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Fiber Reinforcement in Polymer Composites: A Comprehensive Review of Material Properties and Applications

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ABSTRACT

One of the most popular areas that have received a lot of focus concerns fiber-reinforced polymer composites (FRPs) that have desirable, naturally high mechanical characteristics, light weight, and flexibility in multiple applications. High-strength fibers, i.e. glass, carbon, and natural fibers with polymer matrix leads to the development of materials with unmatched mechanical and thermal properties. These composites are widely utilized in such industries such as automotive, aerospace industry, constructions, and the sports industry. This paper draws a critical review on fiber reinforced polymer composites with emphasis on fiber type, material characteristic, fabrication method and uses. The review examines the variations between the natural and synthetic fiber with focus on the merits and the problem facing each. It is shown that the use of natural fiber, in general, is especially interesting since it is sustainable, cost-effective, and biodegradable. Moreover, the paper explains the processing techniques which include, hand lay-up, resin transfer molding and compression molding and these techniques are paramount towards defining the final composite propriety. The epilogue of the paper reviews the present and future possibilities of fiber-reinforced composites and explains new directions in this field within the substitution of hybrid composites and the achievement of nanotechnology in solving material challenges.

INTRODUCTION

Polymer composites of fiber reinforcements are highly developed materials whose application is growing in areas that require high-performance-intensive and sustainable materials (Gupta & Srivastava, 2015). The materials are strategically designed phenomena of the union of polymeric base and reinforcement fibers to attain outstanding mechanical properties better than the mechanical properties of their separate constituents (Petrakli et al., 2020). The product is a composite material and its unique features include lightweight, great strength, and its having inherent corrosion resistance, which makes it perfectly suitable in highly sensitive applications of automotive, aerospace and the building construction field (Motavalli et al., 2010). The use of fiber-reinforced polymers has the achieved quite a significant pace since their strength-to-weight and stiffness-to-weight ratios are quite remarkable, which makes them a viable choice in terms of structural uses with stringent performance requirements (Asmatulu et al., 2013). The flexibility of fiber-reinforced polymer composites enables the engineer to manipulate their mechanical characteristics to their precise specifications by taking care to hone the production process and how fiber reinforced polymer components are arranged accordingly (Das et al., 2022).

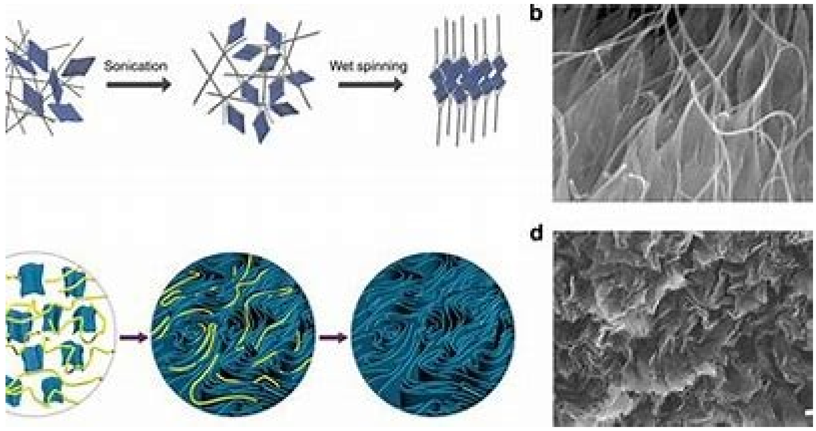


Figure 1: Diagram of natural fiber-reinforced polymer composite structure (Fiber-matrix interface)
(Source available : https://www.nature.com/articles/ncomms1661)

Carbon fiber reinforced polymer composite is among the most advanced composite materials due to the many advantages it possesses, with commonly used materials being the matrix epoxy and the reinforcement as carbon fiber (Wang et al., 2023). The carbon fibers lend their high modulus that contributes immensely to the reinforcement of the composite (Chung, 2018). The process of using fiber-reinforced plastics used in the aerospace industry has grown by leaps and bounds as it utilizes the special phenomenal properties of fiber-reinforced plastics, which are impossible to gain with conventional materials (Bhagwat et al., 2017). The integration of continuous fibers in thermoplastic polymers has been found to be successful in enhancing significant mechanical characteristics of composite to meet the requirement of certain challenging applications like aerospace engineering where the high specific strength is necessary (Kosmachev et al., 2021).

2. Background of Study

The world of composite materials has experienced a game-changing development, thanks to the ambition to acquire better mechanical qualities and ensure sustainability (Surendran et al., 2023). The composites comprising fiber-reinforced polymer garnered massive confidence and have proved to be invaluable in a wide range of structural projects, owing in a big part to their outstanding strength-to-weight and stiffness-to-weight ratios (Asmatulu et al., 2013; Petrakli et al., 2020). Its composites, which have been developed by incorporating fibers into a hosting polymer, possess an exclusive property blend which can be selected to suit a certain performance requirement. The history of these materials dates back to the early days, yet the contemporary solution, especially fiber-reinforced polymers, established its footprint in the middle of the XX century with the aim to expand material strength and rigidity without the corresponding growth in weight (Gupta & Srivastava, 2015). This early discovery mainly revolved around synthetic materials such as glass and carbon, who had very good mechanical properties and therefore became popular very rapidly in high-performance cases (Asmatulu et al., 2013). Because of advantages offered by composites compared to monolithic materials, over time they have been applied in such fields as aerospace, automotive engineering, and many others (Bhagwat et al., 2017).

There is a revolutionary change in the world of composite materials that has been inspired by the quest to acquire improved mechanical properties and sustainability (Surendran et al., 2023). Fiber-reinforced polymer composites have become an essential item in an entire range of structural uses, mostly thanks to their excellent strength-weight and stiffness-weight ratios (Asmatulu et al., 2013; Petrakli et al., 2020). . The composites are created using a designed fibers installed in a polymeric matrix and are endowed with a special property blend that fits a range of performance needs. The origin of these materials dates back to the ancient times but the modern version especially the fiber-reinforced polymer found its roots in the middle of the XX century when the objective was to ensure the strength and the stiffness of the materials grew, with no comparative growth of the weight of the materials (Gupta & Srivastava, 2015). This preliminary investigation was mostly of synthetic materials such as glass and carbon, which are well-known due to their outstanding mechanical capabilities, that soon asserted their authority in high-performance use (Asmatulu et al., 2013). The application of the composites has turned into more as the field of material science has advanced and, the composites have been used in a variety of applications such as aerospace to automotive engineering due to aspects that they provide when compared to the monolithic counterparts (Bhagwat et al., 2017).

Nevertheless, the development of the production of composite materials based on synthetic fibers has led to the risk of climate impact and largely due to the challenge of their disposal and resource sustainability (Barba et al., 2020). The disposal of these materials at end-of-life poses some significant issue, as the conventional ways, which include landfills or dumping them, are not only ecologically unsound, but also uneconomical (Bodros et al., 2006). This has sparked an increasing interest in natural fibers as sustainable products, which are biodegradable and derived out of renewable resources, and usually at cheaper rates (Kumar & Pandi, 2020). Renewability, biodegradability and affordability of natural fibers, such as jute, hemp, and flax ones, offer an attractive alternative, as they do not contrast with an increasing trend of an environmental stewardship approach (Bekele et al., 2024) (Rajesh et al., 2023). Such a move to sustainability does not translate to exclusion of synthetic fibers, but can mean that reinforcement materials make better choices depending on the application needs and the possible environmental impact of such a choice. Even the hybridization of antagonistic substances synthetic and natural fibers is becoming popular, which can be an intervention between the two extremes with references to the advantages of both forms of materials (Shrigandhi & Kothavale, 2021).

3. Justification

Composites composed of fiber-reinforced polymer have become incredibly invaluable in a wide range of engineering practices as well as in industries that require light-weighted but sturdy construction materials (Gupta & Srivastava, 2015). Fiber-reinforced polymer composite is used more frequently in the aviation industry to produce essential parts of aircraft, which experience different moisture conditions over their working lifespan (Das et al., 2022). The composite materials display a rare attribute of both strength and stiffness to weight ratioed materials, which are perfect replacements of conventional materials such as metals in weight sensitive products (Asmatulu et al., 2013). Materials with an increased/greater performance and a lesser impact on the environment, like aerospace industries, automotive, and construction industries, are major industries influencing their demand (Attahu et al., 2022). The study of mechanical characteristics, technological process, and aggregate applications of composites is broad (Rajesh et al., 2023). Since industries are quickly changing to the use of these materials, concern is arising on the necessity of their appropriate disposal to reduce environmental apprehensions (Gopalraj & Kärki, 2020).

4. Purposes of the Study

This study aims at the following objectives:

- To investigate the material properties of fiber reinforced polymer composites e.g. mechanical, thermal and environmental.
- To review the type of fiber that is included in the utilization process of fiber reinforced composites and its impact on the properties of the material.
- To explore the manufacturing process that was embraced in the process of producing fiber-reinforced polymer composites.
- To determine the applications of the fiber-reinforced composites in some of the areas like the aerospace, vehicle, and construction.
- In order to ascertain the current limitation and potential of fiber-reinforced polymer composite.

5. Literature Review

5.1 Composite Fiber Types

Synthetic Fibers: Synthetic fibers which are most often used in the composite materials include glass and carbon fibers. Glass fibers are renowned to have good mechanical qualities, be cheap and applicable in several ways. The carbon fibers, in their turn, offer superior strength-to-weight ratio, and are therefore used in such fields as aerospace and automotive industries.

Natural Fibers: The natural fibers such as jute, hemp, flax, and sisal have been receiving much attention because of their sustainability, cheap cost and non degradable nature. Although they possess inferior mechanical characteristics compared to those of synthetic materials, they are beneficial to the environment requiring that they be used in applications in the automotive industries and construction where reduced weight and environmental sensibility is the primary concern.

5.2 Properties of material

Mechanical Properties: The biggest strength is a reinforced composite and is its wide mechanical strength. The fibers considerably enhance the tensile property, modulus of elasticity and impact on the polymeric socket. Glass fibers are considered to be moderately strong with high stiffness whereas carbon fibers are strong and stiff.

Thermal Properties: Fiber reinforced composites thermal properties are based on the type of polymer matrix. There is excellent thermal resistance by the epoxy and vinyl ester resins. By contrast, natural fiber Composites are generally less thermally stable and their temperature capabilities may be restricted.

Environmental Resistance: The second environmental problem with the composite materials is decay. Manmade fibers are usually more resistant to wet and UV rays. Natural fibers however are prone to moisture absorption and thus their performance is lowered in the long run.

5.3 Techniques of Processing

1. Hand Lay-Up: This is a widely used and less expensive method of manufacturing fiber reinforced composites especially those involving low volume manufacture.
2. Resin Transfer Molding (RTM): Resin transfer molding uses closed molds. It provides greater control of resin distribution, controls and is good with high-performance composite components.
3. Compression Molding: The method is very appropriate in the large-scale production of the composite parts, with the advantage of reasonably controlling the fiber orientation and amount of the resin.

5.4 Applications

- Automotive Industries: Automotive industries have also been a major contributor to the consumption of this kind of fiber reinforced composite due to the necessity of the provision of light weight sophisticated material that is strong simultaneously within the bodyshell and bumpers and the interior component of the automobiles.
- Aerospace Industry: The applications of carbon fiber composites in the aircraft are very wide-spread in fuselages, wings and other sensitive portions of aircrafts as they have high strength-to-weight ratio.
- Construction: Fiber-reinforced composites are used in the construction of structures such as bridges, buildings and pipes because the fiber-reinforced composites are built in a manner that is strong, does not corrode and is also lightweight and during the construction it is applied.

6. Material and Methods

6.1 Design of the Research

The paper has adopted the qualitative research approach in carrying out a critical comparative analysis of fiber reinforced polymer (FRP) composite. The research principally focuses on the secondary information and the same is collected through the extensive scholarly articles, technical articles, trade articles and other credible materials. They will be complied so as to synthesize the fact in a bid to come up with a comprehensive perception on the nature of the fibers used, their contiguity of materials, their technology of construction, and how various industries are going to utilize them.

6.2 Data information gathering

In this review, broad database search was carried out across Google Scholar, Scopus, ScienceDirect and Wiley Online Library to retrieve the data. The local or international newspaper was not of interest, but the emphasis was put on the academically reviewed publications, proceedings of conferences and publications, and books published during last ten years to make the current available information be utilized. Relevance of various studies was narrowed down using keywords such as fiber reinforced polymer composites, natural fibers, synthetics fibers, composite processing techniques and utility of FRP.

6.3 Sample-size

A sample size is how much of the research papers, reports and publications are reviewed since this is a review paper. A few hundred and over articles and research papers will be selected on the basis of relevancy, date and reputation of publication source. The research and articles that got published by popular bodies of research were what was wanted, in order to ensure that the information that is to be conveyed is authentic

6.4 Data synthesis

The found articles were examined and split into other themes:

- Material Properties Mechanical, thermal as well as environmental properties of synthetic and natural fiber reinforced composites.
- Processing Techniques: These are such techniques as hand lay- up, resin transfer molding or compression molding.
- Applications Fiber-reinforced materials Fiber-reinforced materials are utilised in construction, auto and space applications.

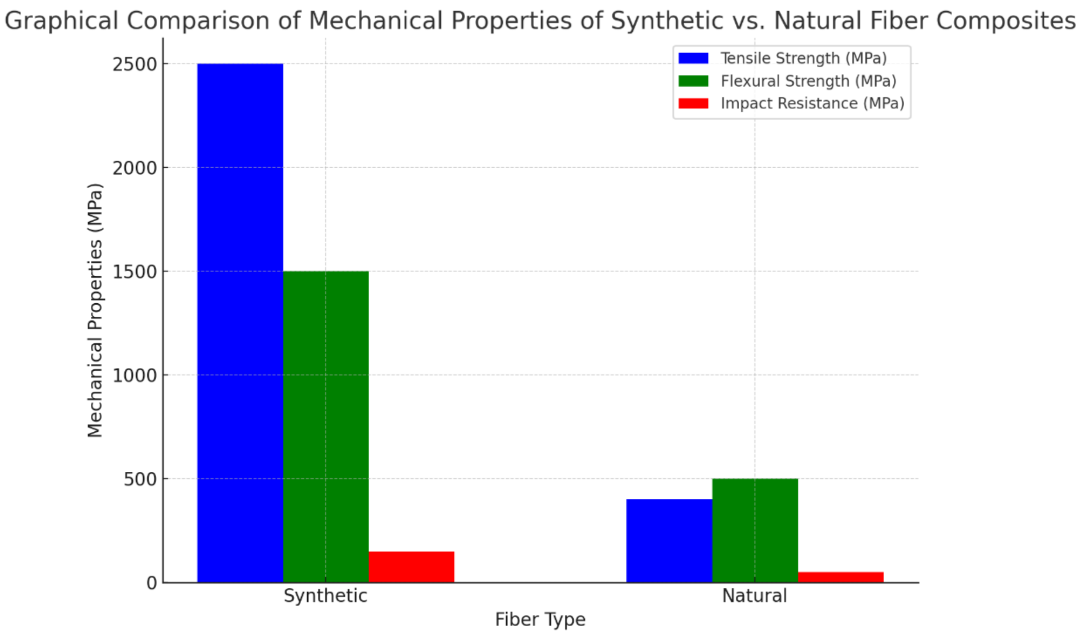
It synthesizes the information that can enable the establishment of the prevailing patterns, tendencies, and literature gaps. The methodology helped to form the complete image of the contemporary situation in the sphere of fiber-reinforced polymer composites.

6.5 Data Analysis

The qualitative data was deciphered using thematic analysis. The key thematic segments were delivered, where the comparison between the natural and synthetic fibers, advancements in the processing techniques and new tendencies towards the hybrid composites were offered. The cross-referencing was done to attain consistency and validity of the results.

Table 1: Comparison of Material Properties of Synthetic and Natural Fiber Reinforced Composites

Material Property	Synthetic Fibers (e.g., Glass, Carbon)	Natural Fibers (e.g., Flax, Hemp, Jute)
Tensile Strength	High (Up to 2500 MPa for carbon fibers)	Moderate (100-500 MPa)
Flexural Strength	High (Up to 1500 MPa)	Moderate (250-700 MPa)
Impact Resistance	High, especially for carbon fibers	Lower (Varies based on fiber type)
Thermal Stability	Excellent, especially for carbon fibers	Moderate (Degrades with moisture)
Density	Low (Glass: 2.5 g/cm³, Carbon: 1.5 g/cm³)	Moderate (1.4-1.6 g/cm³)
Environmental Resistance	Excellent (Resistant to UV, moisture)	Moderate (Sensitive to moisture, UV)
Biodegradability	Not biodegradable	Biodegradable (Eco-friendly)



Graph 1: Graphical Comparison of Mechanical Properties of Synthetic vs. Natural Fiber Composites

which compares the tensile strength, flexural strength, and impact resistance of synthetic vs. natural fiber composites.

7. Disussion and Results

7.1 Summarizing of Conclusions

The findings of this analysis reveal various significant shifts in the field of fiber reinforced polymeric composites. It was observed that the synthetic fibers, particularly the glass fiber and the carbon fiber, continue to dominate in the composite business because of its most desirable mechanical properties. It is having good strength to weight ratios and cannot be degraded easily by the environment and can therefore be used in the arduous applications in the aerospace, automobile and marine industries. However, the introduction of bio fibers such as jute, hemp, flax and Sisal is gaining grounds as alternatives that are sustainable. What is good to the environment about these fibers is that, they are more biodegradable and cut carbon footprints when made. The mechanical qualities of natural fibers are comparatively reduced in relation to the synthetic fibers, whereas utilization of technologies during both processing and treatment of fibers makes them more effective.

Table 2: Applications of Fiber-Reinforced Polymers in Various Industries

Industry	Fiber Type	Application	Advantages
Aerospace	Carbon, Glass	Aircraft wings, fuselages, interior components	High strength-to-weight ratio, fuel efficiency
Automotive	Glass, Natural (Jute)	Car body panels, bumpers, interior parts	Lightweight, cost-effective, sustainable options
Construction	Glass, Natural (Flax)	Structural beams, cladding, reinforcement bars	Durability, resistance to environmental factors
Marine	Carbon, Glass	Boat hulls, decks, masts	Corrosion resistance, high strength-to-weight ratio
Sports Equipment	Carbon, Glass	Tennis rackets, bicycles, kayaks	High performance, lightweight

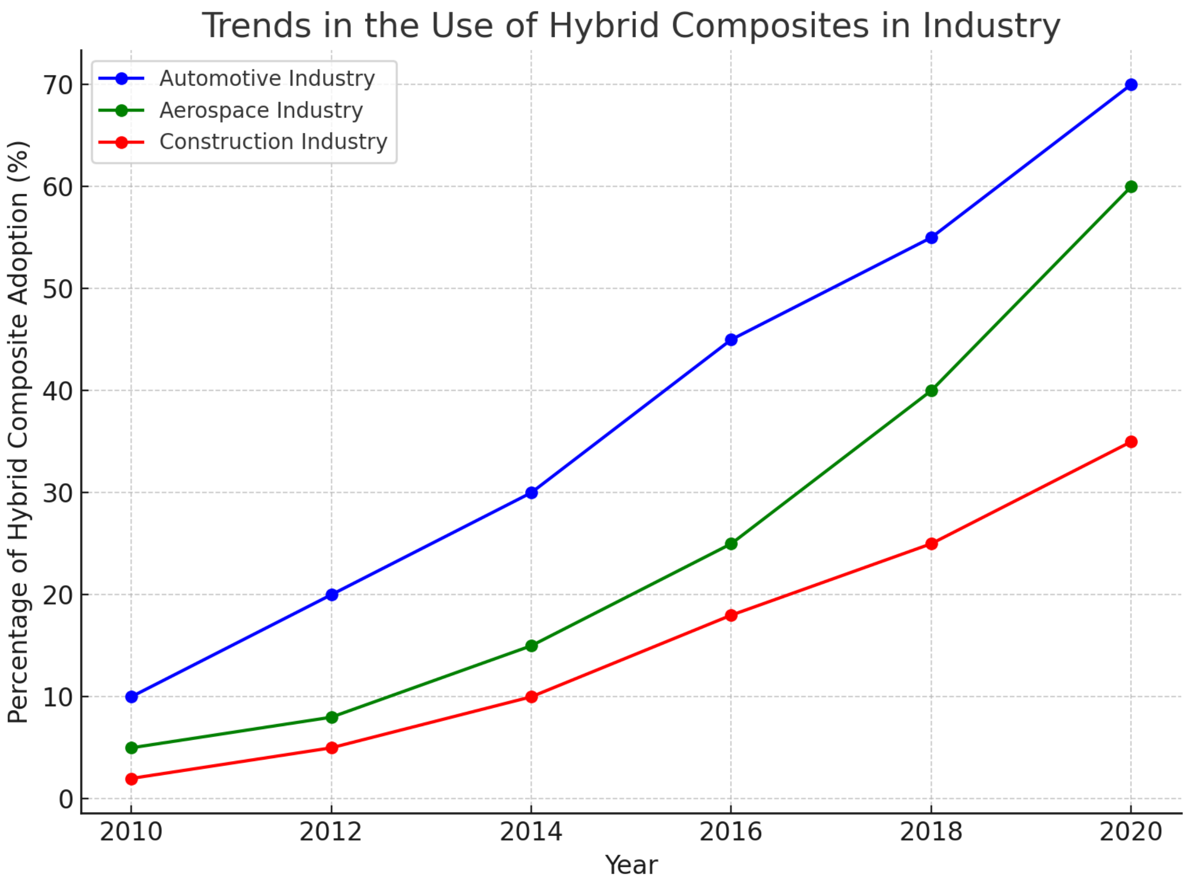


Figure 2: Trends in the Use of Hybrid Composites in Industry

which illustrates the growth of hybrid composites usage over the years in different industries (automotive, aerospace, and construction).

7.2 Composites Alloy

Among the most reveling trends that occurred in the process of the research, there is a tendency towards the gradual increase in the application of the hybrid composite out of the combination of the natural and synthetic fibers. The two types of unique fibers used in the hybrid composites namely, synthetic and natural fibre, the hybrid composites utilize the positive attributes of the two, due to the fact that synthetic fibre is stronger compared to the natural fibre which is sustainable and cost effective. Studies have shown that a mix containing two or more fibers in the composition (hybrid composites) may have a higher tensile strength, higher impact strength, and countless other enhanced features in the mechanical behavior of the composed parts than when only one fiber is used in the mixture (composites). The hybridization offers a more moderate mix in the achievement of superior-performance materials utilizing fewer environmental sources.

7.3 Enhancement in Processing Techniques

The review highlighted some of the development that have been done in processing methods which have boosted the performance of fiber reinforced composite. Of a specific interest are those methods such as the resin transfer molding (RTM) and the compression molding:

Resin Transfer Molding (RTM): It is a closed mold with resin being injected on a mold filled with dry fibers hence it is easier to control the distribution of resins and it has a higher homogeneity of compounds. The RTM can be utilized in the creation of high performing and hence, complex composites which can then be implemented in the aerospace industry or automotive industry.

Compression molding: The process is very widely used in the production of large structures of composites. It entails impregnation of the fiber-matrix composite into a pressurized heightened mold to create the desired consumed final composite material. This is quite apt in mass production since it is highly efficient and exhibits stable properties of materials.

It is predicted that these two techniques have been applied in enhancing the mechanical aspects in the reinforced fiber composites and it has made the manufacturing procedure exceptionally cost effective and effective, especially in the highly demanded industries.

7.4 Eco-friendly and environmental effects

One of the best reasons contributing to the ever-growing interest in the context of such structures is environmental benefits of natural fiber-reinforced composites. Natural binders transformation since it is renewable and biodegradable as compared to that of synthetic binders that are petroleum based. Carbon emission during natural fiber manufacturing process is considerably low as compared to that of other man-made fiber and is a leading factor in changing to more environmentally friendlier manufacturing processes in all sectors. In as much as a good natural fibre has these advantages, it also possesses certain disadvantages in terms of water absorption challenges which could lead to eventual consequent degradation of its mechanical characteristics within a given time. To mitigate this, the recent research has put an emphasis on the development of techniques of treating fiber that would enhance the durability of the natural fiber composites such as the chemical treatment and changes done to the surface.

7.5 complexities and limitations

There are also certain obstructions in addition to high opportunities of Fiber-reinforced polymer composites. This poses the biggest loss of natural fiber composites since they cannot be so strong in terms of their mechanical features compared to the manmade fibers. Additionally, natural fibers are also moisture sensitive and hence it is also a cause of concern as it can lead to swelling, loss in strength and degradation. Further improvement of fiber-matrix interaction, fiber treatment and in inventing hybrid composite so that the advantages of both the natural and artificial fiber can be combined are necessitated to transmute these challenges.

Also, it is unaware of the financial benchmark of the high-performance practices of using natural fibers as opposed to the other factors that could be expensive in terms of the processing cost and treatments of the fibers. There is however an opportunity that such challenges will be overcome in future since the processing means are improving now and the consumer is becoming more demanding to have sustainable products.

In conclusion, FRP composites are the rapidly emerging material which has a colossal prospect of application in different spheres. On the one hand, the glass and carbon synthetic fibres will continue to be the leader due to their high mechanical properties; on the other hand, it is possible to consider the natural fibres as the potential tool to become sustainable. The hybrid composites, made by use of both fibers are good alternative because it combines the requirements of high performing composites and sustainable composites. Processing such as RTM and compression molding have been developed in a bid to drastically improve the efficiencies of the fiber-reinforced composites. However, the problems related to mechanical properties and environmental resistance of natural fibers, nevertheless, remain, and one should scale the technologies in question in order to enhance their performances to make them viable in a broader commercial scope.

8. Study Problems

The present research acknowledges the constraints that determine the direction of the research as it takes into account the insufficient range of fiber types that have been studied in fiber-reinforced polymer composites (Pervaiz et al., 2021). Mostly, the researched materials are made of fibers that are present in most applications and thus cannot recognize the delicate nature and also the design characteristics of composites that have new and less popular types of fibers (Gnatowski et al., 2019; Gupta & Srivastava, 2015). The inclination to create clear-cut fiber types, which creates a solid foundation of composite behaviour, may still be considered, inarguably, not that comprehensive as the bulk of the design chocolate bar that the choice of available reinforcing materials opens (Rajesh et al., 2023). To provide a more detailed examination of fiber reinforced polymer composites and the abilities and limitations of the same, a wider aspect of different types of fibers must be addressed, using natural resources gained fibers, used recycled products, or enhanced synthetic polymer, to have a more balanced outlook of the fiber reinforced polymer composites (Asmatulu et al., 2013). Also, the fact that not much attention was paid to the economical and social implications attached to the use of natural fibers in the production of composites may be attributed to another key limitation. In spite of the fact that technical aspect of the natural fiber composites is addressed, even deeper investigations of economical feasibility and market patterns, as well as the social impact of such manufacturing of such composites and their application, should be undertaken in order to obtain a more accurate understanding of the full sustainability and chances of production of such composites in large scale (Ebissa et al., 2022). They should conduct an entire lifecycle review (environmental implications as well as economic implication and the social implication) to provide the best analysis of the trade-offs that such natural fiber composites make on the ones of the synthetic substitutes. It also deserves to be said that fiber-reinforced polymer composites use in aerospace, marine domain, civil practice, medical practice, and energy are getting extremely popular due to its capability to resist a high regime of force loads and be easy to use (Das et al., 2022).

9. Future Scope

The increased awareness towards environmental issues and the need to introduce new materials that are environment friendly prompted the study to concern itself with the designs of the green composite materials (Plackett et al., 2003). The new materials represent the potential of both natural fibers and bio-based resins in a combined form, which can be used as a competitive add-on to conventional synthetic composites, which occasionally have disposal and environment- related concerns (Kiruthika, 2021; Shrigandhi & Kothavale, 2021). The future studies may be directed at a more environmentally friendly and less expensive production of composite materials due to the targeted utilization of natural fiber and bio-derived resins (Hadibarata et al., 2022; Rao et al., 2021). With the bolstering of mechanical characteristics of the natural fiber composites, the addition of enhanced nanomaterials can prove to be gigantic and offer the material to different branches of engineering (Ateş et al., 2020). With the emphasis being laid on the biodegradable materials made out of natural fiber reinforced composites, much can be accomplished and the future world can be safer and greener and the lives of the next generation can be better lived (Plackett et al., 2003). Hybrid composites are also fluent and can be applicable in the new technologies any and above all in the fields of renewable energy technologies and biomedicines which is supposed to be exploited more (Parashar & Tomar, 2019). Such concerns such as high investment cost, difficulty of technical integration, the implementation of rigid regulatory framework should be dealt with so that using sustainable materials is easy both in construction industry and any other industry (Firoozi et al., 2024).

CONCLUSION

Fiber reinforced polymer composites are important materials, which bear unconventional combinations of forces, pain and plume. The study sheds light on the new importance of the synthetic fibre and the natural fibres in the production process of such things. Synthetic fiber such as those made of glass and carbon are far much better than the natural fiber in performance but on the other hand the natural fiber is green and easily accessible at low cost. The destiny of fiber-reinforced polymer composites is encouraging due to the new advances in the area of processing technology and researches of hybrid composites. The materials will be highly useful in the various industrial sectors in automotive, aerospace and construction to balance newer and utterly environmentally friendly manufacturing procedures.

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