A Comprehensive Review of High Performance Synthetic Fibers for Composite Materials & it's Application

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Abstract

Synthetic fibers, engineered through chemical synthesis, differ significantly from natural fibers derived from living organisms like plants and animals. These fibers are a product of extensive research aimed at mimicking the properties of natural fibers, involving processes such as extruding materials through spinnerets to form fibers. The widespread application of synthetic fibers spans various fields of fiber and textile technology, reflecting their integral role in modern material science. However, their production and use also contribute to environmental issues, such as micro plastic pollution from laundry machines. This review explores the evolution and impact of synthetic fibers, particularly focusing on their reinforcement capabilities in polymer matrix composites (PMCs). These composites are favoured for their lightweight properties coupled with enhanced stiffness, modulus, and strength, making them ideal for numerous industrial applications.

This review emphasize the significance of synthetic fibers in advancing composite material technologies and highlights the ongoing challenges and future research directions aimed at mitigating environmental impacts while enhancing material properties.

Key words:
Synthetic Fibre, Fibre Reinforced Composites, Properties, Application

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1.0 Introduction

Synthetic fibers (SFs) are becoming increasingly significant in fiber-reinforced composite structures worldwide. Due to their lightweight nature and distinct properties, SFs are highly valued for their exceptional characteristics [1, 2, 3]. They are extensively used in developing innovative composite materials for the automotive and aerospace sectors, prized for their outstanding strength and stability [4, 5].

The exploration and application of synthetic fibers are more crucial than ever, as their role in composite reinforcement has revolutionized various industries, including sports equipment and aerospace. Fiber-reinforced composites, for example, provide innovative solutions to previously unsolvable challenges, showcasing a compelling blend of materials science and engineering [6]. This introduction highlights the importance of these fibers, emphasizing their role in advancing composite materials that meet the stringent demands of modern, high-tech applications. Reinforcements in polymer matrix composites (PMCs) are indispensable for bearing structural loads, requiring compatibility with the matrix, the ability to form chemical bonds or adhere effectively, superior properties to the matrix, optimal orientation, and appropriate shaping [7, 8].

This review article seeks to provide an in-depth exploration of high-performance fibers, examining their various types, properties, and applications within composite materials. It will start with a look at the range of synthetic fibers utilized for composite reinforcement, analyzing their main characteristics and the benefits they offer over natural fibers. Following this, the article will delve into the different manufacturing techniques for composites, emphasizing how these processes affect the final product's performance. Additionally, recent research advancements and emerging trends in high-performance composite applications will be discussed, offering valuable perspectives on the continuous innovations within this field.

2. Types of Synthetic Fibre:

Designed for high-performance applications, synthetic fibers come in a range of materials, each with special qualities and applications. High performance synthetic fibres (HPSF) are designed to satisfy particular needs in a

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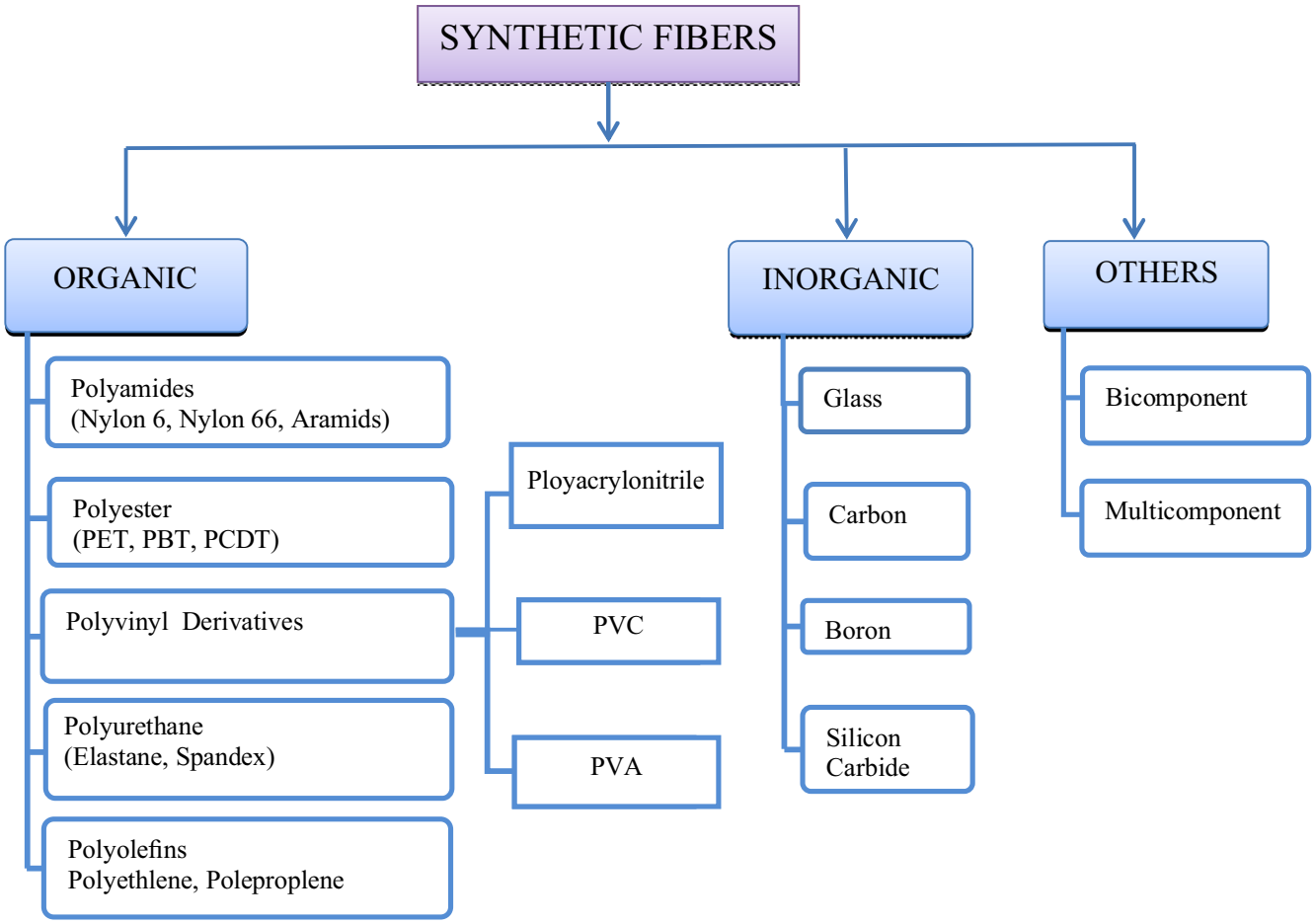

Fig 1. Classification of synthetic fibers.

range of industries because of their remarkable qualities, including conductivity, elongation, modulus, tensile strength, and environmental friendliness. For both traditional and high-tech applications, glass, carbon, aramides, polyolefins, and ceramic fibers are frequently utilized to reinforce composite materials [9,10,11].

3. Fibre properties & their application in composites:

3.1 Polyamides:

The research and manufacturing of textile composites heavily relies onpolyamides, such as Nylon 6, Nylon 66, and Aramid, because of their special qualities and adaptability. These substances are used in many different applications, improving composites' durability and mechanical performance. High mechanical strength and flexibility are characteristics of polyamides. They continue to function at high temperatures, which is essential for applications where heat exposure is present. Because of their chemical resistance, polyamides last longer in a variety of settings [12,13]. Although polyamides have several benefits in textile composites, issues including production hurdles and cost concerns may prevent them from being widely used in some industries, including the military, sportswear, automotive, and aerospace [14].

3.2 Polyesters:

Polyester fibers are appropriate for a variety of uses in textile composites due to their diverse range of characteristics. Because of their great tensile strength, polyester fibers are perfect for structural uses in composite materials. Stretchable fabrics benefit from the latent crimping qualities of some polyester composites, which are enhanced by substantial thermal shrinkage. The structural integrity of the composite is improved by the mixture of polyesters with different inherent viscosities, which enables customized mechanical properties. In line with material science's sustainability objectives, several polyester composites are made to decompose naturally [15]. Polyesters are used in composite materials because of their high strength and low weight, which are essential for the automotive and aerospace sectors. Because of its affordability and mechanical strength, polyester composites are being utilized more and more in geotextile applications [16,17].

3.3 Polyurethane(Elastane,Spandex):

Polyurethane fibers, like Elastane and Spandex, are valued for their elasticity and are predominantly used in the fashion industry, particularly in the manufactureof stretchable clothing. These fibers provide comfort and flexibility, enhancing the functionality of everyday garments [18].

3.4 Polyolefins(Polyethylene,Polypropylene):

Polyolefins, including polyethylene and polypropylene. Polyethylene fibers, particularly ultra-high molecular weight polyethylene, are valued for their lightweight and abrasion-resistant properties. These fibers are usedextensively due to their high strength and minimal moisture absorption, which are beneficial in both consumer products and industrial applications. Polypropylenes are known for their chemical resistance and are used in a myriad of products from packaging to textiles.These fibers are appreciated for their lightweight and durable nature, which makes them suitable for a wide range of applications [19]

3.5 Glass fibre:

Glass fibers offer a number of benefits that enhance concrete's functionality, particularly in construction applications. They improve the material's longevity, mechanical strength, and resistance to environmental effects when added to concrete formulations. Increased fiber content, however, may cause issues with flowability and workability.

Concrete's mechanical properties and durability are greatly improved by glass fiber reinforcement. It increases tensile strength to [20] in certain mixes and compressive strength [21] with the proper fiber content. Additionally, glass fibers improve the flexural strength of concrete, increasing its ability to withstand bending stresses. Strong alkali resistance, reduced water absorption for longer lifespan, and chemical resistance against a range of substances, including Portland cement byproducts, are all advantages of durability [22]. However, there are workability problems; higher fiber doses might result in increased water consumption and decreased flowability, which calls for the use of plasticizers. Both of these factors need to be managed to maintain optimal strength. Therefore, even though glass fibers significantly improve concrete's strength and durability, it is important to carefully analyze how they affect workability for optimal outcomes [23]. Glass reinforced polymer composites (GRPCs) are employed in a wide range of sectors due to its low cost, strength, and portability. GRPC is utilized in roof sheets, windows, sunshades, bathtubs, and other house and furniture storage racks. However, GRPC is widely used in aviation and aerospace for engine cowlings, luggage, containers, and gadget enclosures because other materials often better meet core aircraft needs. Because of its durability and low weight, GRPC is perfect for boat building, while contemporary resins help with water absorption problems. GRPC is widely used in the automotive industry for body frames, door boards, windshields, and other parts, frequently as an affordable substitute for metal assembly [24].

3.6 Carbon Fibre:

Carbon fiber is a desirable material in many high performance applications due to its exceptional qualities. Carbon fiber composites frequently outperform conventional materials due to their remarkable mechanical qualities, which include high modulus and tensile strength. Modifications like acid treatment can improve their overall mechanical performance and impact resistance [25]. Carbon fibers are appropriate for high-temperature applications because of their stability in terms of thermal and electrical conductivity at high temperatures. They also have outstanding electrical conductivity, which is useful for applications that need shielding from electromagnetic radiation [26]. In order to lessen dependency on petroleum-based supplies while maintaining desired mechanical qualities, research on bio-based carbon fibers made from lignin and cellulose is progressing [27].Since carbon fibers are an excellent material with high strength, stiffness, and low weight, the aerospace industry is using them extensively. They came to the conclusion that carbon fibers could offer corrective solutions for a wide range of issues related to the strengthening and degradation of infrastructure [28]. Application of carbon fiber composite material to make printing press and printer rollers, corrosion-resistant materials, and shielding materials [29].The composite material that has the biggest influence on high speed, safety issues, and fuel efficiency is employed in the manufacture of cars. They came to the conclusion that carbon fibers are lighter than traditional materials and may be more advantageous for production that is more economical [30].

3.7 Silica Carbide Fibre (SiC):

SiC fibers' strong performance across a range of parameters is demonstrated by their mechanical characteristics. The ultimate tensile strength and elastic modulus ofSiC fibers are both average [31]. They have outstanding thermal stability, retaining their mechanical integrity even under oxidizing and mechanical stress circumstances at temperatures as high as 1200 degrees Celsius. They can also be used for extended periods of time in hot conditions due to their improved creep resistance [32]. SiC fibers often exhibit superior tensile strength and toughness in comparison to other ceramic fibers. They are also resistant to heat shock, but other ceramic fibers might be more prone to losing strength when exposed to heat [33].Due to their exceptional strength and thermal stability, silica carbide fibers are well suited for high-temperature applications, including turbines for power production, spacecraft, burners, nuclear applications, and airplane engines. When it comes to resilience to environmental conditions and longevity, these fibers provide notable benefits [34].

3.8 Bio Component Fibres:

Fibers that have two different raw material components in one fiber are known as bi-component fibers. Typically, a melt spinning machine is used to prepare bio component fibers. The most prevalent forms of bi-component fibers are segmented-pie (orange), islands in the sea (I/S), side-by-side (S/S), and core-sheath (C/S). The advantages of both components such as strength, hydrophilicity, affordability, etc. are combined in bi-component fibers. C/S bi-component

fibers are frequently utilized as bonding/binding fibers in the nonwoven sector. While micro denier fibers are produced by a very sophisticated extrusion known as a segmented pie fibers are usually used to create self-crimping yarns. Bi-component fiber is anticipated to have significant growth in the upcoming years. In order to address issues and satisfy consumer demands, this kind of fiber is anticipated to advance as a material in a wide range of end-use industries, such as textiles, automotive, home decor, and hygiene [35].

3.9 Multicomponent:

To get particular qualities, such high tenacity or fine denier, multicomponent fibers combine several types of polymers. These fibers are employed in sophisticated applications where certain qualities are essential, such as textiles and filtration [36].

4. Different Manufacturing Techniques for Composites:

4.1 Hand Lay-up:

The Hand Lay-up method is one of the oldest and simplest techniques used in the manufacturing of composites. It involves manually placing the fiber reinforcements into a mold and then applying the resin to saturate these fibers. This method is highly favored for its low cost and the ease of implementation, particularly suitable for large or complex shapes.

4.2 Vacuum Bagging:

Following the initial lay-up, Vacuum Bagging enhances the consolidation and adhesion of the composite materials by applying a vacuum to remove air trapped within the lay-up. This process not only improves the structural integrity but also reduces voids and ensures a more uniform thickness and resin distribution throughout the composite material.

4.3 Resin Transfer Molding:

Resin Transfer Molding (RTM) involves injecting resin under pressure into a fiber preform contained within a mold. This method allows for greater precision in controlling the fiber-to-resin ratio and can be used to produce complex geometric shapes with improved surface finishes and structural properties.

4.4 Low-Temperature Prepreg:

Low-Temperature Prepreg techniques involve the use of pre-impregnated fibers (prepregs), where the fibers are pre-coated with a partially cured resin. This allows for easier handling and more accurate placement. The curing process occurs at lower temperatures compared to traditional prepreg methods, making it suitable for applications sensitive to high temperatures.

4.5 Spray Lay-up:

Spray Lay-up is similar to hand lay-up but involves spraying the resin and chopped fibers simultaneously onto the mold. This technique is faster than hand lay-up and allows for a quicker build-up of the composite material, making it ideal for large-scale productions or items requiring a thicker composite structure [37].

5. Application in Composite Materials:

5.1 Aerospace:

Synthetic fibers like glass and carbon are essential to the aerospace industry since they are used to make airplane parts. These fibers are included into important parts, such as the engine and fuselage, because of their exceptional strength-to-weight ratio and heat resistance. For instance, to ensure longevity, carbon fibers are woven in a linear sequence inside the fuselage, whereas aramid and Dyneema textiles reinforce the structure in places like the wheels, engine, and flaps. Synthetic fibre reinforced polymer (SFRP) composites provide lightweight, heat-resistant solutions with remarkable mechanical, tri-biological, and electrical qualities, which makes them ideal for long-lasting aviation materials [38,39].

5.2 Automotive:

Synthetic fibers are quite advantageous to the automobile sector, especially when it comes to lightweighting and reinforcing vehicles. Carbon fibers are used in a variety of auto parts to increase performance and fuel economy by reducing weight and increasing durability. The employment of these fibers in both non-structural and structural elements demonstrates their adaptability and improves the general functionality and safety of automobiles [40].

5.3 Medical Device:

Synthetic fibers are utilized in the medical field for a number of purposes, including as implants and prostheses, where their resilience to biological conditions and compatible with human tissue are essential. These materials aid in the creation of strong, lightweight medical equipment that can comfortably and functionally serve patients even under the most demanding conditions. Composite materials have become increasingly adaptable in healthcare due to advancements in synthetic compounds, surgical procedures, and sterilization practices. These days, several implants and devices are used in modern medical applications. Composites are widely employed in artificial hearts, pacemakers, dental implants, cardiovascular transplants, cardiac valves, eyeglass lenses, sutures, skeletal and joint replacements, biosensors, and more. In the end, these materials improve people's standards of life by supporting healing, repairing defects, and replacing or restoring the function of injured or deteriorating tissues or organs [41].

5.4 Sports Equipment:

Because there is a great need for materials that are both lightweight and durable, composite materials are widely used in sports equipment. Commonly seen in products like hockey sticks, bicycles, and tennis rackets, synthetic fibers like carbon and glass offer greater strength without

sacrificing weight. The performance characteristics of sporting equipment are greatly improved by this application, giving players better handling and better results overall [42].

5.5 Geo-textile:

Another use that demonstrates the adaptability and usefulness of synthetic fibers is in geo-textiles. These materials are essential for improving soil stability, erosion prevention, and earth structure strengthening in civil engineering projects. Synthetic fibers are perfect for these applications where longevity is crucial because of their resilience to chemicals and durability [43].

6. Challenges & Limitation:

The environment and the industries involved are impacted by the numerous obstacles and restrictions associated with the development and use of synthetic fibers. Environmental effect, cost, production complexity, and recycling challenges are important considerations. Due to their production and extraction from non-renewable resources like gas and petroleum, synthetic fibers like polyester and nylon contribute to environmental deterioration, especially greenhouse gas emissions that hasten climate change. The production method also uses a lot of water, particularly when dying, which causes freshwater to be depleted and untreated effluent to contaminate the area. Since many synthetic fibers are based on petrochemicals, their production costs are correlated with the price of petroleum as well. Because of this connection, the price of synthetic fiber is susceptible to changes in the oil market, which presents manufacturers with financial difficulties. Technological and financial challenges impede the recycling of synthetic fibers. Sorting is made more difficult by the wide range of synthetic materials since different fiber types require different recycling techniques. Because recycled fibers are typically of a lower standard than virgin fibers, their attractiveness is limited, and the textile industry's transition to a circular economy is slowed down. Technical and financial limitations prevent fiber-to-fiber recycling from being widely adopted at this time; more research and funding are needed to make it reality [44].

7. Conclusion:

By exploring the diverse realm of synthetic fibers, we have brought attention to their vital contributions to the development of composite materials for a range of industrial uses. The importance of synthetic fibers has already been extensively studied, demonstrating their unmatched benefits in their durability, toughness, lightweight, and flexibility in a variety of applications, including medical devices, sports equipment, and aerospace and automotive. The various uses of these fibers as well as their synthesis methods highlight the creative approaches being used to improve their qualities and practicality in modern innovation and daily life.

Future research and development efforts must be focused on minimizing the negative effects of synthetic fibers while optimizing their positive effects, given the persistent concerns around them. Future breakthroughs are made possible by the encouraging trajectory of innovations, especially in the fields of the field of nanotechnology environmentally friendly manufacturing, and smart composite materials. With the promise of ground-breaking capabilities that will further influence the field of engineering and material science, synthetic fibers have enormous potential to contribute to technological advancement and sustainability as we investigate and enhance these materials.

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