming years.

Table 3
Top countries focus on natural fibre reinforced thermoplastic composites in automotive sector in 2000–2025.

Country	Total publication
Germany	154
USA	100
France	61
China	61
India	48

With 100 papers, the USA comes in second, indicating that this field has robust research. The substantial node size and wide-ranging connections to several nations, such as China, Japan, and Germany, indicate active involvement in global collaboration initiatives. In order to scale up for automotive applications, the USA focuses on high-performance polymer composites, hybrid composite structures, and automated composite production processes. Natural fibre-reinforced thermoplastic composites are now a competitive alternative to traditional synthetic composites thanks to funding from the National Science Foundation for research into biodegradable thermoplastics, improved fibre modifications, and nanocomposite reinforcement. Links with Japan and Canada imply common research in fibre-matrix interactions and mechanical property improvement, while collaborations with China point to possible cooperative efforts in manufacturing scalability and green car materials.

France is a key player in sustainable material advances, especially in the processing of natural fibres and bio-based thermoplastic matrices, as shown by its 61 publications. Fig. 2 illustrates the close ties between France and Germany, Switzerland, and Italy, which are a result of research projects spearheaded by the European Union. Sustainable Materials, Polymer Science, and Circular Economy Research are the primary research areas linked to France. These fields help create environmentally acceptable thermoplastic composites reinforced with natural fibres that have optimal mechanical and thermal qualities.

Government policies that promote environmentally friendly production and lightweight materials for electric vehicles (EVs) have helped China rapidly expand its research in natural fibre reinforced thermoplastic composites, leading to 61 publications to date. Fig. 2 illustrates China's tight linkages to Germany, the US, and other Asian countries like as Japan and Singapore, highlighting global partnerships in composite processing, low-cost fibre treatments, and the integration of automotive components. China is a key player in the introduction of natural fibre reinforced thermoplastic composites into a wide range of automotive applications because of its high-volume production capability and focus on scalable manufacturing techniques. The Made in China 2025 program has supported research on biodegradable polymer composites, hybrid fibre-reinforced structures, and energy-efficient manufacturing techniques. Relationships with the United States suggest knowledge exchange in high-performance composite modelling and simulation, while partnerships with Germany indicate collaborative efforts in industrial applications and advanced composite testing.

With 48 articles, India is a new hub for research on thermoplastic composites reinforced with natural fibres, especially by using its wealth of natural fibre resources including kenaf, jute, and coir. The map in Fig. 2 illustrates India's close ties to Canada, the United States, and Germany, suggesting an increase in international cooperation. Research in India is concentrated on low-cost, high-performance thermoplastic composites reinforced with natural fibres, with an emphasis on

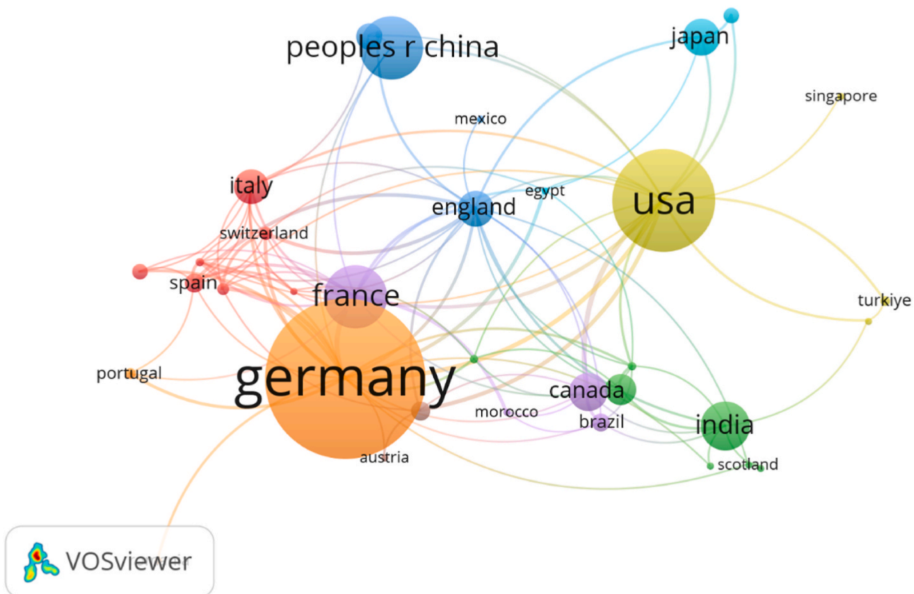

Fig. 2. International collaboration among the top countries (minimum number 20 document per country, excluding the isolated node).

improving thermoplastic resin, optimizing mechanical performance, and modifying the fibre surface. Sustainable composite development has been financed by government-backed programs like the National Bioplastics Mission and Make in India, which are in line with the worldwide trend toward environmentally friendly automotive materials.

To advance natural fibre reinforced thermoplastic composites into commercial automobile applications, Germany, the United States, France, China, and India must work closely together. Fiber treatment methods, the choice of thermoplastic matrix, and composite processing technologies have advanced significantly as a result of collaborative research projects, knowledge-sharing programs, and industry alliances. In vehicle design, these global initiatives guarantee that natural fibre reinforced thermoplastic composites will continue to develop as a high-performance, environmentally friendly substitute for traditional synthetic composites.

3.3. Keywords

A network of keywords pertaining to natural fibre reinforced thermoplastic composites in automotive applications is shown in Fig. 3, which highlights the interrelated research subjects in this area. It is

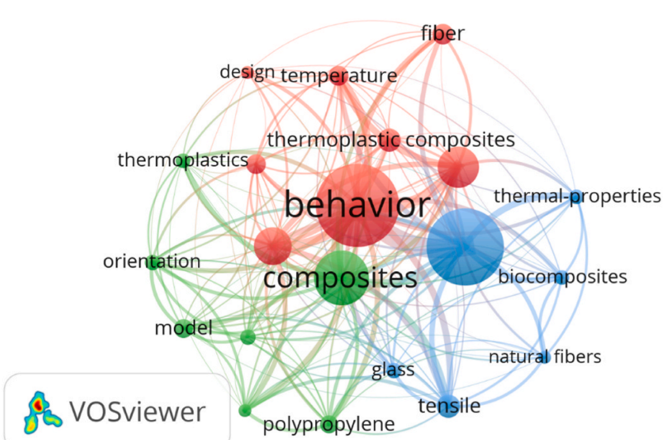

Fig. 3. Network of keywords pertaining to natural fibre reinforced thermoplastic composites in automotive applications (minimum number of occurrences: 20, 25 out of 928 keywords meet the threshold).

made up of many color-coded clusters, each of which represents a separate concentration area. The connecting lines show the co-occurrence correlations between various study areas, while the node sizes show the prevalence of terms.

The fact that the red cluster is focused on the term "behavior" suggests that a significant amount of study is concentrated on the mechanical and thermal performance of thermoplastic composites reinforced with natural fibre. Researchers are examining the effects of fibre reinforcement on the structural characteristics of thermoplastic matrices under various operational and environmental circumstances, as indicated by keywords like "fiber," "thermoplastic composites," and "design temperature." Heat resistance, degradation, and processing conditions are crucial factors in the creation of composite materials, as shown by the existence of "thermal properties." This cluster is mostly related to mechanical engineering, materials science, and polymer physics, with the goal of improving the performance, longevity, and effectiveness of thermoplastic composites reinforced with natural fibres for use in automobiles.

The green cluster is centered on "composites," emphasizing research on polymer selection, fibre orientation, and material formulation. According to terms like "polypropylene," "thermoplastics," and "model," scientists are enhancing fibre-matrix interactions to boost the mechanical and structural soundness of thermoplastic composites reinforced with natural fibres. The fact that "orientation" is present highlights even more how fibre alignment affects tensile strength, stiffness, and impact resistance—all of which are vital characteristics for automotive applications. Natural fibre reinforced thermoplastic composites may be lightweight and structurally strong enough to satisfy industrial standards thanks to this study area, which is especially pertinent to composite engineering, polymer processing, and advanced manufacturing.

The blue cluster, which is focused on "biocomposites," emphasizes the rising need for ecologically friendly and sustainable composite materials. Keywords like "natural fibers," "tensile," and "glass" are used, indicating a significant focus on contrasting natural fibres with synthetic reinforcements like glass fibres. The relationship between "biocomposites" and "thermal properties" suggests that studies are being conducted to examine the performance of bio-based reinforcements in a range of thermal environments, which is essential to their feasibility in automobile parts. This cluster supports the worldwide movement to increase the use of renewable resources in composite production and decrease dependency on synthetic polymers by aligning sustainability science, green chemistry, and eco-friendly materials research.

Research on natural fibre reinforced thermoplastic composites is a multidisciplinary field, as seen by the interactions among these groups. It is suggested that fibre-matrix compatibility and structural design have a major role in composite performance due to the close relationships between the red cluster (mechanical behavior) and the green cluster (material optimization). The blue cluster (biocomposites and sustainability), on the other hand, is connected to both the red and green clusters. This indicates that more research is being done on creating bio-based composites without sacrificing durability or mechanical strength. Research into hybrid composites, which blend natural and manmade materials to strike a balance between sustainability and high-performance applications, is further shown by the connections between "biocomposites," "polypropylene," and "thermal properties."

In summary, the VOSviewer visualization in Fig. 3 highlights the complex research environment surrounding natural fibre reinforced thermoplastic composites in automotive applications, highlighting the interaction of environmental sustainability, material optimization, and mechanical performance. The connections among the clusters show that interdisciplinary research is necessary to create next-generation natural fibre reinforced thermoplastic composites that satisfy ecological and performance standards. This research should integrate knowledge from materials science, polymer engineering, mechanical testing, and environmental sustainability. It is anticipated that future developments in this area would further refine bio-based materials, better processing methods, and expand the general use of thermoplastic composites reinforced with natural fibres in the automotive sector.

4. Natural fibre

The two main categories of fibres are natural and synthetic fibres. All types of fibres that come from either plants or animals are considered natural fibres. They are strong, flexible materials with a high aspect ratio. Natural fibre is a mixture of hollow cellulose fibres that have been gathered by lignin acting as a binder in a hemicellulose matrix. Currently, numerous investigations on the reinforcing of natural fibres using bio-based polymers and synthetic-based polymers have been carried out [21–23]. Natural fibres are readily available from natural sources, are a renewable resource, and have several benefits [24]. For example, they give composite materials a high specific stiffness and strength, have a favourable fibre aspect ratio, and are biodegradable [25]. There are numerous sources for natural fibres. These sources can come from minerals, plants, and animals. Cotton, flax, hemp, bamboo, sisal, and jute are examples of typical plant-based natural fibres. They primarily consist of cellulose. It is worth noting that research extends beyond these common fibres to explore other promising natural resources with unique structures. For instance, fibres from Luffa cylindrica (sponge gourd) have been investigated for their distinct porous network, which offers potential for applications in sound absorption and packaging, as detailed in a dedicated review on luffa fibre composites [26]. Popular fibres like wool, silk, angora, and mohair come from animals. Fig. 4 displays the classification of natural fibres used to fabricate composite laminates.

Natural fibre can also be described as an accumulation of cells having a small diameter relative to their length. Although there are many fibrous materials in nature, particularly cellulosic ones like cotton, wood, grains, and straw, very few of them can be exploited to make textiles or for other industrial uses. A fibre's suitability for commercial usage is influenced by a variety of factors, including its length, strength, pliability, elasticity, resistance to abrasion, absorbency, and other surface characteristics. Most textile fibres are thin, flexible, and rather robust. They are elastic in that when under tension, they will stretch, and when the tension is released, they will partially or entirely return to their original length.

Natural fibres are in high demand across the automotive, construction, electrical, and electronic industries which makes them fiercely competitive. However, the building and automobile industries are the biggest consumers of natural fibre composites. In the automotive industry, it has taken the place of glass fibres as reinforcement and has become a highly appealing alternative [28]. Growing environmental concerns have led to ongoing research into natural fibres and their composites as replacements for synthetic fibres in engineering materials, giving rise to a preference for natural fibre [29]. Compared to glass fibre, natural fibre production can reduce costs by 10–30 % and its composites can further help lower noise levels in cars [29]. Additionally, natural fibre can reduce weight by nearly 30 % compared to synthetic fibre [30].

4.1. Structure of natural fibre

Natural fibre typically contains between 60 and 80 percent cellulose, between 5 and 20 percent lignin or (pectin), and up to 20 percent moisture [6]. Fig. 5 illustrates the primary chemical components of

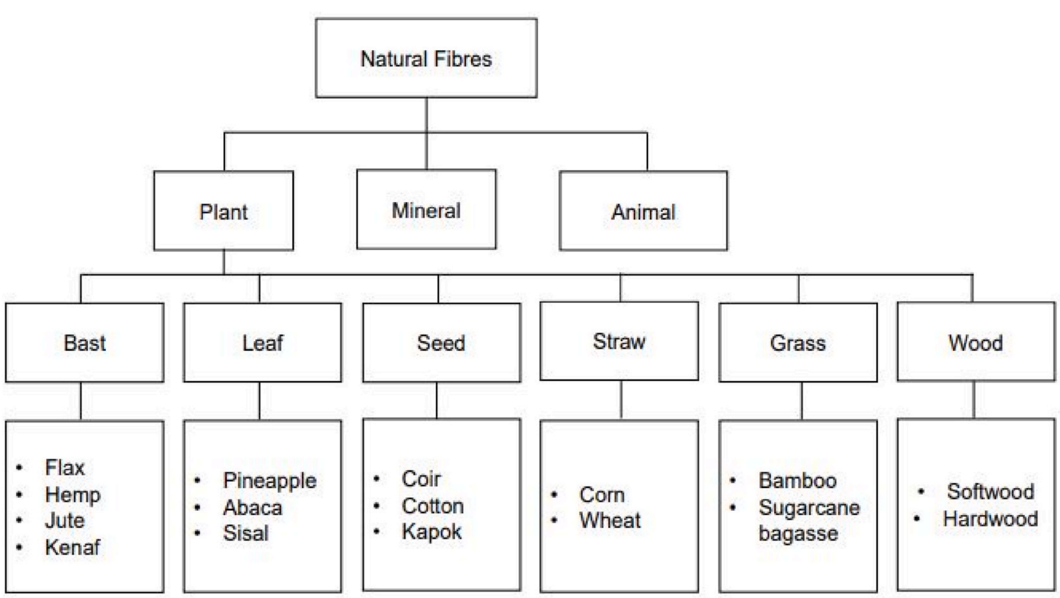

Fig. 4. Type of natural fibres retrieved from Ref. [27].

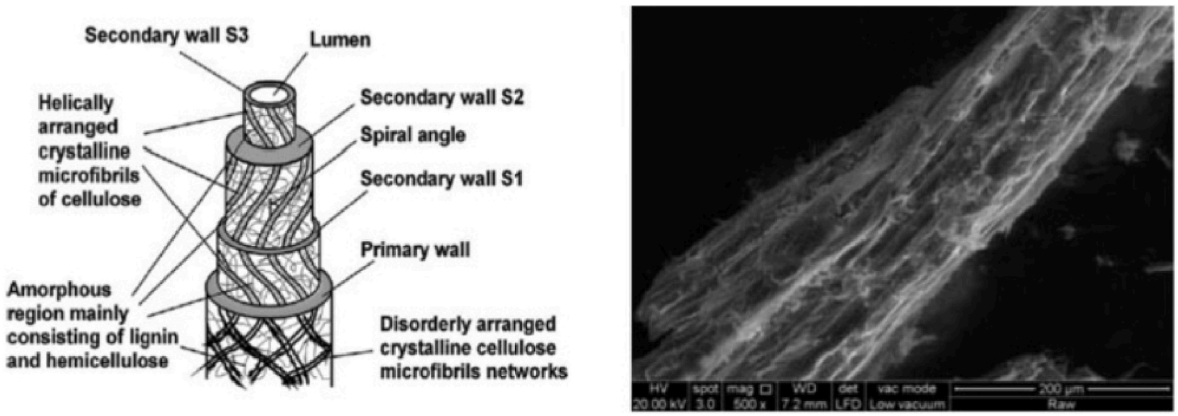

Fig. 5. Structure of natural fibre retrieved from Ref. [33].

natural plant fibres, which are cellulose, hemicellulose, and lignin. In natural fibre, the hemicellulose serves as a reconciler between the cellulose and the lignin [31]. The lignin serves as a water reservoir for the fibre, defends it from biological attack, and stiffens the stem to withstand the effects of gravity and wind. The prolonged chain conformation of the 30- to 100-cellulose molecules in the microfibril attests to the fibre's mechanical strength [32].

The general characteristics of natural fibres are a function of their composition, as detailed in Table 4. Specifically, a high cellulose content (e.g., cotton at 95 %) correlates with superior tensile strength, whereas a high hemicellulose content (e.g., bamboo at 30 %) improves thermal characteristics, biodegradability, and moisture absorption capabilities [34].

4.2. Benefits of natural fibre

It is essential to have a thorough understanding of the characteristics of natural fibres to increase their performance and broaden their applications in the creation of composite materials. The chemical properties, physical characteristics such as fibre size, degree of defect, strength, and structure and mechanical properties all affect how well these fibres work.

Natural fibre has an endless supply because it is made from renewable resources. The amount of carbon dioxide absorbed by the plant during its growth phase and the amount emitted when it decomposes are equal. Natural fibres are therefore carbon neutral which is no carbon emission. It takes in the same volume of carbon dioxide that they do [35]. When compared to the manufacturing of natural fibre, the manufacture of synthetic fibre produces extraordinarily high gas pollutant emissions [36]. Natural fibres have several benefits, which makes as a popular choice in various industrial applications. Natural fibres are derived from renewable resources, such as plants and animals. This makes them a sustainable choice, as they can be produced without depleting finite resources and are biodegradable, reducing environmental impact. Unlike synthetic fibres, natural fibres decompose easily, reducing the burden of non-biodegradable waste in landfills and oceans [37]. Natural fibres, like cotton and linen, allow air to circulate through the fabric, making them comfortable to wear in hot and humid conditions. They help wick moisture away from the body, keeping the wearer cool and dry. Some natural fibres, like wool, are incredibly durable and can last for many years with proper care. They are resistant to wear and tear, making them a good investment in the long run.

As natural fibres are non-abrasive compared to screws and other metallic elements, they aid to prevent tool wear and machine damage that are frequently caused by non-organic fillers, allowing for a higher volume of natural fibres in the polymer matrix. Additionally, neither skin irritation nor injury are caused by the processing. They are also lighter in weight than synthetic fibres as a result [38]. Natural fibres are known for their softness and comfort against the skin. Fabrics like cotton and silk are gentle and non-irritating, making them suitable for sensitive skin. The cultivation and processing of natural fibres generally have a lower environmental impact compared to the production of synthetic fibres, which often involves chemical-intensive processes [39]. Compared to glass fibre composites, the use of natural fibres can reduce component weight by approximately 20–30 %, contributing to improved fuel efficiency and lower energy consumption during vehicle operation [40]. From a cost perspective, natural fibre composites have demonstrated potential savings up to 30 % depending on fibre type and processing route [41]. Furthermore, life cycle assessment (LCA) studies indicate that natural fibre production results in significantly lower CO_2 emissions compared to synthetic fibres, supporting their adoption as eco-friendly alternatives for sustainable automotive design. Table 5 shows the mechanical properties of natural fibres and synthetic fibres.

Table 4
Chemical composition of natural fibre retrieved from Ref. [34].

Fibres	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Waxes (%)
Bamboo	26–43	30	28	–
Banana	64	20	5	–
Cotton	95	2	1	0.4
Flax	70–73	18–20	2	6
Jute	71	14	13	2
Hemp	70	22	6	2
Coir	31–42	10.0–20	40–46	4
Oil Palm	65	–	29	–
Pineapple	80	–	12.8	–
Kenaf	45–57	8.0–13	21.5	0.8
Sisal	73	14	11	2
Ramie	68–76	13–15	1	6

5. Drawback of natural fibre

Although natural fibres are being considered as a possible replacement for synthetic fibres, they have some drawbacks, including a lack of technological advancements in the manufacturing of raw materials, a lack of improved equipment for processing natural fibres, which lowers efficiency and rate of production, and high variability in their mechanical properties (e.g., tensile strength, modulus) due to factors such as plant source, growing conditions, and extraction methods [42]. This inconsistency, along with the incompatibility of the functional groups on the surfaces of natural fibres and the hydrophobic resin systems currently in use for various end-uses [43,44]. At temperatures between 170 and 200 °C, natural fibres can start to deteriorate [45]. This severe thermal constraint significantly limits processing options; it creates a narrow processing window for many matrices and prohibits the use of higher-melting-point polymers like polypropylene (PP) or polyamide (PA) without risking severe fibre degradation. As a result, using natural

Table 5
Mechanical properties of natural fibres as compared to conventional reinforcing fibre retrieved from Ref. [27].

Fibre	Density (g/cm^3)	Elongation (%)	Young Modulus (GPa)	Tensile Strength (MPa)
Cotton	1.5–1.6	3.0–10.0	5.0–12.5	287–597
Jute	1.3–1.46	1.5–1.8	10.0–30.0	393–800
Hemp	1.48	1.6	70	550–900
Ramie	1.5	2.0–3.8	44–128	220–938
Flax	1.4–1.5	1.2–3.2	27.6–80	345–1500
E-glass	2.5	2.5–3.0	70	2000–3500
S-glass	2.5	2.8	86	4570
Sisal	1.33–1.5	2.0–14	9.0–38.0	400–700
Kenaf	1.45	1.6	53	215.4
Coir	1.2	15.0–30.0	4.0–6.0	175–220

fibres as reinforcement in some thermoplastic matrices with high melting temperatures has drawbacks. Many variables, including the absence of consistency in processing and surface treatments, influence the variability in their mechanical properties.

The disadvantages of using and applying natural fibres have been described as being their low wettability and susceptibility to moisture absorption [24,46]. Moisture makes it possible for the final product's dimensions to vary, which weakens the interfacial bond between the fibre and the matrix [47]. Restricted access caused by geographic barriers between countries where natural fibres are grown and countries where they are used as reinforcement in composites production, such as North America, the UK, France, Germany, and Spain, is an often overlooked but significant barrier to the widespread use of natural fibres in composites applications. Poor fibre orientation and aspect ratio, as those observed in natural fibre, result in a composite material with subpar mechanical properties [48].

During manufacture, natural fibres are frequently twisted, which results in poor resin impregnation and consequently poor mechanical properties [48]. The mechanical characteristics of the resultant composites have been observed to be decreased by the presence of vacancy in natural fibres as the void content increases with increased reinforcement [49].

6. Key solution to enhance the properties of natural fibre

6.1. Fibre modifications

6.1.1. Chemical treatments

Hydrophobic polymers are fundamentally incompatible with strongly polarized cellulose fibres. It is frequently possible to achieve compatibility between two incompatible materials by adding a third material that has qualities halfway between the other two. In materials, there are numerous coupling mechanisms. The primary chemical bonding hypothesis does not appear to be sufficient on its own, necessitating the consideration of other ideas, such as the shape of the interface, acid-base reactions at the interface, surface energy, and wetting phenomena.

Challabi et al. [50] state that natural fibres, such as pineapple leaf fibres, possess superior strength and mechanical properties compared to other natural fibres. This makes them suitable for reinforcement in polymer composites [51]. The main drawbacks of natural fibres in composites are their poor compatibility with the matrix and relatively high moisture absorption. Consequently, chemical treatments are being thought of to improve the surface properties of the fibre [52,53]. Many research types have indicated that natural fibre treatments would promote higher attributes, especially in terms of mechanical, thermal, and water barrier properties. The treated fibres have a clean surface without impurities such as ash, wax and pectin, which allows us to see this improvement.

When used to strengthen polymer matrix such as thermoplastic, alkaline treatment, also known as mercerization, is one of the most used chemical processes for natural fibres. The breaking of hydrogen bonds in the network structure caused by alkaline treatment is a significant alteration that raises surface roughness. This process depolymerizes cellulose, exposes the short length crystallites, and eliminates some of the lignin, wax, and oils covering the exterior surface of the fibre cell wall [54]. The ionization of the hydroxyl group to the alkoxide is promoted by the addition of aqueous sodium hydroxide (NaOH) to natural fibre [55].

In the context of exterior automotive applications, where components are frequently subjected to rain, UV exposure, and temperature fluctuations, fibre modifications play a crucial role in enhancing environmental durability. Treatments such as alkaline, silane, or acetylation reduce hydrophilic hydroxyl groups and remove surface impurities, thereby lowering moisture absorption and improving dimensional stability under wet or humid conditions [56,57]. At the same time, improved fibre–matrix adhesion minimizes microvoid formation, which reduces pathways for water penetration and delays UV-induced ageing [58]. Moreover, silane coupling agents and similar treatments strengthen the fibre–matrix interface, enabling better stress transfer and slowing the onset of thermal degradation at elevated temperatures [59]. Collectively, these modifications mitigate the natural vulnerabilities of fibres, moisture sensitivity and limited thermal resistance and thus enhance the long-term reliability of natural fibre-reinforced thermoplastic composites for exterior automotive components.

Chemical compound silane has the formula SiH4. Glass fibres are coupled to a polymer matrix using silanes, which stabilizes the composite material. The amount of cellulose hydroxyl groups at the fibre-matrix interface may be decreased by silane coupling agents [60]. The hydrolysable alkoxy group causes the production of silanols when there is moisture present. When the silanol and fibre hydroxyl groups combine, a stable covalent connection is created with the cell wall and is chemisorbed onto the fibre surface [55]. Because of the covalent interaction between the matrix and the fibre, the hydrocarbon chains provided by the application of silane prevent the fibre from expanding by forming a crosslinked network.

The process of adding an acetyl functional group (CH3COO-) to an organic molecule is known as acetylation. Cellulosic fibres are plasticized via the esterification process known as acetylation of natural fibres. Before the lignocellulosic material is utilized to make fibre, acetic acid (CH3COOH), a chemical byproduct, must be removed from it. The cell wall's polymer hydroxyl groups are replaced chemically with acetyl groups by acetic anhydride (CH3–C(=O)–*O*–C(=O)–CH3), changing the characteristics of these polymers to make them hydrophobic [61]. Natural fibres' tendency to absorb moisture can be lessened by acetylation, which also improves the dimensional stability of composite materials. For use in fibre-reinforced composites, acetylation was utilized to treat the fibre's surface [62,63].

6.1.2. Physical treatments

Although physical processes like stretching, calendaring, thermostreatment, and the creation of hybrid yarns do not alter the chemical makeup of the fibres, they do alter the fibre's structural and surface characteristics, which has an impact on the mechanical attachment to polymers [64].

Physical methods for modifying fibre surface include electric discharge, such as corona and cold plasma treatment. One of the more intriguing methods for surface oxidation activation is corona treatment. It is a procedure that modifies the cellulose fibre's surface energy and, in the case of wood, increases the number of aldehyde groups. Cold plasma treatment, which introduces surface crosslinking while surface energy can increase or decrease, and reactive free radicals and groups can be produced, can produce a variety of surface modifications depending on the type and nature of the gases used [65]. For "non-active" polymer substrates like polystyrene, polyethylene, polypropylene, etc., electric discharge methods are known to be very effective. They are used effectively to modify cellulose fibres, reduce the melt viscosity of cellulose-polyethylene composites, and enhance the mechanical properties of cellulose-polypropylene composites [62,66].

Mercerization, a physical technique for altering cellulose fibre that has been extensively used to cotton products, is another option. Cellulose fibres are subjected to the alkaline process known as mercerization, which depends on the type and concentration of the alkaline solution, its temperature, the length of time it is exposed to the alkali, the material's tensile strength, and any additives. However, it is also feasible to utilize mercerization on natural fibres, and under ideal circumstances, this guarantees an improvement in the tensile qualities and absorption traits.

More recently, advanced deposition techniques like nanospraying have emerged as effective physical treatment methods. For instance, coating fibres with nanocellulose via this method significantly enhances interfacial adhesion. This enhancement is attributed to the large surface area exposed by the nanocellulose coating, the formation of a rigid and stiff network interconnected by hydrogen bonds, and an increase in the overall stiffness of the reinforcement [67].

6.2. Fibre designs in composites

6.2.1. Stacking sequences of natural fibres

Different stacking sequences have an impact on the mechanical properties of hybrid composites [12,68,69]. The quantity, thickness, and weight of each layer all affect the composites' fibre composition. Individually, synthetic fibres are stronger than natural fibres because hybrid composites are made of both natural and synthetic fibres. The mechanical properties of hybrid composites are greatly influenced by the fibre type used [70,71]. The mechanical capabilities of the hybrid composites increased when additional synthetic fibres were added to the composite configurations.

An exemplary case is the stacking sequence involving Kevlar and kenaf. It is demonstrated by research that stacks of Kevlar only have the highest tensile strength, measured at 309.85 MPa. In contrast, stacks of kenaf only have the lowest tensile strength, measured at 67.55 MPa, due to the low strain compatibility of the fibres. However, the combination of kenaf and Kevlar in several stackings shows an increase in tensile strength and modulus strength [72]. Moreover, Sujon et al. [73] conducted the experimental investigation of the mechanical and water absorption properties on fibre stacking sequence and orientation of jute/carbon polymer hybrid composites [73]. Experimental results revealed that fibre orientation and stacking sequence of the fibre layers have a significant influence on the mechanical properties of the composite materials. Furthermore, Selver et al. [74] investigated the impact and post-impact behaviour of glass and glass/natural fibre hybrid composites with various stacking sequences. It was also observed that natural and hybrid composites absorbed more energy than that of glass composites between 20 and 40 J [74].

6.2.2. Hybridisation with synthetic fibre

Hybridization is one way to improve their mechanical performance and expand their applications. Research on natural fibre-reinforced hybrid composites with one or more forms of natural or synthetic reinforcement is becoming more popular [75]. The primary factors governing the mechanical properties of hybrid composites are the vol/wt ratio of the fibres, the stacking order of the fibre layers, the type of fibres, and the impact of environmental factors [76–79]. The resulting combination may lead to either a synergistic enhancement or a reduction in properties, depending on the compatibility and arrangement of the fibres. Typically, hybrid fibres can be configured in one of three main ways: (1) interlayer, (2) yarn-by-yarn, and (3) fibre-by-fibre, as illustrated in Fig. 6.

Hybrid composites combine two or more fibres within a polymer matrix. The primary goal of hybridization is to create a synergistic blend of mechanical properties, such as stiffness, ductility, and strength, that cannot be achieved with single fibre reinforced composites. As a result of these enhanced properties and their inherent advantages, which include low cost, a high strength to weight ratio, and simple manufacturability, hybrid composites have a wide range of uses in engineering [81]. Notably, a natural fibre reinforced hybrid composite can achieve strength and stiffness properties that are competitive with glass fibre reinforced composites [30].

Fig. 7 shows a variety of samples of stacking order of laminates using PLA film, woven kenaf (WK) and woven polyester (WP) done by Das et al. [82]. It is to determine the effect of stacking sequence and fibre content on mechanical and morphological properties of woven kenaf/polyester fibre reinforced polylactic acid (PLA) hybrid laminated composites. The PLA film, polyester fabric, and woven kenaf were cut into 200 mm × 200 mm pieces based on the mould size.

Figs. 8 and 9 depict the tensile strength and elongation at break produced by all the specimens. S4 and S8 produce significantly higher tensile strength than the rest. S8 has the highest because it uses mainly the woven polyester as for the stacking sequences while S4 uses one layer of kenaf woven for stacking sequences. S7 also produce high tensile strength at 60 MPa mainly only using woven kenaf. This finding substantiates the capability of natural fibres to achieve high tensile strength. Consequently, it is evident that the hybridization of natural fibres with other composite fibres can yield superior mechanical results.

From research, the woven kenaf/Kevlar hybrid laminated composites had improved the impact properties of the composites by up to 46 % [72]. The tensile property of hybrid composites showed an increment with the increment content of synthetic fibres (woven Kevlar) in the composite composition. Moreover, the result from the previous works has shown that laminated composites with synthetic fibre at the outermost layer exhibited higher tensile and flexural properties than when positioned in the interior layers [82].

These results revealed that the type of fibres, fibre content, and stacking sequences would influence the mechanical properties of the hybrid laminated composites. Besides that, the stacking sequence of woven jute/glass fabric reinforced polyester hybrid composites increased the flexural and interlaminar shear strength by 6.7 % and 21.2 %, respectively [84].

Another example of hybridization is between glass fibre and kenaf fibre. From past research, pure kenaf mat/polymer composite showed the lowest tensile strength and modulus, which were 35.8 MPa and 3.6 GPa, respectively [75]. However, after hybridization with glass and carbon fibre, the result from the experiment show it has the highest tensile strength and modulus (225 MPa and 21.5 GPa) compared to kenaf mat/glass/polymer composite, which had 203 MPa and 13.5 GPa tensile strength and modulus, respectively [75].

7. Thermoplastic matrix

Thermoplastic polymers have gained popularity as matrix materials for fibre-reinforced composites due to several advantages over thermosetting resins. Their ability to soften and be reshaped when heated offers excellent reprocessability, impact resistance, and environmental durability [85]. Moreover, their notable fracture toughness and shorter processing times make them well-suited for applications requiring rapid production and recyclability. While polymers are primarily categorized

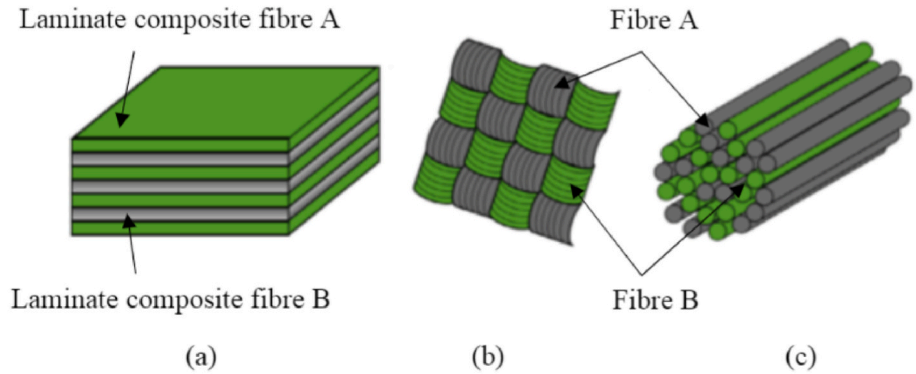

Fig. 6. Hybrid fibre configurations: (a) interlayer; (b) yarn-by-yarn; and (c) fibre by-fibre (Adapted with copyright permission from Swolf et al. [80]).

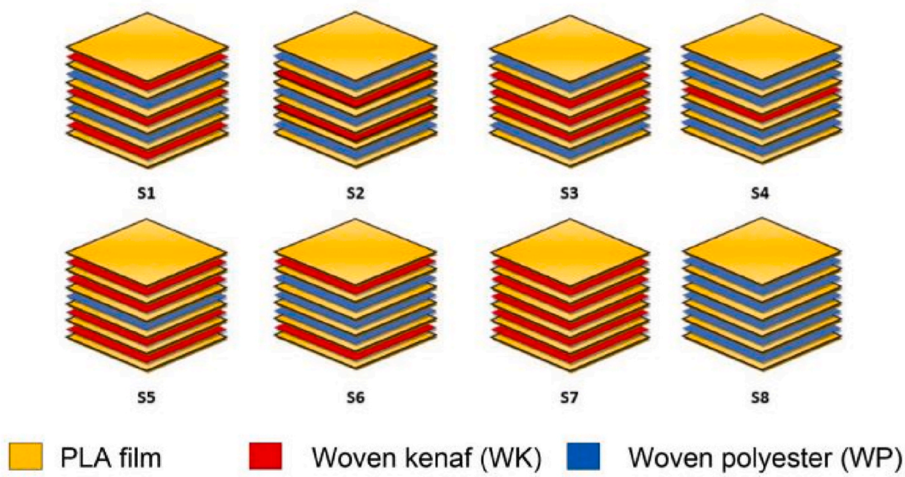

Fig. 7. Example of hybridization retrieved from Das et al. [82].

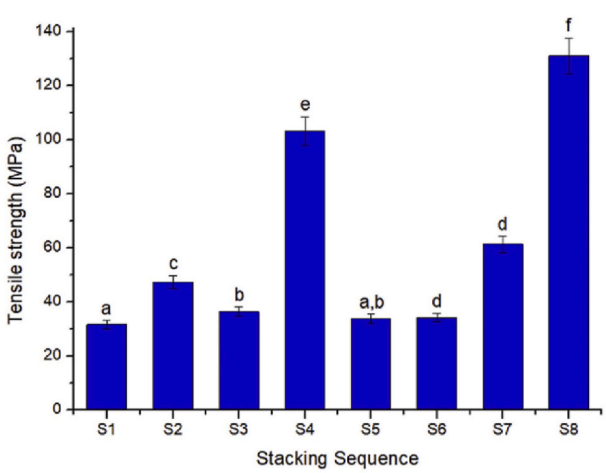

Fig. 8. Tensile strength against stacking sequences retrieved from Ref. [83].

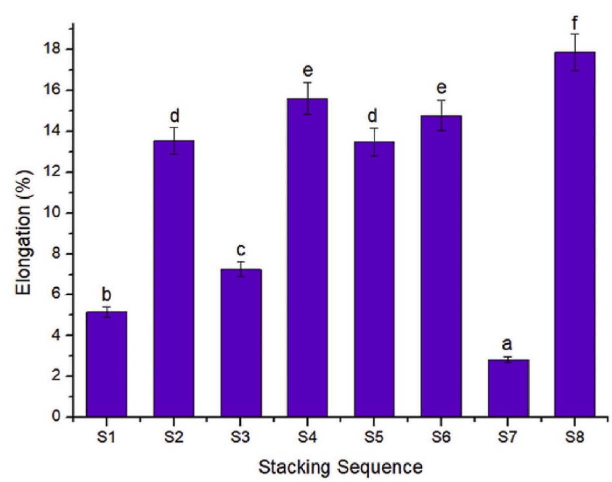

Fig. 9. Elongation against stacking sequences retrieved from Ref. [83].

into thermosets and thermoplastics, other matrix materials such as biopolymers and elastomers are also utilized in composite manufacturing, each offering distinct properties and processing characteristics [86,87]. The classification of various thermosets and thermoplastics is displayed in Fig. 10.

Thermoplastics can be softened and melted upon heating, enabling faster manufacturing compared to thermoset materials. They exhibit superior ductility and impact resistance and can be joined through various welding techniques. Thermoplastic matrices offer key advantages in processability and recyclability [89]. Unlike thermosets, which harden permanently, thermoplastics can be remoulded and reprocessed using heat. This not only simplifies manufacturing techniques like injection moulding, compression moulding, and thermoforming, but also supports material recovery and reuse at end-of-life. Table 6 summarises the common characteristics of each type of matrix.

The properties of thermoplastic matrix composites depend

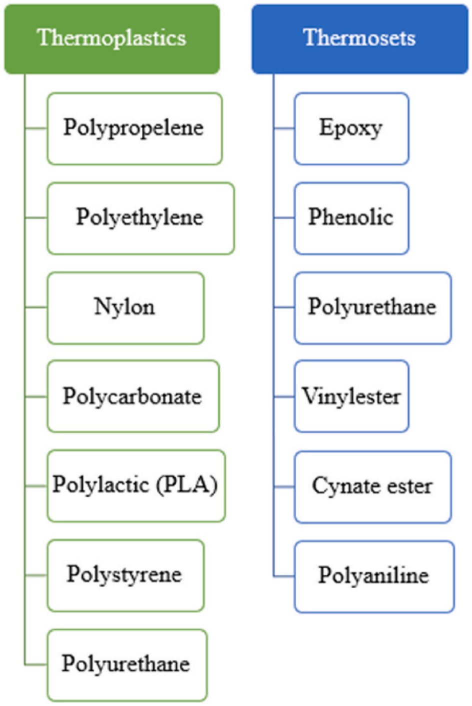

Fig. 10. Type of thermoplastics and thermosets materials [88].

significantly on the choice of matrix and fibre reinforcements, with natural fibres often preferred for their cost-effectiveness. In general, the volume of the matrix inside the composite depends on how the fibres are arranged and affect the matrix's volume fraction rate. However, regarding the fabrication features, the maximum volume fraction of fibres ranges from 50 % to 65 % [91]. One of the essential mechanical characteristics limiting the use of engineering materials is tensile strength. Many efforts have been undertaken in recent years to combine the mechanical properties of composite materials to reduce fabrication costs, eliminate internal flaws, and increase lifetime service.

In the automotive sector, short, randomly oriented fibres are commonly employed; however, this may affect the composite's isotropy. The incorporation of fibres and fillers into thermoplastic matrices enhances mechanical strength, improves thermal stability, and reduces mould shrinkage, making these composites ideal for a broad range of automotive applications. The combination of high mechanical performance and recyclability positions these composites as a sustainable alternative to traditional materials, addressing increasing environmental demands.

8. Manufacturing techniques

The fabrication of natural fibre reinforced thermoplastic polymer composites involves diverse methods such as film stacking and compression moulding, each with specific processing parameters that strongly influence the mechanical performance. Processing pressure plays a vital role in achieving optimal fibre-matrix adhesion while minimising issues like fibre relaxation and shrinkage. Similarly, compaction temperature is critical; higher temperatures generally improve the flexural modulus, although excessive heat can degrade mechanical properties if not carefully controlled. The mechanical and thermal performance of thermoplastic PPCs is influenced by factors including the polymer's molecular weight, morphology, and the fabrication technique employed. As noted by Qiao et al. [92], thermal stability is particularly important for applications involving elevated temperatures, with processing methods directly affecting the final properties, as summarised in Table 7. Moving beyond these methods, Thermoplastic Resin Transfer Moulding (T-RTM or TP-RTM) has emerged as a technique that offers enhanced control over these critical parameters. This process is an adaptation of the conventional Resin Transfer Moulding (RTM) technique, originally conceived for thermosetting matrices, but instead utilizes low-viscosity reactive thermoplastic systems [84]. In TP-RTM, a mixture of monomers and/or oligomers, combined with a catalyst and often an activator, is injected into a closed mould containing a dry reinforcement preform. The key differentiator is that the polymerization reaction occurs in situ within the mould, forming the high-molecular-weight thermoplastic matrix and resulting in the final composite part in a single-step synthesis [85]. This technique allows for the use of various reinforcements, including thick fibres and 3D structures, and enables the production of large, complex geometry parts with good fibre impregnation, controlled fibre volume fraction, and a reduced number of voids [85].

9. Mechanical properties

Natural fibre-reinforced polymer composites offer numerous mechanical advantages, making them promising materials for a variety of engineering applications. These composites are characterised by high specific strength, low density, renewability, good stiffness, and flexibility. Additionally, they are biodegradable, cost-effective, widely available, and exhibit low energy consumption during processing as well as minimal abrasiveness [93–95]. As many natural fibres are derived from agricultural waste, particularly in Malaysia and other Asian countries, their use contributes to environmental sustainability [53,96]. Table 8 summarises recent studies focusing on the mechanical performance in particularly tensile, flexural, and impact properties of chemically treated natural fibre-reinforced polymer composites.

Polylactic acid (PLA), a biodegradable thermoplastic, has garnered considerable interest due to its potential to replace conventional petroleum-based polymers such as polypropylene (PP). Unlike PP, PLA allows for the development of fully biodegradable composites without the need for chemical modifications. While PP has been extensively used as a matrix in abaca fibre-reinforced composites, PLA has also been explored for the same purpose, although studies on PLA/LAF composites

Table 6
Common properties of thermoplastic and thermoset resins [90].

Matrix type	Polymer	Tensile strength (MPa)	Tensile modulus (GPa)	Flexural strength (MPa)	Flexural modulus (GPa)	Young's modulus (GPa)	Impact (J/m)	Elongation (%)
Thermoplastic	PP	26–41.4	0.95–1.78	55.2	0.83–1.73	0.3–1.7	20–267	15–700
	HDPE	14.5–38	0.41–1.49	13.8–48.3	0.41–1.38	0.6–1.1	20–1068	12–800
	PEEK	70–103.5	3.1–3.8	110–110.4	2.8–3.9	3.7	120	50
	ABS	40	2.2	97	2.1	2.59	138	90–130
	PPS	65.6–901	2.6–3.9	96–151	3.4–4.1	3.90	10.7–133	1.1–6.0
	PEI	103.5–104.9	3.0	144.9–151.8	3.0–3.5	–	53.4–133	6–60
Thermoset	Polyester	20–105	2.1–3.5	53.8–265	0.36–16	1–16	0.3 0–0.45	0.5–3.3
	Vinyl ester	73–85	3.0–3.5	125–150	3.5	2.7	0.16	5.0–6.0
	Epoxies	55–130	2.7–4.1	80	1.5	2.4	0.18	4.5

Table 7
Key characteristics, limitations, and the extent of processing parameter research across various fabrication techniques for thermoplastic composites [92].

Fabrication Method	Main Features	Drawbacks	Parameters Investigation
Film stacking without filament winding	• Popularity • Ease of fabrication	• V_f is sensitive to matrix film thickness	• Many studies on temperature, pressure, time, and cooling rate
Film stacking after filament winding	• Popularity • Mostly used for unidirectional composites	• V_f is sensitive to matrix film thickness	• Many studies on temperature, pressure, time, and cooling rate
Hot pressing after powder impregnation	• Relatively less used	• V_f is sensitive to impregnation time and powder size	• Few studies on temperature, impregnation time, and reprocessing
Hot pressing after solution impregnation	• Relatively less used • Good impregnation due to low matrix viscosity	• Additional chemicals • Removal of chemical after impregnation	• Few studies on temperature • Less studies on others
Hot pressing after matrix melts impregnation (infusion)	• Relatively less used	• Impregnations extend and V_f depend on matrix viscosity and flow	• Few studies on temperature • Less studies on others
Injection moulding of matrix with or without hot pressing	• Often used for composites • Suitable for complex and large composite structures	• Requires advanced injection machine • Complicated process • More processing parameters	• Some studies on injection temperature, speed, and time
Fibers intermingling with hot pressing	• Relatively less used • Better distribution of matrix around fibres	• V_f depends on intermingled polymer fibres as matrix	• Lack of studies on different processing parameters
Hot compaction using polymer fabrics only	• Popularity • One type of polymer used (better for recycling) • High V_f • Better fibre/matrix bonding	• V_f is sensitive to compaction temperature	• Many studies on temperature, pressure, time, and cooling rate
Hot compaction using composite films with matrices and fabrics	• Popularity • Commercialization • Better for recycling • High V_f • Better fibre/matrix bonding	• V_f is sensitive to compaction temperature • Potential of worse bonding between composite films	• Many studies on compacted temperature, pressure, time, and cooling rate
Additive manufacturing via fused deposition method	• Relatively new • Design flexibility • Energy saving • Complex structures	• Time consuming • Void fraction	• Very limited data on printing parameters due to extremely less studies

Table 8
Mechanical properties of various natural fibre reinforced thermoplastic composites.

Fibre loading (%)	Natural Fibre	Matrix	Fabrication Process	Flexural		Tensile		Impact	(a) Ref.
				Strength (MPa)	Modulus (GPa)	Strength (MPa)	Modulus (GPa)	Strength (f) (kJ/m^2)(g)	
30 %	Wood	Polypropylene	Pelletizing and injection moulding	3.25	32	2.6	58	2.8	[97]
50 %	Abaca	Polypropylene	Injection moulding	82	–	76	–	4.6	[98]
30 %	Abaca	Polylactic acid	Injection moulding	124	7.89	74	8.03	5.3	[99]
30 %	Talc	Polypropylene	Pelletizing and injection moulding	3.6	25	3.3	49	2.9	[97]
30 %	Jackfruit wood sawdust	ABS	Extruding and injection moulding	1.36	27.95	2.14	48.53	50.62	[100]
25 %	*Anogeissus leiocarpus* sawdust	rPET	Extruding and injection moulding	–	–	0.482	2.89	2.82	[101]
12.5 %	Kenaf	PET	Hybrid with glass fibre with 12.5 % using compression moulding	13	1.4	–	–	–	[102]

remain relatively limited.

Jaszkiewicz et al. [103] compared PLA and PP composites reinforced with lignocellulosic abaca, man-made cellulose, and glass fibres at 30 wt % fibre content. They found that PLA-based composites demonstrated superior tensile strength, but inferior impact strength compared to their PP counterparts, regardless of fibre type. Overall, abaca fibre composites exhibited lower mechanical performance than those reinforced with man-made cellulose or glass fibres. In a similar investigation, Bledzki et al. [99] evaluated PLA and PP composites reinforced with abaca fibre. Their findings confirmed that PLA-based composites generally outperformed PP-based ones. Specifically, the incorporation of 30 wt% abaca fibre into PLA increased tensile and flexural strengths by 17.46 % and 13.76 %, respectively. The impact strength of abaca fibre/PLA composites was also notably higher about 140.91 % greater which than that of neat PLA.

Further studies by Oladejo and Omoniyi [101]. assessed the mechanical performance of recycled polyethylene terephthalate (rPET) composites reinforced with Anogeissus leiocarpus sawdust. Different weight ratios of sawdust to rPET were examined, ranging from 1:1 to 1:5. The highest values for modulus of rupture (3.86 MPa), modulus of elasticity (642 MPa), and impact strength (42.33 J/m^2) were achieved at the 1:5 ratio. In contrast, the lowest values as such 1.81 MPa (modulus of resilience), 201 MPa (modulus of elasticity), and 14.11 J/m^2 (impact strength) that were observed at the 1:1 ratio.

Yu et al. [97] explored the mechanical behaviour of injection-molded polypropylene composites reinforced with lignocellulosic wood fibres at various loadings and compared them to conventional PP/talc composites used in automotive applications. Results showed that the highest tensile and bending strengths were attained at 30 wt% wood fibre content as displayed in Fig. 11. Notably, PP/wood fibre composites exhibited comparable mechanical properties to PP/talc composites, supporting the viability of natural alternatives in automotive components.

Phung et al. [100] investigated acrylonitrile butadiene styrene (ABS) composites reinforced with jackfruit wood sawdust in loadings ranging from 0 to 30 wt%. Young's modulus improved by 19 % with an increase in sawdust loading up to 25 wt% but showed a sharp decline beyond this point. Similarly, flexural modulus remained relatively unchanged between 10 and 25 wt% but dropped significantly with 30 wt% loading. Flexural strength decreased by 67 % as sawdust content rose from 0 to 30 wt%, and elongation declined by 70 %. Tensile strength showed variable trends, while impact strength decreased by 15 % between 0 and 20 wt% loading, then slightly increased by 2.3 % up to 30 wt%. From morphological surface analysis as shown in Fig. 12, they revealed that increased sawdust content led to microcracks and rough fracture surfaces due to stress concentrations and weak interfacial bonding. However, the incorporation of maleic anhydride polyethylene (MAPE) as a compatibilizer improved interfacial adhesion through hydrogen bonding and interaction with the ABS matrix.

Tamrakar et al. [102] examined hybrid polyethylene terephthalate (PET) composites reinforced with kenaf and glass fibres for underbody shield applications. The composites included all-glass (25 wt%), all-kenaf (25 wt%), and hybrid formulations (12.5 wt% of each fibre type), bonded with Acrodur® resin. Mechanical testing was conducted under dry and saturated conditions at ambient (23 °C) and elevated temperatures (70 °C). In dry conditions, hybrid composites with kenaf fibre showed higher flexural modulus and strength than the all-glass composite. After water saturation, although the mechanical properties of natural fibre composites were reduced, they remained comparable to those of saturated all-glass composites. Exposure to 70 °C significantly deteriorated performance, with modulus values decreasing by approximately 55 % in natural fibre-reinforced systems. However, freeze-thaw cycles and extended freezing did not affect performance. Interestingly, after re-drying, all composites showed improved flexural strength, attributed to increased crosslinking within the Acrodur matrix. Additional testing confirmed that kenaf fibres could effectively replace glass fibres without compromising acoustic or structural performance. While this review has focused on experimental characterisation, the predictive modelling of these properties through numerical techniques like Finite Element Analysis (FEA) presents a significant opportunity to reduce developmental time and reliance on empirical methods [104].

10. Development and advances of natural fibre composites in automotive manufacturing

Recently, interest in natural fibre-based composites has increased. Biodegradability, low cost, superior thermal properties, low density, comparable specific mechanical properties, recyclability, high toughness, lower energy consumption, non-irritation to the skin, reduced tool wear, and carbon dioxide sequestration are benefits of natural fibres over conventional reinforcement [10]. This means that natural-based composites can be used as a substitution for the material in automotive manufacturing. In addition, the effective utilization of raw natural fibres as indispensable component in polymers for developing novel low-cost eco-friendly composites with properties such as acceptable specific strength, low density, high toughness, good thermal properties, and biodegradability is one of the most rapidly emerging fields of research in polymer engineering and science. In fact, raw natural fibre–reinforced composites are the subject of numerous scientific and research projects, as well as many commercial programs. Keeping in mind the immense advantages of raw natural fibres, in the present article they concisely review raw natural fibre/polymer matrix composites with particular focus on their mechanical properties [105,106].

Researchers and manufacturers have been actively exploring different types of natural fibres to determine their suitability for specific automotive applications. Factors like strength, stiffness, density, and availability play a crucial role in selecting the right natural fibre for a particular use. Researchers have been developing hybrid composites that combine natural fibres with other reinforcing materials like glass fibres or carbon fibres. This approach can enhance the overall performance and tailor the properties of the composite to meet specific automotive requirements [107].

A study examines the structural design and assessment of a vehicle bonnet constructed from bio-composite material derived from flax plant fibres. The impact test results demonstrate the appropriateness of these fibres for bonnet fabrication. Moreover, these fibres yield lightweight components and enhanced compression characteristics. Mechanical investigations were conducted on specimens exposed to different moisture conditions throughout seven natural fibres (jute, coir, kenaf, flax, abaca, sisal, hemp). The results derived from these fibres indicate significant promises for automotive applications. The analysis reveals that the alkalization of fibres might compromise fibre strength and lead to inferior mechanical qualities [108].

A previous study was conducted by Lee et al. [109] produced long kenaf fibre/polylactic acid composites via a carding and punching technique, subsequently employing hot compression moulding. The application of the coupling agent markedly enhanced the adhesion of the fibre matrix. Consequently, an enhancement in flexural strength was noted. The 50 wt% kenaf fibre composites exhibited a flexural strength of 70 MPa. Meanwhile study by Bernard et al. [110] investigated the processing parameters that contribute to the improvement of mechanical properties in kenaf fibre reinforced polypropylene composites. The composites were produced through a compression moulding technique, employing various operating temperatures and barrel speeds. Remarkable mechanical properties were observed for the composites produced at a temperature of 230 °C and a barrel speed of 16 Hz. Hence, the advancement of natural fibre composite materials should emphasize insights, selective assembly, and interchangeability. While natural fibre

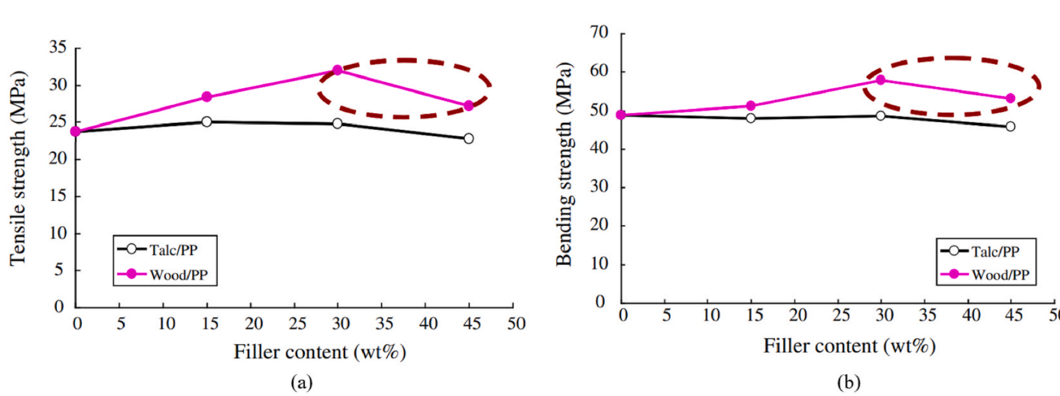

Fig. 11. (a) Tensile and (b) bending strength of PP/lignocellulosic wood and PP/talc composites [97].

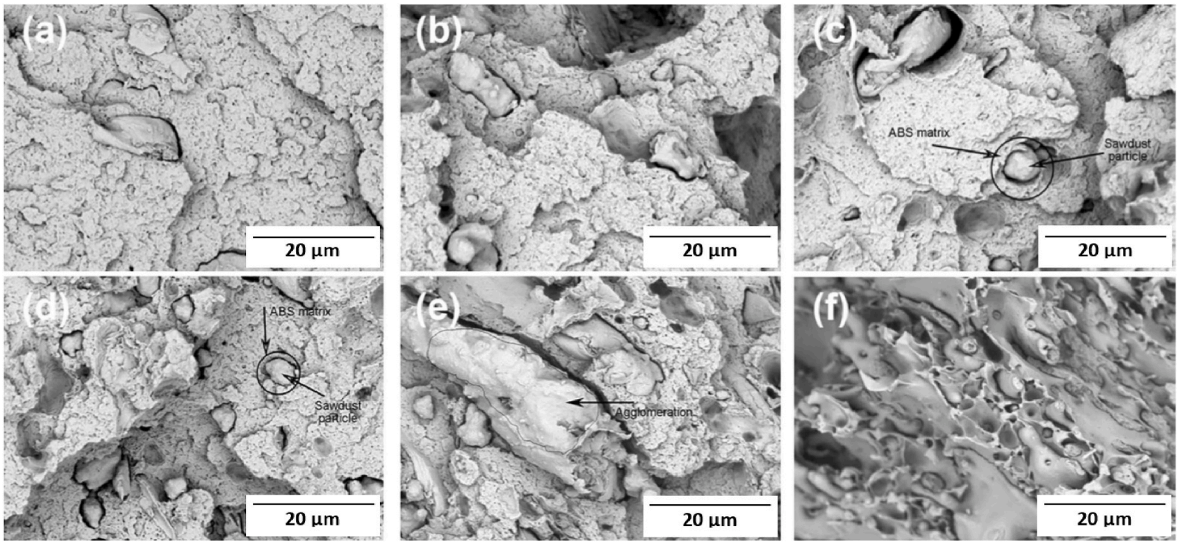

Fig. 12. SEM analysis of impact fracture surfaces of (a) ABS, (b) 10 wt% sawdust/ABS, (c) 15 wt% sawdust/ABS, (d) 20 wt% sawdust/ABS, (e) 25 wt% sawdust/ABS, and (f) 30 wt% sawdust/ABS composites at 2000 × magnification [100].

composites are still in the developmental phase, future efforts should focus on standardization through experimental methodologies, careful selection of fibres and matrices, and enhancing the reusability of these composites.

The development of car parts using natural fibre-reinforced composites has been accepted by the automotive sectors, including Cambridge Industry in the USA, Proton Company in Malaysia, and German automakers [111]. However, the extensive use of natural fibre in automobile interiors has been constrained by the high mechanical performance requirements placed on external vehicle components like bumper beams. Against all obstacles, German automakers are working to make sure that every part of the car is made of recyclable or biodegradable materials. Natural fibre composites have been used in the construction of automotive interior and exterior components with the dual purpose of reducing vehicle weight and enhancing the manufacturing process' sustainability. The inexpensive cost of materials, sustainability, and low density relative to glass fibre are the main benefits of employing natural fibres in composites [112]. Moreover, natural fibre composites have been used in automotive interiors to reduce noise, vibration, and harshness levels. They provide acoustic insulation and a comfortable cabin environment for passengers [28].

A previous study by Manimaran et al. [113] investigates the fibre that is generated from the bark of the *Azadirachta indica* plant and carry out an analysis of its physical and chemical properties. Based on the findings, it can be concluded that these fibres are an excellent choice for composite materials, particularly for use in the automotive technology sector. The composite material is reasonably safe, stable, and lightweight, according to the findings of a structural analysis that was performed on an automotive hood that was made from natural flax fibre using commercial analytical software [114]. Kim et al. utilize pineapple and cassava flour fortified with poly lactic acid (PLA) and polybutylene succinate (PBS) to investigate volatile organic compound emissions. The outcomes are juxtaposed with polypropylene and polyethylene polymers. The findings indicate a substantial decrease in odour emissions with pineapple, cassava/PLA, and PBS-based composites, making this characteristic highly appropriate for the design of car interior components.

Natural fibre polymer composites are finding more sophisticated uses in the field of automobile engineering. The most alluring nanomaterial for high-performance applications is nanocellulose, which may be separated from natural fibre due to the growing need for sophisticated materials with customized physical and mechanical qualities. Vehicles that are lighter in weight will use less fuel, which will cut carbon dioxide emissions. Brazilian automakers Ford, General Motors, Volkswagen, and Honda have already started using natural fibre biocomposites in their automobile seats, dashboard coverings, and trunk lids. In the Ford flex quarter trim panel, cover line assembly, and storage bin, 20 % of wheat straw natural fibre reinforced polypropylene (PP) polymer matrix is shown in Fig. 13. Despite these advancements, challenges remain, such as ensuring consistent quality, addressing moisture sensitivity, and reducing costs associated with natural fibre composites. However, with ongoing research and development, natural fibre composites are likely to play an increasingly significant role in the automotive industry's journey toward sustainability and reduced environmental impact [3].

Biocomposites must have desirable features such as high-quality performance, durability and reliability standards like those in common petroleum plastics used, particularly in automotive applications, to replace glass fibre reinforced plastic and grow into other commercial uses. Demands for lightweight car parts and good end-of-life disposal practices have unintentionally created a pathway for lowering fuel consumption and, consequently, greenhouse gas emissions. In addition, these natural fibre reinforced polymer matrix materials are anticipated to be used by major automakers in Europe, Korea, the United States, Japan, and Brazil to improve weight reduction, processing effectiveness, and mechanical qualities. The automotive sector uses a variety of natural fibre reinforced polymer composites, as shown in Table 9.

11. Current usage of natural fibre reinforced polymer composites in exterior body applications

As the foundation of the automotive industry, car parts have assumed an increasingly significant role. The automobile industry in general will become more competitive thanks to the auto parts sector. The selection of materials for these components is therefore critical, influencing vehicle performance, weight, and cost. The development of adjacent product industries, such as a number of the steel, instrument, plastic, and glass industries, can be aided by the auto components industry's high permeability with other industries. Auto parts make up around 50 % of the value chain in the global automobile sector [116]. With the global procurement of automobile businesses, the auto parts sector, which is the most significant component of the automobile industry chain and is at the top of the chain, has seen an increase in competition [116]. To provide a clear overview of the various automotive parts and

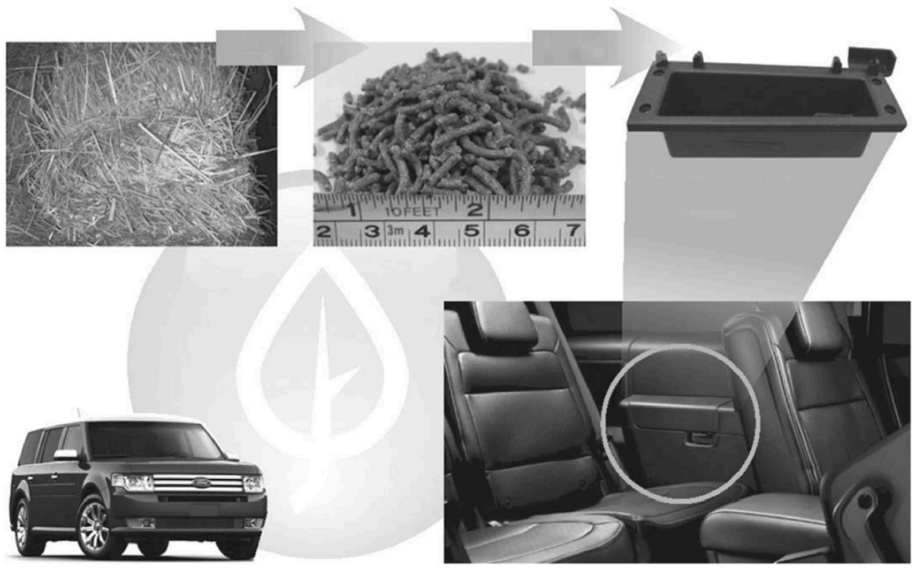

Fig. 13. Car part made from natural fibre [112].

Table 9
The application of NFPC in the automotive industry [115].

Country	Manufacturer	Model	Application
France	Peugeot	406	Front and rear door panels, seat backs, and parcel shelf
France	Citroen	C3 Picasso, C5	Parcel shelves, boot linings, door panels, interior door paneling, and mud guards
Germany	Opel	Vectra, Astra, Zafira	Door panels, pillar cover panel, head-liner panel, and instrumental panel
Germany	Volkswagen	Passat Variant, Golf, A4, Bora	Seat back, door panel, boot-lid finish panel, and boot liner
Germany	Audi	A2, A3, A4, A4Avant, A6, A8, Roadstar, Coupe	Boot liner, spare tire lining, side and back door panels, seat back, and hat rack
Germany	Daimler	A, C, E, and S class	Pillar cover panel, door panels, car windshield/car dashboard, and business table
Germany	BMW	3, 5, and 7 series and other Pilots	Seat back, headliner panel, boot lining, door panels, noise insulation panels, and molded foot well linings

their function, Table 10 below depicts a summary view on automotive components.

As mentioned in the introduction, the material for the automotive part is currently shifting from metal to plastic composite due to the properties of the material being much better in terms of performance. As seen in Fig. 14, the percentage of plastics in vehicles has steadily increased from 1970 to 2020, while the use of metals has correspondingly decreased. This trend underscores the industry’s move towards the materials like NFPCs to meet fuel efficiency and environmental goals.

The selection of materials for automotive exterior parts is governed by a range of critical criteria, including durability, ease of manufacture, and thermal, chemical, and mechanical resistance [117]. While automobiles are made from a variety of substances, aluminium, polymers, and carbon fibre composites are among the primary materials used for these components. For instance, the exterior parts made of composites are prized for being lighter, safer, and more fuel-efficient. A composite material, typically consisting of high-performance fibres like carbon or glass embedded in a polymer matrix, offers properties superior to its individual constituents [117]. The stiffness and strength of carbon fibre composites are on par with or better than steel. They also don’t corrode or rust like steel or aluminium, and by making vehicles lighter, they might greatly improve fuel efficiency [118]. The body of the car may weigh less if aluminium were used. Recent research has revealed that

Table 10
Automotive component summary.

Automotive component	Description	Example
The chassis	The chassis of an automobile incorporates all the major assemblies consisting of an engine, components of transmission system such as clutch, gearbox, propeller shaft, axles, a control system such as brakes and steering, and suspension system of the vehicle.	monocoque chassis, ladder frame chassis, backbone chassis
The engine	The engine is the source of motive power for an automobile. Obviously, it is a very important part of the automobile because in the absence of an engine, the automobile may not move at all, and its basic function of transporting passengers or goods would be defeated.	engine block, engine valve, crank shaft, water pump, piston, combustion chamber
The transmission system	The transmission system transmits power developed by the engine to the road wheels. The power available as output from the engine is in the form of rotation of the crankshaft.	clutch, gearbox, differential, axle
The interior	The car interior is the inner components inside a vehicle that drivers and passengers feel when they sit inside a car. They are major safety features. They are also offering incentives for the right decision.	seat fabric, sun visor, assist grip, luggage trim, rear shelf, toolbox, box for underfloor storage, tonneau cover, dashboard silencer, hardwood floor, floor carpet, clutch pedal, brake pedal, gas pedal, parking or emergency brake speedometer, airbag, gear selector, vehicle audio system
The exterior	The car exterior is the outer components outside a vehicle.	rear bumper, side mirror, wiper blade, front bumper, indicators, door, window glass, car spoiler

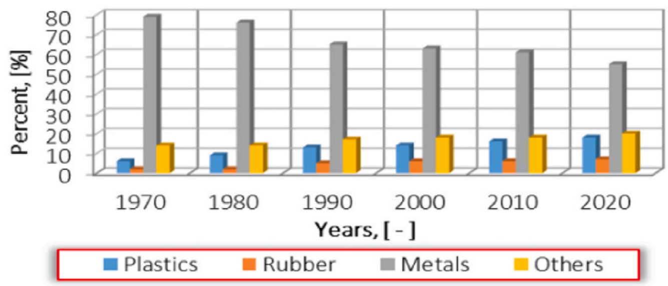

Fig. 14. Change in vehicle composition from 1970 to 2020 retrieved from Ref. [109].

switching from steel to aluminium can reduce the weight of the body in white by up to 50 % [117]. The use of aluminium may enable the vehicle to be lighter. The most noteworthy features are its light weight, high specific energy absorption, and exact strength. Aluminium is corrosion-resistant, but due to its low flexibility modulus, it cannot be used to replace steel parts. As a result, such components must be redesigned to adopt the same mechanical strength. Furthermore, natural Fiber Polymer Composites (NFPCs) have gained significant attention in the automotive industry as an eco-friendly alternative to traditional materials for various components, which offers a range of advantages that make them suitable for automotive applications [119]. The following subsections will delve into the specific potential and current usage of NFPCs for key exterior components, namely car spoilers (Section 11.1), brake pads (11.2), and side mirrors (11.3). Table 11 summarises the material used for exterior parts in automotive.

11.1. Car spoiler

The outside bodywork system of an automobile includes automotive spoilers, which function to produce downforce for traction. Automobile spoilers are sometimes made to avoid air flow separation from causing drag, especially for cars with a high angle between the rear edge and the tail section Usually, materials like ABS, polyurethane, aluminium, carbon fibre, and glass fibre are used to make spoilers. Due to its affordability, ABS is a frequently used material but has poor durability. However, while being more expensive, carbon fibre is preferred by manufacturers of high-performance vehicles because of its lightweight, high strength, and durability.

The usage of more environmentally friendly materials for the spoiler construction, like kenaf-based polymer composites, is one of the recently investigated designs. With the emergence of such natural fibre polymer composites, spoilers composed of glass fibre and carbon fibre composites will be lighter and less expensive than ABS spoilers. The recyclability of spoilers constructed of kenaf polymer composites will also be advantageous because it has a significant influence on the present standards for car design. Despite these benefits, there is still a need for kenaf polymer composites in the construction of vehicle spoilers. Currently, Mansor et al. [120] has developed car spoiler from kenaf fibre reinforced polymer composites based on concurrent engineering techniques as depict in Fig. 15.

Table 11
Summary for material used for exterior part.

Material	Application	Advantage	Drawback
Aluminium	body panel, side mirror, trunks, roofs, fenders, outer plates	light weight, corrosion resistant, recyclable, energy efficient, safer [118].	Heat intolerance
Composite and Plastic	rear bumper, wiper blade, front bumper, door panel	high strength-to-weight ratio, good rigidity, and strong chemical and corrosion resistance [117].	Expensive, some of them non-recyclable, difficult manufacturing process.

11.2. Brake pad

A vehicle's brakes are an essential part that let drivers slow down, stop, and maintain their speed while passing on a downhill route [121]. A crucial regulator of motion and vehicle safety are the brakes. Brake pads that do not function properly can cause accidents because they crash into a vehicle that stops suddenly. Finally, the vehicle crashes because it is uncontrollable. pass a car on a downhill road and collide with it or plunge into a ravine. This is because of the brake force's capacity, which is based on the properties of the brake pad material.

From Fig. 16, specimens D and E have lower wear than specimen A, B, C and commercial brake pad, so that they have higher wear resistance than others. As a result, increasing coconut fibre content has shown good wear resistance in braking. That is because by increasing the composition coconut fibre contributed to increasing hardness value which has affected to decrease wear of brake [121]. Brake pads made of a natural composite material that excess content coconut fibre in them show quite similar test results with the commercial brake pads. Through suitable composition comparisons, the findings of this study demonstrate that coconut fibre and wood powder can be used for brake pads of vehicle.

11.3. Side mirror

Side mirrors are frequently attached to the outside of automobiles. The side mirror serves as a tool for seeing the car's characteristics. The average frontal area of a pair of side mirrors is between 2 and 3 percent of the total frontal area [122]. The side mirror increases the vehicle's drag when it is operating. Only when the speed exceeds 60 km/h does the side mirror add to the drag [122]. A side mirror is a mirror mounted on the outside of automobiles to aid the driver in seeing regions behind and to the sides of the vehicle, which are outside the driver's field of vision. To accommodate drivers of different heights and seating positions, the side mirror is fitted with manual or remote vertical and horizontal adjustment. Car side mirrors are located on the left and right side of the car. Side mirrors act as a "second eye," enhancing the driver's field of vision by reflecting the rear, side, and bottom of the vehicle. This enables the driver to see the rear directly and can help the driver see the surroundings and road conditions clearly. As a result, the driver may decide to act, particularly while cutting someone off or parking.

In general, natural fibre reinforced thermoplastic composites can be applied as new emerging material for side door mirror components. Fig. 17 shows the common components in a side mirror for cars. This is due to the combination of natural fibre with thermoplastic matrix can have great impact resistance and good structural integrity to resist the dynamic loads.

12. Conclusion

The focus of this study is the utilization of natural fibre reinforced

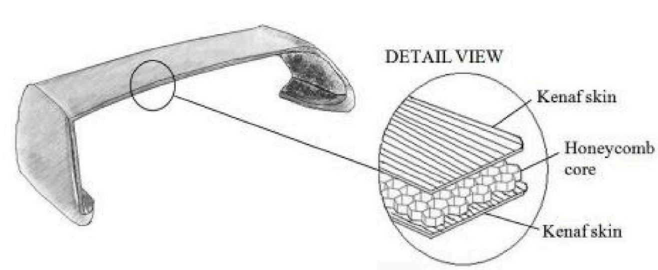

Fig. 15. Spoiler made from natural fibre [120].

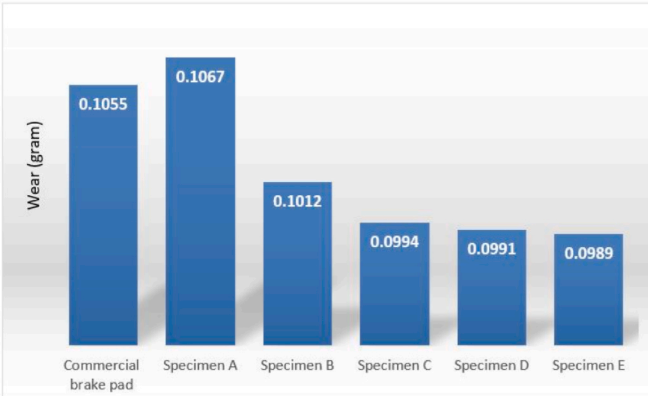

Fig. 16. Wear test result for commercial brake pad and specimen [121].

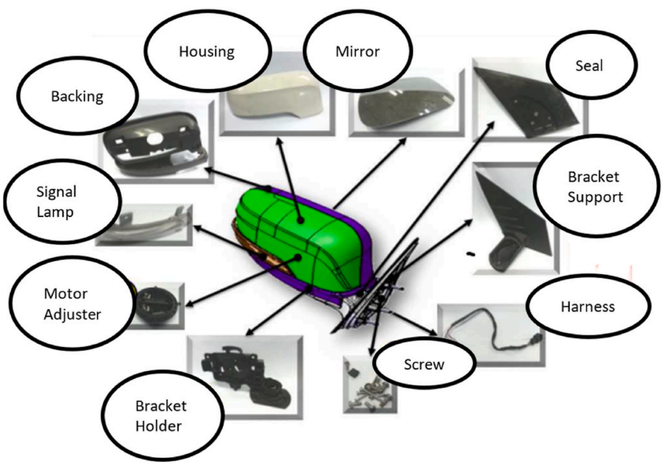

Fig. 17. Common components parts in car side mirror [123].

thermoplastic composites for the manufacturing of automotive components. Natural fibres possess favourable characteristics such as lightweight, affordability, low density, and widespread availability in the natural environment, rendering them highly suitable for integration into the automotive industry. Nevertheless, there are certain fundamental and technological challenges that need to be addressed to fully harness the potential of these fibres. There is still ongoing work towards establishing standardized comprehensive design and process guidelines for reinforced thermoplastics, particularly in areas such as design, prediction of failure modes, and long-term effects like durability, creep and fatigue [124]. It would be beneficial to consider expanding the utilization of process models and related software to enhance process optimization and reduce the reliance on trial and error in manufacturing. However, overcoming these technical hurdles is only one part of the challenge. Scaling up production for complex exterior parts presents significant further obstacles, including ensuring a consistent supply of high-quality natural fibres, adapting high-volume manufacturing processes to prevent thermal degradation, and meeting the rigorous quality and performance standards required by automotive original equipment manufacturers (OEMs). For widespread automotive adoption, economic and environmental feasibility must be addressed in tandem. The cost of chemical treatments such as silane, and acetylation adds a processing step that can impact the final cost-competitiveness of NFPCs against glass-filled composites. Similarly, the end-of-life recyclability of these treated natural fibre composites remains an open question; the impact of surface modifications on the degradation and re-processability of the thermoplastic matrix requires thorough investigation. Furthermore, to fully embrace circular economy principles, future research should expand to investigate the use of waste generated during natural fibre processing (e.g., textile scraps, agricultural residue) as a reinforcement material, resulting in truly closed-loop sustainable composites for the automotive industry. Overcoming these hurdles is critical for transitioning NFPCs from niche to high-volume applications and will directly contribute to the global sustainability goals of creating lighter, carbon-neutral, and fully recyclable vehicles. Through a combined bibliometric and technical review, this paper has evaluated the key properties and research landscape of natural fibre reinforced thermoplastic composites, which present a promising alternative for obtaining lightweight and more environment-friendly materials for the automotive sector. This paper can assist researchers to achieve further technical solutions in the field of natural fibre reinforced thermoplastic composites for automotive components.

Authors' contributions

M.A.M. Rizal and M.Y. Salim conceptualize the manuscript. M.A.M. Rizal handles funding and project administration. M.A.M. Rizal, A.H. Nordin, M.N.N. Harjar, Mohammed Sanal B., K.Z. Hafila, and Q. Ma write the original manuscript. M.Y. Salim, M.R. Ishak, M.R. Razman, Z. Ramli, T. Khan and T. A. Sebaey review and edit the manuscript.

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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References

[1] Salim MY, Fitri MFM, Rizal MAM, Supian ABM, Dzulkifli MH, Ilyas RA, Hassan SA. Layering sequences of fibreglass meshes: effects on the quasi-static indentation and flexural properties of Kenaf/Acrylonitrile butadiene styrene composites. Fibers Polym 2025;26:2057–68. https://doi.org/10.1007/s12221-025-00941-0.

[2] Asyraf MRM, Syamsir A, Ng LF, Sheng DDCV, Tee LY, Madenci E, Anggraini V. Elucidating the effect of stacking sequence on water absorption, flexural, and impact properties of banana pseudostem fiber–reinforced unsaturated polyester composites. Biomass Convers Biorefinery 2025;15:7787–98. https://doi.org/10.1007/s13399-024-05666-3.

[3] Holbery J, Houston D. Natural-fiber-reinforced polymer composites in automotive applications. Jom 2006;58:80–6. https://doi.org/10.1007/s11837-006-0234-2.

[4] Verma D, Senal I. 6. Natural fiber-reinforced polymer composites: feasibiliy study for sustainable automotive industries. Elsevier Ltd; 2019. https://doi.org/10.1016/B978-0-08-102426-3.00006-0.

[5] Lau K, Hung P, Zhu M, Hui D. Properties of natural fi bre composites for structural engineering applications. Compos Part B 2018;136:222–33. https://doi.org/10.1016/j.compositesb.2017.10.038.

[6] Kalia S, Dufresne A, Cherian BM, Kaith BS, Av L, Njuguna J, Nassiopoulos E. Cellulose-Based Bio- and Nanocomposites : a review. Int J Polym Sci 2011;2011. https://doi.org/10.1155/2011/837875.

[7] Bouzouita A, Notta-cuvier D, Raquez J, Lauro F, Dubois P. Poly (lactic acid) -Based materials for Automotive Applications. https://doi.org/10.1007/12; 2017.

[8] Ferreira FV, Pinheiro IF, De Souza SF, Mei LHI, Lona LMF. Polymer composites reinforced with natural fibers and nanocellulose in the automotive industry : a short review. J Compos Sci 2019.

[9] Hariprasad K, Ravichandran K, Jayaseelan V, Muthuramalingam T. Acoustic and mechanical characterisation of polypropylene composites reinforced by natural. J Mater Res Technol 2020;9:14029–35. https://doi.org/10.1016/j.jmrt.2020.09.112.

[10] Olhan S, Khatkar V, Behera BK. Review : Textile-based natural fibre-reinforced polymeric composites in automotive lightweighting review : Textile-based natural fibre-reinforced polymeric composites in automotive lightweighting. https://doi.org/10.1007/s10853-021-06509-6; 2021.

[11] Asyraf MRM, Hassan SA, Khan T, Fitri M, Fauzi M, Ilyas RA, Khan T. Hybrid Kenaf Fibre/Fibreglass meshes reinforced thermoplastic ABS composites based on quasi-isotropic mechanism: a brief review Hybrid Kenaf Fibre/Fibreglass meshes reinforced thermoplastic ABS composites based on quasi-isotropic mechanism: a brief Re-vie. J Nat Fibre Polym Compos 2023;2:2821–3289. https://www.researchgate.net/publication/376890700.

[12] Muhammad Fitri MF, Muhammad Asyraf MR, Abu Hassan S. Hybridizing Kenaf and glass fibres as reinforcement in ABS composites: current trends, properties and potential application in aircraft radome. J Kejuruter 2024;36:2075–96. https://doi.org/10.17576/jkukm-2024-36(5)-25.

[13] Ramasubbu R, Madasamy S. Fabrication of automobile component using hybrid natural fiber fabrication of automobile component using hybrid natural fiber reinforced polymer composite. https://doi.org/10.1080/15440478.2020.1761927; 2020.

[14] Cellulose fibers: Bio- and nano-polymer composites. https://doi.org/10.1007/978-3-642-17370-7; 2011.

[15] Tijssen RJW, Winnink J. Twenty-first century macro-trends in the institutional fabric of science: bibliometric monitoring and analysis. Scientometrics 2016;109: 2181–94. https://doi.org/10.1007/s11192-016-2041-z.

[16] Hervas-Oliver JL, Gonzalez G, Caja P, Sempere-Ripoll F. Clusters and industrial districts: where is the literature going? Identifying emerging sub-fields of research. Eur Plan Stud 2015;23:1827–72. https://doi.org/10.1080/09654313.2015.1021300.

[17] Skosana SJ, Khoathane C, Malwela T. Driving towards sustainability: a review of natural fiber reinforced polymer composites for eco-friendly automotive light-weighting. J Thermoplast Compos Mater 2024. https://doi.org/10.1177/08927057241254324.

[18] Wu J, Yang Z, Hu X, Wang H, Huang J. Exploring driving forces of sustainable development of China's new energy vehicle industry: an analysis from the perspective of an innovation ecosystem. Sustain Times 2018;10. https://doi.org/10.3390/su10124827.

[19] Zhang W, Xu J. Advanced lightweight materials for automobiles: a review. Mater Des 2022;221:110994. https://doi.org/10.1016/j.matdes.2022.110994.

[20] Singh MK, Mohanty AK, Misra M. Upcycling of waste polyolefins in natural fiber and sustainable filler-based biocomposites: a study on recent developments and future perspectives. Compos Part B Eng 2023;263. https://doi.org/10.1016/j.compositesb.2023.110852.

[21] Vijaya Ramnath B, Junaid Kokan S, Niranjan Raja R, Sathyanarayanan R, Elanchezhian C, Rajendra Prasad A, Manickavasagam VM. Evaluation of mechanical properties of abaca-jute-glass fibre reinforced epoxy composite. Mater Des 2013;51:357–66. https://doi.org/10.1016/j.matdes.2013.03.102.

[22] Tay CH, Mazlan N, Hameed Sultan MT, Abdan K, Lee CH. Mechanical performance of hybrid glass/kenaf epoxy composite filled with organomodified nanoclay. J Mater Res Technol 2021;15:4415–26. https://doi.org/10.1016/j.jmrt.2021.10.062.

[23] Pappu A, Pickering KL, Thakur VK. Manufacturing and characterization of sustainable hybrid composites using sisal and hemp fibres as reinforcement of poly (lactic acid) via injection moulding. Ind Crops Prod 2019;137:260–9. https://doi.org/10.1016/j.indcrop.2019.05.040.

[24] Peças P, Carvalho H, Salman H, Leite M. Natural fibre composites and their applications: a review. J Compos Sci 2018;2. https://doi.org/10.3390/jcs2040066.

[25] Wasti S, Kore S, Yeole P, Tekinalp H, Ozcan S, Vaidya U. Bamboo fiber reinforced polypropylene composites for transportation applications. J Front Mater 2022: 1–14. https://doi.org/10.3389/fmats.2022.967512.

[26] Alhijazi M, Safaei B, Zeeshan Q, Asmael M, Eyvazian A, Qin Z. Recent developments in Luffa natural fiber composites: review. Sustain Times 2020;12: 1–25. https://doi.org/10.3390/su12187683.

[27] Nurazzi NM, Asyraf MRM, Fatimah Athiyah S, Shazleen SS, Rafiqah SA, Harussani MM, Kamarudin SH, Razman MR, Rahmah M, Zainudin ES, Ilyas RA, Aisyah HA, Norrrahim MNF, Abdullah N, Sapuan SM, Khalina A. A review on mechanical performance of hybrid natural fiber polymer composites for structural applications. Polymers 2021;13:2170. https://doi.org/10.3390/polym13132170.

[28] Adesina OT, Jamiru T, Sadiku ER, Ogunbiyi OF, Beneke LW. Mechanical evaluation of hybrid natural fibre–reinforced polymeric composites for automotive bumper beam: a review. Int J Adv Manuf Technol 2019;103. https://doi.org/10.1007/s00170-019-03638-w. 1781–1797.

[29] Abdirohman K, Adhitya M. Effect of water and seawater on mechanical properties of fiber reinforced polymer composites : a review for amphibious aircraft float development. Effect of water and seawater on mechanical properties of fiber reinforced polymer composites : a review for a, https://doi.org/10.1088/1757-899X/694/1/012035; 2019.

[30] Pickering KL, Efendy MGA, Le TM. A review of recent developments in natural fibre composites and their mechanical performance. Compos Part A Appl Sci Manuf 2016;83:98–112. https://doi.org/10.1016/j.compositesa.2015.08.038.

[31] Kamaruddin ZH, Jumaidin R, Selamat MZ, Ilyas RA. Characteristics and properties of lemongrass (Cymbopogan citratus): a comprehensive review. J Nat Fibers 2021:1–18. https://doi.org/10.1080/15440478.2021.1958439.

[32] Kalia S, Kaith BS, Kaur I. Pretreatments of natural fibers and their application as reinforcing material in polymer composites-a review. Polym Eng Sci 2009;49: 1253–72. https://doi.org/10.1002/pen.21328.

[33] Sreenivas HT, Krishnamurthy N, Arpitha GR. A comprehensive review on light weight kenaf fi ber for automobiles. Int J Lightweight Mater Manuf 2020;3: 328–37. https://doi.org/10.1016/j.ijlmm.2020.05.003.

[34] Ali A, Shaker K, Nawab Y, Jabbar M, Hussain T, Militky J, Baheti V. Hydrophobic treatment of natural fibers and their composites—A review. J Ind Text 2018;47: 2153–83. https://doi.org/10.1177/1528083716654468.

[35] Dunne R, Desai D, Sadiku R, Jayaramudu J. A review of natural fibres, their sustainability and automotive applications. J Reinforc Plast Compos 2016;35: 1041–50. https://doi.org/10.1177/0731684416633898.

[36] Mansor MR, Salit MS, Zainudin ES. Life cycle assessment of natural fiber polymer composites life cycle assessment of natural fiber polymer composites. https://doi.org/10.1007/978-3-319-13847-3; 2015.

[37] Barış KE, Tanaçan L. Production of banana waste fiber cement composite. Proc Int Civ Eng Archit Conf 2019;2:258–66.

[38] Gupta MK, Srivastava RK, Bisaria H. ISSN 2277-7156 review article potential of Jute fibre reinforced polymer composites. A Review 2015;5:30–8.

[39] Kamath SS, Sampathkumar D, Bennehalli B. A review on natural areca fibre reinforced polymer composite materials. Cienc e Tecnol Dos Mater 2017;29: 106–28. https://doi.org/10.1016/j.ctmat.2017.10.001.

[40] Joshi SV, Drzal LT, Mohanty AK, Arora S. Are natural fiber composites environmentally superior to glass fiber reinforced composites? Compos Part A Appl Sci Manuf 2004;35:371–6. https://doi.org/10.1016/j.compositesa.2003.09.016.

[41] Ullah S, Akhter Z, Palevicius A, Janusas G. Review: natural fiber-based biocomposites for potential advanced automotive applications. J Eng Fiber Fabr 2025;20. https://doi.org/10.1177/15589250241311468.

[42] Ari A, Karahan M, Kopar M, Ahrari M, Khan RMWU, Hussain M. Comparative analysis of natural fibres characteristics as composite reinforcement. Ind Textil 2023;74:403–11. https://doi.org/10.35530/IT.074.04.2022110.

[43] Rohit K, Dixit S. A review - future aspect of natural fiber reinforced composite A review - future aspect of natural fiber reinforced composite. Polym Renew Resour 2018;7. https://doi.org/10.1177/204124791600700202.

[44] Varis J, Chauhan V, Ka T. Review of natural fiber- reinforced engineering plastic composites , their applications in the transportation sector and processing techniques. https://doi.org/10.1177/0892705719889095; 2019.

[45] Dicker MPM, Duckworth PF, Baker AB, Francois G, Hazzard MK, Weaver PM. Green composites: a review of material attributes and complementary applications. Compos Part A Appl Sci Manuf 2014;56:280–9. https://doi.org/10.1016/j.compositesa.2013.10.014.

[46] Hariprasad T, Dharmalingam G, Raj P. Study of mechanical properties of banana_coir hybrid composite using experimental and FEM techniques. J Mech Eng Sci 2013;4:518–31.

[47] George J, Sreekala MS, Thomas S. A review on interface modification and characterization of natural fiber reinforced plastic composites. Polym Eng Sci 2001;41:1471–85. https://doi.org/10.1002/pen.10846.

[48] Sinitsky O, Trabelsi N, Priel E. The mechanical response of epoxy – sisal composites considering fiber anisotropy: a computional and experimental Study. Fibers 2022.

[49] Arrakhiz FZ, El Achaby M, Kakou AC, Vaudreuil S, Benmoussa K, Bouhfid R, Fassi-fehri O, Qaiss A. Mechanical properties of high density polyethylene reinforced with chemically modified coir fibers : impact of chemical treatments. J Mater 2012;37:379–83. https://doi.org/10.1016/j.matdes.2012.01.020.

[50] Challabi AJH, Chieng BW, Ibrahim NA, Ariffin H, Zainuddin N. Effect of superheated steam treatment on the mechanical properties and dimensional stability of PALF/PLA biocomposite. Polymers 2019;11. https://doi.org/10.3390/polym11030482.

[51] Ekoputra FA, Sulistijono S, Ismail I. Effect a chemical treatment of pineapple leaf fiber (PALF) for mechanical properties as a reinforced composite matrix polyesters. IPTEK J Proc Ser 2018;0:19. https://doi.org/10.12962/j23546026.y2018i4.3840.

[52] Nnodu OG, Igwe IO, Ojingwa A, Nwapa C, Oragwu PI, Okonkwo SN. Effects of chemical modifications of pineapple leaf fibre on the properties of polypropylene composites. J Polym Sci Technol 2020;5:25–37.

[53] Hazarika D, Gogoi N, Jose S, Das R, Basu G. Exploration of future prospects of Indian pineapple leaf , an agro waste for textile application. J Clean Prod 2017; 141:580–6. https://doi.org/10.1016/j.jclepro.2016.09.092.

[54] Mohanty AK, Misra M, Dreal LT. Surface modifications of natural fibres and peformance of the resulting biocomposite. Compos Interfaces 2001;8:313–43.

[55] Ramamoorthy S, Skrifvars M, Rissanen M. Effect of alkali and silane surface treatments on regenerated cellulose fibre type (lyocell) intended for composites. https://doi.org/10.1007/s10570-014-0526-6; 2014.

[56] Md Nor SS, Abdul Patah MF, Mat Salleh M. Surface modification of bio-based composites via silane treatment: a short review. J Adhes Sci Technol 2023;37: 801–16. https://doi.org/10.1080/01694243.2022.2049087.

[57] Asyraf MRM, Syamsir A, Supian ABM, Usman F, Ilyas RA, Nurazzi NM, Norrrahim MNF, Razman MR, Zakaria SZS, Sharma S, Itam Z, Rashid MZA. Sugar palm fibre-reinforced polymer composites: influence of chemical treatments on its mechanical properties. Materials 2022;15:3852. https://doi.org/10.3390/ma15113852.

[58] Lukachevskaia IG, Kychkin A, Kychkin AK, Vasileva ED, Markov AE. Effect of 2000-Hour ultraviolet irradiation on surface degradation of glass and basalt fiber-reinforced laminates. Polymers 2025;17. https://doi.org/10.3390/polym17141980.

[59] Aziz T, Ullah A, Fan H, Jamil MI, Khan FU, Ullah R, Iqbal M, Ali A, Ullah B. Recent progress in silane coupling agent with its emerging applications. J Polym Environ 2021;29:3427–43. https://doi.org/10.1007/s10924-021-02142-1.
[60] Nurazzi NM, Shazleen SS, Aisyah HA, Asyraf MRM, Sabaruddin FA, Mohidem NA, Norrrahim MNF, Kamarudin SH, Ilyas RA, Ishak MR, Abdullah N, Nor NM. Effect of silane treatments on mechanical performance of kenaf fibre reinforced polymer composites: a review. Funct Compos Struct 2021;3:045003. https://doi.org/10.1088/2631-6331/ac351b.
[61] Hill C, Khalil H. Effect of fiber treatments on mechanical properties of coir or oil palm fiber reinforced polyester composites. J Appl Polym Sci 2017;4628. https://doi.org/10.1002/1097-4628(20001128)78.
[62] Li X, Tabil LG, Panigrahi S. Chemical treatments of natural fiber for use in natural fiber-reinforced composites: a review. J Polym Environ 2007;15:25–33. https://doi.org/10.1007/s10924-006-0042-3.
[63] Zaman HU, Khan RA. Acetylation used for natural fiber/polymer composites. J Thermoplast Compos Mater 2019. https://doi.org/10.1177/0892705719838000. 089270571983800.
[64] Yuan Y, Guo M, Wang Y. Flax Fibers as Reinforcement in Poly (Lactic Acid). 2011. p. 547–53.
[65] Mishral S, Misra M, Tripathy SS, Nayak SK. The influence of Chemical surface modification on the performance of sisal-polyester biocomposites. Polym Compos 2002;23:164–70.
[66] Kalaprasad O, Joseph K, Thomas S. Theoretical modelling of tensile properties of short sisal fibre-reinforced low-density polyethylene composites, vol. 2; 1997.
[67] Jabbar A, Hussain J, Basit A, Naeem MS, Javaid MU, Karahan M, Nazir A. Influence of chemical treatments and nanocellulose spray coating on the mechanical, low velocity impact and compression after impact performance of nonwoven Jute composites. J Nat Fibers 2020;17:1785–97. https://doi.org/10.1080/15440478.2019.1598918.
[68] Fitri MFM, Asyraf MRM, Hassan SA, Ilyas RA. Unveiling the physico-mechanical properties of kenaf yarn fiber-reinforced acrylonitrile butadiene styrene composites: effect of quasi-isotropic lay-up sequences. Polym Compos 2024;45:9362–75. https://doi.org/10.1002/pc.28414.
[69] Asyraf MRM, Syamsir A, Supian ABM, Zaki MAFM, Hazrati KZ, Ashraf W, Anggraini V, Madenci E, Özkılıç YO, Aksoylu C. Investigating the influence of stacking sequences on the physical and mechanical characteristics of Coconut Coir fiber-reinforced unsaturated polyester composites. Fibers Polym 2024;25:661–72. https://doi.org/10.1007/s12221-023-00465-5.
[70] O.J. Shesan, A.C. Stephen, Improving the mechanical properties of natural fiber composites for structural and biomedical applications, (n.d.) 1–27.
[71] Bin Salim MY, Farokhi Nejad A, Yahya MY, Dickhut T, Rahimian Koloor SS. Mechanical characterization of hybrid steel wire Mesh/Basalt/Epoxy fiber-reinforced polymer composite laminates. J Compos Sci 2024;8. https://doi.org/10.3390/jcs8050184.
[72] Sreenivas HT, Krishnamurthy N. Influence of stacking sequence and orientation of the fabric on mechanical properties of twill Kenaf/Kevlar reinforced unsaturated polyester hybrid composites. J Ind Text 2022. https://doi.org/10.1177/15280837211019901.
[73] Sujon M, Habib M, Abedin M. Experimental investigation of the mechanical and water absorption properties on fiber stacking sequence and orientation of jute/carbon epoxy hybrid composites. J Mater Res Technol 2020;9:10970–81. https://doi.org/10.1016/j.jmrt.2020.07.079.
[74] Selver E, Dalfi H, Yousaf Z. Investigation of the impact and post-impact behaviour of glass and glass/natural fibre hybrid composites made with various stacking sequences. Experimental and theoretical analysis 2022. https://doi.org/10.1177/1528083719900670.
[75] Malik K, Ahmad F, Yunus N, Gunister E, Dawood S, Ali S, Mani C, Syahir M, Larry A. The hybridization effects of glass and carbon fibers on the mechanical properties of Kenaf Mat/epoxy composites. J Nat Fibers 2022:1–16. https://doi.org/10.1080/15440478.2022.2127437. 00.
[76] Fiore V, Di Bella G, Valenza A. The effect of alkaline treatment on mechanical properties of kenaf fibers and their epoxy composites. Compos Part B Eng 2015;68:14–21. https://doi.org/10.1016/j.compositesb.2014.08.025.
[77] Dzaibidin MZ, Salim MY, Yahya MY, Ng LF. Tensile Modulus prediction of glass Fiber/Stainless steel Wire mesh-reinforced hybrid composites via rule of hybrid mixtures. J Res Updates Polym Sci 2025;14:112–9. https://doi.org/10.6000/1929-5995.2025.14.12.
[78] Salim MY, Fitri MFM, Rizal MAM, Ilyas RA, Dzulkifli MH, Hassan SA, Mohd Supian AB, Razman MR. Energy absorption and mechanical performance of kenaf yarn/fibreglass mesh/acrylonitrile butadiene styrene composites: influence of mesh density. J Mater Res Technol 2025;36:6890–901. https://doi.org/10.1016/j.jmrt.2025.04.291.
[79] Nejad AF, Bin Salim MY, Koloor SSR, Petrik S, Yahya MY, Hassan SA, Shah MKM. Hybrid and synthetic FRP composites under different strain rates: a review. Polymers 2021;13. https://doi.org/10.3390/polym13193400.
[80] Swolfs Y, Gorbatikh L, Verpoest I. Fibre hybridisation in polymer composites: a review. Compos Part A Appl Sci Manuf 2014;67:181–200. https://doi.org/10.1016/j.compositesa.2014.08.027.
[81] Safri S, Sultan M, Jawaid M, Jayakrishna K. Impact behaviour of hybrid composites for structural applications : a review. Compos Part B 2018;133:112–21. https://doi.org/10.1016/j.compositesb.2017.09.008.
[82] Das SC, Paul D, Grammatikos SA, Siddiquee AB, Papatzani S, Vidakis N, Petousis M. Effect of stacking sequence on the performance of hybrid natural/synthetic fi ber reinforced polymer composite laminates. Compos Struct 2021;276:114525. https://doi.org/10.1016/j.compstruct.2021.114525.
[83] M.N.M. Azlin, S.M. Sapuan, M.Y.M. Zuhri, E.S. Zainudin, Effect of stacking sequence and fiber content on mechanical and morphological properties of woven kenaf/polyester fiber reinforced polylactic acid (PLA) hybrid laminated composites, J Mater Res Technol 16 (n.d.) 1190–1201. https://doi.org/10.1016/j.jmrt.2021.12.046.
[84] Ahmed KS, Vijayarangan S. Tensile , flexural and interlaminar shear properties of woven jute and jute-glass fabric reinforced. polyester composites 2008;7:330–5. https://doi.org/10.1016/j.jmatprotec.2008.06.038.
[85] Huda MK, Widiastuti I. Natural Fiber reinforced polymer in automotive application: a systematic literature review. IOP Conf Ser Earth Environ Sci 2021;1808. https://doi.org/10.1088/1742-6596/1808/1/012015.
[86] Abbas AGN, Aziz FNAA, Abdan K, Nasir NAM, Huseien GF. A state-of-the-art review on fibre-reinforced geopolymer composites. Constr Build Mater 2022;330:127187. https://doi.org/10.1016/j.conbuildmat.2022.127187.
[87] Asyraf MRM, Syamsir A, Ishak MR, Sapuan SM, Nurazzi NM, Norrrahim MNF, Ilyas RA, Khan T, Rashid MZA. Mechanical properties of hybrid lignocellulosic fiber-reinforced biopolymer green composites: a review. Fibers Polym 2023;24:337–53. https://doi.org/10.1007/s12221-023-00034-w.
[88] Supian ABM, Asyraf MRM, Syamsir A, Ma Q, Hazrati KZ, Azlin MNM, Mubarak Ali M, Ghani A, Hua LS, SaifulAzry S, Razman MR, Ramli Z, Nurazzi NM, Norrrahim MNF, Thiagamani SMK. Kenaf/glass fiber-reinforced polymer composites: pioneering sustainable materials with enhanced mechanical and tribological properties. Polym Compos 2024. https://doi.org/10.1002/pc.28785.
[89] Cong CW, Hong KL, Nordin NNA, Rizal MAM, Saad APM, Saad WAA, Sheng DDCV, Noordin MA, Dzulkifli MH. Sisal fibre reinforced polymer composites for structural applications: a brief review. J Mek 2024;47:154–62. https://doi.org/10.11113/jm.v47.502.
[90] Islam S, Karim FE, Islam MR, Saeed MA, Alam KA, Khatun MM. Thermoset and thermoplastic polymer composite with date palm fiber and its behavior: a review. SPE Polym 2025;6:1–31. https://doi.org/10.1002/pls2.10157.
[91] Al-Furjan MSH, Shan L, Shen X, Zarei MS, Hajmohammad MH, Kolahchi R. A review on fabrication techniques and tensile properties of glass, carbon, and kevlar fiber reinforced polymer composites. J Mater Res Technol 2022;19:2930–59. https://doi.org/10.1016/j.jmrt.2022.06.008.
[92] Qiao Y, Fring LD, Pallaka MR, Simmons KL. A review of the fabrication methods and mechanical behavior of continuous thermoplastic polymer fiber–thermoplastic polymer matrix composites. Polym Compos 2023;44:694–733. https://doi.org/10.1002/pc.27139.
[93] Asim M, Abdan K, Jawaid M, Nasir M, Dashtizadeh Z, Ishak MR, Hoque ME, Deng Y. A review on pineapple leaves fibre and its composites. Int J Polym Sci 2015;2015. https://doi.org/10.1155/2015/950567.
[94] Kumar S, Prasad L, Patel VK, Kumar V, Kumar A, Yadav A, Winczek J. Physical and mechanical properties of natural leaf fiber-reinforced epoxy polyester composites. Polymers 2021;13. https://doi.org/10.3390/polym13091369.
[95] Mishra S, Misra M, Tripathy SS, Nayak SK, Mohanty AK. Potentiality of pineapple leaf fibre as reinforcement in PALF-polyester composite: surface modification and mechanical performance. J Reinforc Plast Compos 2001;20:321–34.
[96] Gnanasekaran S, Nordin NIAA, Hamidi MMM, Shariffuddin JH. Effect of Alkaline treatment on the characteristics of pineapple leaves fibre effect of Alkaline treatment on the characteristics of pineapple leaves fibre and PALF/PP biocomposite. J Mech Eng Sci 2021;15:8518–28. https://doi.org/10.15282/jmes.15.4.2021.05.0671.
[97] Yu Y, Yang Y, Murakami M, Nomura M, Hamada H. Physical and mechanical properties of injection-molded wood powder thermoplastic composites. Adv Compos Mater 2013;22:425–35. https://doi.org/10.1080/09243046.2013.843828.
[98] Punyamurthy R, Sampathkumar D, Ranganagowda RPG, Bennehalli B, Srinivasa CV. Mechanical properties of abaca fiber reinforced polypropylene composites: effect of chemical treatment by benzenediazonium chloride. J King Saud Univ Eng Sci 2017;29:289–94. https://doi.org/10.1016/j.jksues.2015.10.004.
[99] Bledzki AK, Jaszkiewicz A, Scherzer D. Mechanical properties of PLA composites with man-made cellulose and abaca fibres. Compos Part A Appl Sci Manuf 2009;40:404–12. https://doi.org/10.1016/j.compositesa.2009.01.002.
[100] Phung AT, Dzung HT, Linh NPD, Duc VM, Liem NT. Acrylonitrile butadiene styrene/wood sawdust particles composites: mechanical and morphological properties. Iran Polym J (Engl Ed) 2024;33:67–78. https://doi.org/10.1007/s13726-023-01236-y.
[101] Oladejo KO, Omoniyi TE. Dimensional stability and mechanical properties of wood plastic composites produced from sawdust of Anogeissus leiocarpus (Ayin) with recycled polyethylene teraphthalate (PET) chips. Eur J Appl Eng Sci Res 2017;5:28–33.
[102] Tamrakar S, Kiziltas A, Mielewski D, Zander R. Characterization of kenaf and glass fiber reinforced hybrid composites for underbody shield applications. Compos Part B Eng 2021;216. https://doi.org/10.1016/j.compositesb.2021.108805.
[103] Jaszkiewicz A, Bledzki AK, Franciszczak P. Improving the mechanical performance of PLA composites with natural, man-made cellulose and glass fibers - a comparison to PP counterparts. Polimery/Polymers 2013;58:435–42. https://doi.org/10.14314/polimery.2013.435.
[104] Alhijazi M, Zeeshan Q, Qin Z, Safaei B, Asmael M. Finite element analysis of natural fibers composites: a review. Nanotechnol Rev 2020;9:853–75. https://doi.org/10.1515/ntrev-2020-0069.
[105] Kannan G, Thangaraju R. Recent progress on natural lignocellulosic fiber reinforced polymer composites : a review recent progress on natural

lignocellulosic fiber reinforced polymer composites : a review. J Nat Fibers 2021: 1–32. https://doi.org/10.1080/15440478.2021.1944425. 00.
[106] Salim Y, Yahya MY, Israr HA, Azwan S, Roslan MN, Abdullah MN. Oblique impact behavior of unidirectional natural fiber reinforced composites. Int J Adv Appl Sci 2018;5:161–4.
[107] tak Lau K, yan Hung P, Zhu MH, Hui D. Properties of natural fibre composites for structural engineering applications. Compos Part B Eng 2018;136:222–33. https://doi.org/10.1016/j.compositesb.2017.10.038.
[108] Symington M, Banks W, West O. Tensile testing of cellulose based natural fibers for structural. J Compos Mater 2008:1–26. https://doi.org/10.1177/0021998308097740.
[109] Lee BH, Kim HS, Lee S, Kim HJ, Dorgan JR. Bio-composites of kenaf fibers in polylactide: role of improved interfacial adhesion in the carding process. Compos Sci Technol 2009;69:2573–9. https://doi.org/10.1016/j.compscitech.2009.07.015.
[110] Bernard M, Khalina A, Ali A, Janius R, Faizal M, Hasnah KS, Sanuddin AB. The effect of processing parameters on the mechanical properties of kenaf fibre plastic composite the effect of processing parameters on the mechanical properties of kenaf fibre plastic composite. Mater Des 2015;32:1039–43. https://doi.org/10.1016/j.matdes.2010.07.014.
[111] Mohammed L, Ansari MNM, Pua G, Jawaid M, Islam MS. A review on natural fiber reinforced polymer composite and its applications. Int J Polym Sci 2015; 2015. https://doi.org/10.1155/2015/243947.
[112] Akampumuza O, Wambua PM, Ahmed A, Li W, Qin XH. Review of the applications of biocomposites in the automotive industry. Polym Compos 2017; 38:2553–69. https://doi.org/10.1002/pc.23847.
[113] Kim K, Lee B, Kim S, Kim H, Yun J, Yoo S, Sohn J. Reduction of VOC emission from natural flours filled biodegradable bio-composites for automobile interior. J Hazard Mater 2011;187:37–43. https://doi.org/10.1016/j.jhazmat.2010.07.075.
[114] Puglia D, Biagiotti J, Kenny JM. A review on natural fibre-based composites - part II: application of natural reinforcements in composite materials for automotive industry. J Nat Fibers 2004;1:23–65. https://doi.org/10.1300/J395v01n03_03.
[115] Atiqah A, Jawaid M, Sapuan SM, Ishak MR, Ansari MNM, Ilyas RA. Physical and thermal properties of treated sugar palm/glass fibre reinforced thermoplastic polyurethane hybrid composites. J Mater Res Technol 2019. https://doi.org/10.1016/j.jmrt.2019.06.032.
[116] Caiyuan C, Long W. Research on auto parts industry upgrading based on. Internet of Things 2015:474–8.
[117] Todor M, Kiss I. Systematic approach on materials selection in the automative industry for making vehicles lighter. Safer And More Fuel – Efficient 2016;1:91–7.
[118] Fentahun MA, Mahmut P, Savaş A. Materials used in automotive manufacture and material selection using ashby charts, vol. 8; 2018. p. 40–54. https://doi.org/10.5923/j.ijme.20180803.02.
[119] Baillie C. Green composites: polymer composites and the environment. https://doi.org/10.1016/C2013-0-17863-4; 2004.
[120] Mansor MR, Sapuan SM, Hambali A. Conceptual design of kenaf polymer composites automotive spoiler using TRIZ and Morphology Chart methods, vol. 761; 2015. p. 63–7. https://dx.doi.org/10.4028/www.scientific.net/AMM.761.63.
[121] Kholil A, Dwiyati S, Wirawan R, M E. Brake pad characteristics of natural fiber composites from coconut fibre and wood powder brake pad characteristics of natural fiber composites from coconut fibre and wood powder. J Phys Conf Ser 2019. https://doi.org/10.1088/1742-6596/2019/1/012068.
[122] Al-obaidi A, Otten W. Aerodynamic analysis of personal vehicle side mirror. J Eng Sci Technol 2018:52–64.
[123] Rahim ZA, Bakar NA. Complexity planning for product design using TRIZ. Adv Mater Res 2015. https://dx.doi.org/10.4028/www.scientific.net/AMR.903.396.
[124] Asyraf MRM, Ishak MR, Razman MR, Chandrasekar M. Fundamentals of creep, testing methods and development of test rig for the full-scale crossarm: a review. J Teknol 2019;81. https://doi.org/10.11113/jt.v81.13402.

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