Chapter-2

Literature review

This chapter aims to provide background information on the topics covered in this thesis and highlight the importance of the present study. It explores various aspects of Synthetic Fiber Reinforced Polymer Composites (SFRPCs), emphasizing their physical, thermal, mechanical, and tribological characteristics. Additionally, this section reviews relevant research papers available on these subjects, offering insights into the current state of knowledge in the field.

- Synthetic fibers and Synthetic fiber-reinforced polymer composites.
- Importance of Nanoparticles and its interface in Polymer matrix composites.
- Surface modification of fiber by chemical treatment and nanoparticle coating.
- Fabrication method of fiber-reinforced polymer composites.
- Physical and Mechanical properties of fiber-reinforced polymer composites.
- Thermal and thermo-mechanical properties of fiber-reinforced polymer composites.
- Tribological Properties of fiber-reinforced polymer composites.
- Analysis of the Frictional Properties of fiber-reinforced polymer Composites Using Machine Learning Techniques.

2.1 Synthetic fibers and Synthetic fiber-reinforced polymer composites

Synthetic Fiber Reinforced Polymer (FRP) Composites have gained global significance as essential materials in fiber-reinforced composite structures due to their superior mechanical properties, lightweight nature, and durability. The classification of synthetic fibers is shown in Figure 2.1. The increasing demand for high-performance and lightweight materials has accelerated the widespread use of synthetic fibers (SFs), such as carbon fibers, glass fibers, aramid fibers, and polymeric fibers, owing to their excellent

tensile strength, impact resistance, thermal stability, tribological properties, and corrosion resistance [13]. Over the last two decades, these advanced materials have become indispensable in critical applications across the aerospace, automotive, defense, marine, construction, and sports industries. While natural fibers (NFs) are considered sustainable alternatives, synthetic fibers continue to dominate due to their superior mechanical flexibility, elasticity, and resistance to moisture, chemicals, and extreme temperatures. The limited availability of natural fibers further necessitates the increased adoption of SFs, contributing to the rapid expansion of the synthetic fiber industry in diverse applications. Compared to conventional high-density metals, SF-reinforced composites offer unique advantages, such as an exceptional strength-to-weight ratio, high fatigue resistance, and outstanding electrical conductivity, making them particularly suitable for use in wind energy systems, marine structures, pipelines, and infrastructure development.

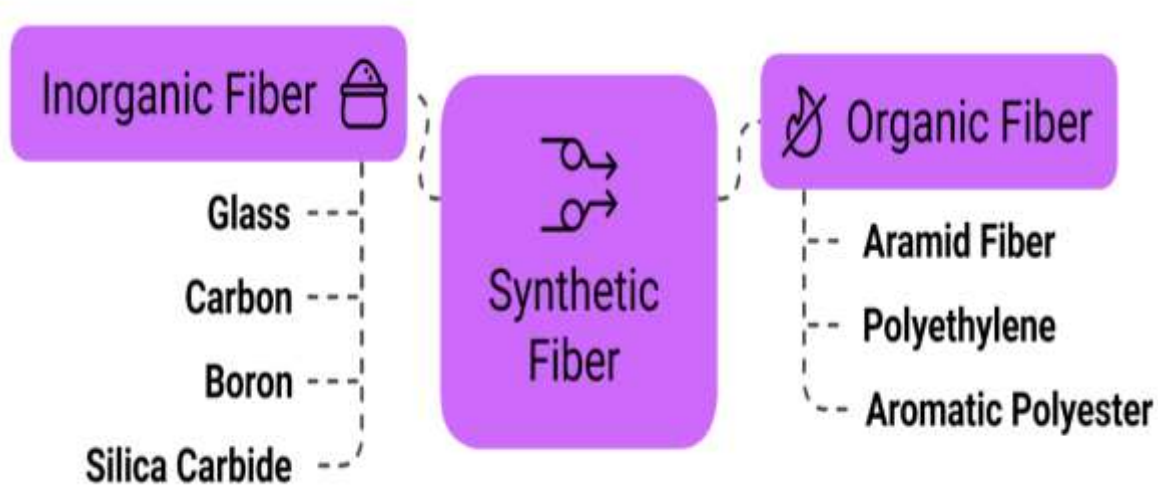

Figure 2.1 Classification of synthetic fibers

The manufacturing of synthetic fibers involves multiple processing stages, including chemical treatment, spinning, winding, and packaging, with polymerization serving as the fundamental chemical process. Polymerization involves forming

macromolecules through repeated linkages of polymer units, wherein raw materials (petrochemical-based monomers) undergo chemical modification, melting, or dissolution to produce a viscous liquid, which is then extruded into fibers using a spinneret. The industrial spinneret controls fiber diameter, a crucial factor for different industrial applications. Once extruded, the fibers are dried into continuous strands and subjected to a winding process that converts them into yarn for further processing. Electro-spinning is another widely utilized technique for producing synthetic fibers, offering precise control over fiber morphology and diameter. This electrostatic fiber production method enables the fabrication of nanofibers with high surface area-to-volume ratios, tunable porosity, and exceptional nanostructural control, making them ideal for use in medical, filtration, and energy storage applications [15]. Electro-spun fibers closely mimic extracellular matrices, making them suitable for biomedical applications such as tissue engineering, wound healing, and drug delivery systems. With continuous advancements in nanotechnology, researchers are extensively exploring the remarkable nanoscale properties of electrospun fibers, which have expanded their applications in high-performance composite materials. The demand for SF-reinforced polymer composites continues to surge as industries seek stronger, lighter, and more durable materials that can withstand extreme conditions. These composites are classified based on the type of reinforcement, matrix material, and manufacturing technique, offering significant enhancements in load-carrying capacity, toughness, fatigue resistance, and impact strength. Their exceptional mechanical and thermal properties make them ideal for various industrial applications, including structural engineering, marine infrastructure, sports equipment, and high-performance infrastructure development. The mechanical properties of synthetic fiber as shown in Table 2.1. By integrating advanced polymer matrices with high-strength synthetic fibers, FRP composites consistently outperform conventional materials in terms of strength, durability, and

environmental resistance. Furthermore, synthetic fiber composites play a crucial role in reinforced concrete applications, where they enhance structural integrity, improve load distribution, and prevent crack propagation. This has led to their widespread use in bridge construction, rehabilitation of aging infrastructure, and seismic retrofitting, providing corrosion-resistant and high-strength alternatives to traditional steel reinforcements. In the renewable energy sector, synthetic FRP composites are extensively used in the manufacturing of wind turbine blades, where their lightweight and high stiffness properties contribute to improved energy efficiency and extended operational life. Recent advancements in fiber hybridization, nanomaterial reinforcement, and additive manufacturing techniques have further expanded the capabilities of FRP composites, enabling the development of smart materials embedded with sensors, self-healing properties, and enhanced recyclability [14]. These innovations are instrumental in extending the lifespan of FRP structures and reducing maintenance costs, making them increasingly viable for long-term applications.

Table 2.1 Mechanical properties of synthetic fibers [16]

Fiber	Tensile Strength (MPa)	Young's modulus (GPa)	Density (g/cm^3)	Elongation (%)
Carbon	4000	230-240	1.4	1.4-1.8
Aramid	3000-3150	63-67	1.4	3.3-3.7
E-glass	2000-3500	70	2.5	2.5
S-glass	4570	86	2.5	2.8

In response to growing environmental concerns, researchers and engineers are focusing on sustainable alternatives, such as bio-based polymer matrices and recyclable synthetic fibers, to minimize the ecological impact of composite waste disposal. Efforts are also directed toward improving fiber-matrix bonding, hybrid reinforcement systems, and advanced recycling technologies to enhance the mechanical and tribological performance

of FRP composites. Additionally, advancements in automated composite manufacturing, 3D printing, and nanotechnology are revolutionizing the production of high-performance composite materials, making them more efficient and cost-effective [17]. The future of synthetic fiber-reinforced polymer composites lies in the development of multifunctional materials that integrate smart technologies, improved sustainability, and adaptive performance. With continued research in material science, automated manufacturing processes, and nanocomposites, synthetic FRP composites will remain at the forefront of modern engineering applications, driving progress in lightweight, high-strength, and durable material solutions across various industries. The integration of cutting-edge innovations such as self-sensing materials, embedded electronic components, and adaptive structures is expected to push the boundaries of FRP composite applications in aerospace, defense, and space exploration. Additionally, advancements in computational modeling and artificial intelligence-driven material design are facilitating the optimization of composite performance, allowing for the development of next-generation materials tailored for extreme environments [18]. The versatility of synthetic fiber composites ensures their continued relevance in industrial and consumer applications, where demand for lightweight, durable, and corrosion-resistant materials is ever-increasing. The continued adoption of FRP composites in advanced manufacturing and infrastructure projects signifies their importance in shaping the future of sustainable engineering solutions.

2.2 Importance of Nanoparticles and its interface in Polymer matrix composites.

2.2.1 Importance of Nanoparticles in Polymer matrix composites.

Nanoparticles, such as carbon nanotubes (CNTs) and montmorillonite, have significantly advanced in recent years and are now extensively utilized in polymer

composites across various industries, including electronics, aerospace, sports, and entertainment. Their unique nano-scale structure, exceptional mechanical strength, and high surface area make them highly effective as reinforcement agents, improving the overall mechanical, thermal, and tribological performance of polymer matrices [19, 20]. Among these, graphene nanoplatelets (GNPs) are particularly effective in polymeric matrices, where they contribute to enhancing wear resistance, structural integrity, and load-bearing capacity. Additionally, the incorporation of solid lubricants, fibers, and nanoparticles into polymer composites further improves tribological properties, reducing friction and wear while also lowering manufacturing costs, making them more viable for large-scale applications [21]. The addition of nanoparticles in polymer nanocomposites has been widely recognized for its ability to improve mechanical strength, thermal stability, and electrical conductivity, making these materials suitable for advanced structural applications where durability and high performance are required [22].

One of the key factors in determining the effectiveness of polymer-based nanocomposites is the interface between the polymer matrix and fiber, as the interfacial surface area plays a critical role in defining the composite's overall properties. A strong interfacial bond between fiber and polymer chains enhances load transfer efficiency, improving mechanical properties, thermal resistance, and impact strength [23, 24]. Furthermore, the uniform distribution of nanoparticles ensures the formation of hydrogen bonding interactions between the fiber and matrix, which further contribute to thermal stability, increased storage modulus, and enhanced mechanical integrity. These nanoparticles also function as stress-transfer agents, restricting matrix chain mobility and dislocation movement, which in turn hinders crack propagation, leading to increased fracture toughness and long-term durability [25, 26]. Additionally, nanoparticles serve as

nucleating agents, promoting controlled crystallization and influencing composite microstructure, thereby optimizing material morphology and performance [27].

The synthesis and processing of nanoparticles are crucial for ensuring their structural integrity and functional efficiency in polymer nanocomposites. Various techniques are employed to fabricate these nanoscale materials, including mechanical and chemical exfoliation, which effectively overcome van der Waals forces between layers of graphite, facilitating efficient layer separation and dispersion. Other widely used synthesis methods include sol-gel processing, which transforms precursor solutions into gel-like networks that are later processed into nanoparticles, and hydrothermal synthesis, where nanoparticles are formed under high-pressure and high-temperature aqueous conditions. Additionally, chemical vapor deposition is used to generate nanoparticles through gas-phase chemical reactions, depositing ultrafine layers onto a substrate. Mechanical milling, which produces nanoparticles through mechanical deformation, grinding, impact, or Physical vapor deposition, which involves vaporizing materials onto a substrate to facilitate nanoparticle formation, are also widely utilized techniques [28, 29].

The integration of nanoparticles into polymer composites significantly enhances their mechanical robustness, tribological properties, erosion resistance, thermal and electrical conductivity, barrier performance, and flammability resistance. These enhancements contribute to increased dimensional stability, optical properties, and lightweighting, making these materials suitable for applications that require high durability and multi-functional properties. Moreover, nanoparticles enable the development of customized functionalities, such as antimicrobial coatings, self-healing surfaces, and smart materials with tailored responses to external stimuli. As a result, polymer-based nanocomposites reinforced with nanoparticles are increasingly being adopted in high-

performance industries, including automotive, biomedical, and defense sectors, where advanced material properties are essential for safety, reliability, and efficiency [30, 31].

Further advancements in polymer nanocomposites are focused on improving their processing techniques and compatibility with various polymer matrices. One of the major challenges in incorporating nanoparticles into polymers is achieving uniform dispersion and preventing agglomeration, which can lead to defects and reduced mechanical performance. Cicco et al. [32] are exploring surface functionalization techniques, where nanoparticles are chemically modified to enhance their affinity with polymer chains. Functionalized nanoparticles exhibit better dispersion and stronger interfacial adhesion, leading to improved load transfer efficiency and mechanical integrity of the composite material. Another promising area of research is the development of hybrid nanocomposites, where multiple types of nanoparticles are combined to achieve synergistic effects. These hybrid approaches are particularly useful in applications requiring multifunctionality, such as electromagnetic shielding, flexible electronics, and thermal management systems. The thermal properties of polymer nanocomposites are also significantly improved by incorporating nanoparticles as observed by [33] et al. Nanoparticles with high thermal conductivity, such as boron nitride and alumina, facilitate efficient heat dissipation, reducing thermal expansion and improving dimensional stability. This makes them ideal for applications in electronic packaging, heat exchangers, and aerospace components, where thermal management is crucial for performance and reliability.

In the biomedical field, nanoparticles in polymer composites have opened new possibilities for advanced healthcare applications. Electrospun nanofiber scaffolds containing bioactive nanoparticles are widely used in tissue engineering and regenerative medicine. These scaffolds mimic the extracellular matrix, promoting cell adhesion, proliferation, and differentiation. Additionally, polymer nanocomposites embedded with

silver or zinc oxide nanoparticles exhibit strong antimicrobial properties, making them suitable for medical implants, wound dressings, and drug delivery systems [34]. The impact of nanoparticles on the tribological performance of polymer composites has been extensively studied, with significant improvements observed in wear resistance, friction reduction, and lubrication efficiency. The addition of nanoparticles such as graphene, molybdenum disulfide, and polytetrafluoroethylene (PTFE) enhances the self-lubricating properties of polymers, reducing material degradation and extending service life in high-wear applications. These benefits have led to the widespread adoption of nanoparticle-reinforced composites in automotive components, industrial machinery, and aerospace bearings [35]. Moreover, polymer nanocomposites are playing a crucial role in sustainable material development. With growing concerns about environmental pollution and plastic waste, researchers are exploring bio-based polymer matrices reinforced with biodegradable nanoparticles. Starch, cellulose, and chitosan-based nanocomposites offer a renewable and eco-friendly alternative to conventional petroleum-based plastics. These materials exhibit comparable mechanical and barrier properties while being compostable and environmentally friendly. Nanoparticles also contribute to the flame-retardant properties of polymer composites. The inclusion of flame-retardant nanoparticles, such as layered silicates, magnesium hydroxide, and phosphorus-based compounds, enhances the thermal stability and char formation of polymers. This reduces flammability, delays ignition, and suppresses smoke generation, making these materials safer for use in construction, transportation, and electronic applications [36].

In summary, integrating nanoparticles into polymer composites have revolutionized material science by offering enhanced mechanical, thermal, electrical, and tribological properties. The advancements in synthesis techniques, surface functionalization, and hybrid nanocomposites have expanded the applications of these materials across various high-

performance industries. As research continues to focus on sustainable and multifunctional materials, nanoparticle-reinforced polymer composites are expected to play a pivotal role in future technological innovations. Their potential in emerging fields such as nanomedicine, smart textiles, and renewable energy storage highlights the transformative impact of nanotechnology on material engineering.

2.2.2 Importance of Interface in Polymer matrix composites.

The interface in fiber-reinforced polymer (FRP) composites serves as a critical transition region between the fiber reinforcement and the polymer matrix, fundamentally influencing the overall mechanical, tribological, chemical, and physical properties of the composite material. It is the zone where the fiber and matrix interact either through mechanical interlocking, physical adhesion, or chemical bonding, directly impacting the load transfer efficiency and structural integrity of the composite. The effectiveness of this interface determines the strength, toughness, and durability of the composite, making it a crucial factor in advanced material design [37, 38]. The microstructure of the interface plays a pivotal role in defining the adhesion characteristics between fiber and matrix, ensuring stress distribution and minimizing the risk of crack propagation under mechanical loads. A well-designed interface enhances interfacial bonding, promoting effective stress transmission and reducing the likelihood of delamination or fiber pull-out during mechanical loading. Researchers have demonstrated that an optimized interface with strong adhesion leads to increased impact resistance, superior residual strength, and improved environmental stability, making FRP materials suitable for applications in aerospace, automotive, and construction industries. In contrast, a weak fiber-matrix interface can lead to large-scale delamination, compromising the mechanical performance and longevity of the composite material. To enhance the interface properties, various surface treatments and chemical modifications are applied to fibers, including oxidation, plasma treatment, and

grafting of functional groups, which improve wettability and chemical reactivity, ultimately increasing adhesion strength between the fiber and matrix. Moreover, the incorporation of nanoparticles into the interface region further enhances the interfacial bond strength by acting as stress transfer agents, restricting matrix chain mobility, and promoting controlled crystallization within the polymer matrix [39, 40].

The fiber-matrix interface also governs crucial functional properties such as damage tolerance, impact resistance, and environmental stability, making it a vital aspect of composite material performance. The interphase, which is the region between fiber and matrix, exhibits unique micromechanical properties that significantly influence the bulk composite behavior. By controlling the composition, structure, and distribution of this interphase, researchers can tailor composite materials for specific applications requiring high-performance attributes. The adhesion mechanism between fiber and matrix is often attributed to three main effects: mechanical anchoring of the polymer onto the fiber surface, absorption through secondary physical bonding, and molecular interactions at the interface [41]. Synthetic fibers, despite their superior mechanical properties, exhibit relatively poor adhesion to polymer matrices due to their smooth surface and chemical inertness. To address this issue, various interfacial modification techniques have been developed to increase the surface polarity of fibers, improve their wettability, and promote stronger chemical interactions with the matrix. Additionally, optimizing fiber surface roughness can create more mechanical interlocking sites, thereby enhancing the load-bearing capacity of the composite. The control of interfacial properties is essential in ensuring the stability of the composite under varying environmental conditions, such as temperature fluctuations, humidity, and chemical exposure. The interface also contributes to the thermal and electrical conductivity of FRP composites, enabling multifunctional capabilities beyond structural reinforcement [42]. Advanced characterization techniques, such as atomic force

microscopy (AFM), SEM, and spectroscopy methods, allow for precise analysis of interfacial bonding strength, microstructural features, and failure mechanisms, further driving innovations in composite interface design. As the demand for high-performance, lightweight, and durable materials increases across industries, the continued research and development of fiber-matrix interfaces will be crucial in optimizing the mechanical and functional properties of FRP composites, ensuring their widespread adoption in modern engineering applications.

2.3 Surface modification of fiber by chemical treatment and nanoparticle coating.

2.3.1 Surface modification of fiber by chemical treatment

Surface modification of fiber by chemical treatment is a crucial technique to enhance fiber-matrix adhesion, improve mechanical properties, and ensure the durability of composite materials. Various chemical treatment methods, including oxidation, hydrolysis, sulfonation, halogenation, complexation, and desizing, have been widely explored to introduce functional groups, increase surface roughness, and promote interfacial bonding. Desizing, particularly using acetone, is a critical pretreatment for carbon fibers, as it effectively removes surface contaminants and sizing agents, thereby improving wettability and bonding properties between the matrix and carbon fiber. This process ensures better load transfer and enhances the overall mechanical properties of fiber-reinforced composites. Oxidation treatments using nitric acid, chromic acid, or potassium permanganate create hydroxyl, carbonyl, and carboxyl groups, improving fiber reactivity, while enzymatic hydrolysis and alkali treatments with NaOH or KOH increase surface roughness but may weaken fibers under harsh conditions. Sulfonation introduces sulfonic groups to improve hydrophilicity, halogenation using chlorine-based agents enhances

flame retardancy, and complexation techniques modify fiber surfaces by altering hydrogen bonding for advanced applications like e-textiles [38, 43, 44]. Among these, oxidation treatment using a mixture of nitric acid (HNO_3) and sulfuric acid (H_2SO_4) has proven to be the most effective, particularly for aramid fibers, as it alters the amorphous phase by breaking amide bonds in the fiber backbone, generating amide and carboxyl groups that enhance fiber-matrix interactions more efficiently than other methods. Unlike enzymatic hydrolysis or alkaline treatments that may degrade the fiber, the nitric-sulfuric acid treatment maintains fiber integrity while introducing highly reactive functional groups for strong interfacial adhesion. Compared to chromic acid or ozone oxidation, the HNO_3-H_2SO_4 method provides a more uniform functional group distribution, ensuring superior load transfer in composites. It also surpasses sulfonation and halogenation by reinforcing mechanical properties without compromising thermal stability, making it ideal for high-performance fiber-reinforced composites in aerospace, automotive, and defense applications [45, 46]. To further optimize CFRPs, researchers have introduced polar groups such as carboxyl, hydroxyl, epoxy, and amino, which enhance surface wettability and promote chemical bonding, while non-covalent interactions like van der Waals forces, hydrogen bonding, and electrostatic forces further strengthen the interface without reducing fiber tensile strength. Various surface treatments, including plasma treatment, sizing/coating, vapor deposition, in-situ self-assembly, chemical grafting, and multi-scale structural surface engineering, have been employed to enhance wettability, chemical bonding, and mechanical interlocking between fiber and matrix, thereby forming a transition layer that distributes stress uniformly and prevents stress concentration. Among functionalization approaches, oxidative treatments via wet chemistry, such as the Hummers method, have been the most efficient, introducing carboxyl (-COOH) and hydroxyl (-OH) groups that can be further modified for enhanced interfacial bonding. Hydrolysis under

acidic or alkaline conditions increases active functional groups such as hydroxyl, carboxyl, and amino, while phosphoric acid treatment further enhances surface activity [47, 48]. Advanced modifications, such as nitrification followed by reduction and in-situ synthesis of hyperbranched polysiloxane, improve UV resistance, surface activity, and mechanical properties, whereas mesoporous silica aerogel grafting enhances insulation properties by reducing thermal conductivity. While alkali treatments hydrolyze polymer ester bonds to increase surface roughness, their effectiveness depends on alkali concentration and can weaken fibers under extreme conditions, whereas enzymatic hydrolysis offers controlled degradation and improved adhesion. Oxidation treatments with nitric acid, chromic acid, or potassium permanganate enhance surface reactivity by introducing hydroxyl, carbonyl, and carboxylic acid groups, while ozone oxidation generates hydroxyl groups for hydrogen bonding with polymer matrices. Sulfonation improves dyeability and hydrophilicity by introducing sulfonic groups, and halogenation enhances flame retardancy using chlorine-containing agents. Complexation modifies fiber surfaces via Lewis acid-base interactions, effectively altering hydrogen bonding for applications such as metalation in e-textiles [43]. Despite the broad range of chemical treatments available, oxidation using a nitric-sulfuric acid mixture remains the most effective for aramid fibers, while acetone desizing plays a crucial role in improving carbon fiber adhesion by removing residual sizing agents. Unlike alkali or enzymatic hydrolysis, which may degrade fibers, these treatments achieve a balance between surface modification and mechanical strength, offering superior functional group distribution and enhanced load transfer in composites. Additionally, they maintain fiber thermal stability, making them the preferred choices for applications requiring high-performance, durable, and thermally stable composites. The continuous advancement of chemical treatment methods, particularly oxidative treatments and desizing using acetone,

may play a critical role in improving fiber-matrix interfaces, leading to stronger, more resilient composite materials for industrial and technological applications [49, 50].

2.3.2 Surface modification of fiber by nanoparticle coating.

The coating enhances fiber or substrate properties by applying a protective or functional layer using methods like dip-coating, electrophoretic deposition, spray-coating, and chemical vapor deposition (CVD). These techniques improve adhesion, durability, corrosion resistance, and functional performance of the fibers. The details study of coating method are as follows:

2.3.2.1 Dip Coating Method:

Various studies have employed the dip coating method as shown in Figure 2.2. To apply nanomaterials onto different types of fibers, enhancing their properties for various applications. For instance, one study has been done by Kim et al. [51], focused on creating graphene-coated glass fiber (GF) composites using dip coating for de-icing purposes. Similarly, another research project by Balaji and Sasikumar et al. [52] utilized this method to produce smart composites for Structural Health Monitoring (SHM) systems by coating Glass Fiber with reduced graphene oxide (rGO). In the case of jute fibers treated with alkali [53, 54], dip coating was employed to apply reduced graphene oxide and multi-layer graphene flakes. This process facilitated a chemical bond between the fibers' cellulose structure and GO, while the rough fiber surface effectively trapped graphene flakes, resulting in a uniform coating of carbon nanomaterials. Moreover, aramid fibers (AF) underwent surface modification through dip coating with graphene oxide, leading to improvements in tensile strength and electrical conductivity [55]. In another study [56], a one-step dipping method was utilized to create multi-scale carbon fiber (CF) or carbon nanotube reinforcements using coupling agent called KH560. Dip coating has been widely

recognized as an effective and economical technique for enhancing fiber properties in various engineering applications. This method enables the uniform deposition of carbon nanomaterials onto fiber surfaces, significantly improving mechanical strength, tribological performance, electrical conductivity, and thermal stability. The resulting smart composites exhibit superior functionality, making them ideal for applications in the automotive and aerospace industries, as well as for de-icing systems, structural health monitoring, and advanced reinforced materials. The simplicity and cost-effectiveness of dip coating further establish it as a preferred method for large-scale industrial implementation.

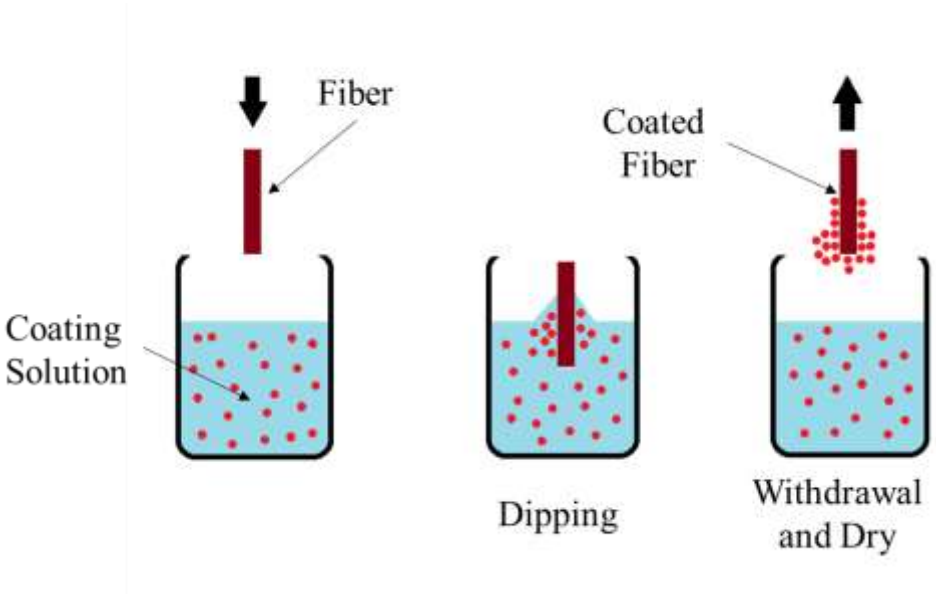

Figure 2.2. Dip Coating Method of nanoparticles on fibers

2.3.2.2 Electrophoretic Deposition Method (EPD):

Electrophoretic deposition (EPD) is a method where nano particles suspended in a fluid are utilized for coating, facilitated by an electric field between substrates and a counter electrode. This process typically occurs within a cell comprising two electrodes submerged in a dispersion of charged nano particles, with voltage applied. The EPD method, as shown in Figure 2.3, serves as a common technique for depositing nanoparticles onto various substrates [57]. Factors such as nano particle concentration in the suspension [58],

suspension stability, deposition duration, and applied voltage influence both the quality and quantity of nano particle deposition onto the substrate. In a study focusing on carbon fiber and glass fiber roving and woven fabrics, EPD was employed using aqueous and non-aqueous suspensions of GO and CNTs. The study varied the supplied voltage from 2.5 to 10 V cm^{-1} to understand the impact of GO coating on the GF surface at a constant deposition time. Results indicated a linear relationship between deposition voltage and the uniformity and quantity of GO coating on the GF surface [59, 60]. Moreover, the study by Guo et al and Deng et al. [61, 62] investigated the effect of ultrasonication during the EPD process for CNTs and GO deposition on CF surfaces. Ultrasonically-assisted EPD demonstrated increased thickness and uniformity of CNTs and GO coatings compared to the EPD-only process. To enhance composite material conductivity, electrically conducting reduced graphene oxide was synthesized from the coated GO through subsequent treatment. Another study done by Chen et al. [63] to deposit GO onto CF surfaces, subsequently chemically reducing it to rGO. EPD faces challenges such as deposition control issues, electrode polarization, limited material compatibility, and expensive related to other methods.

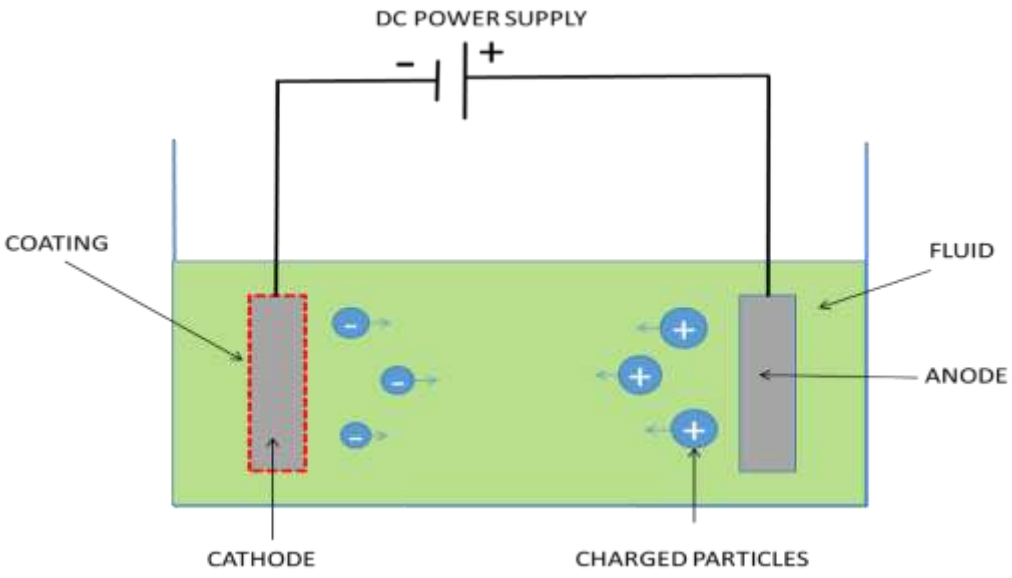

Figure 2.3. Electrophoretic Deposition Method of nanoparticles on fibers

2.3.2.3 Spray Coating Method:

Spray coating is a widely used technique for depositing nanoparticle materials onto fiber and fabric surfaces, offering a simple yet effective approach for coating irregularly shaped surfaces with nanomaterials to achieve desired properties [64, 65]. The most commonly used apparatus for spray coating consists of an airbrush gun connected to an air compressor, enabling controlled deposition of nanomaterials onto substrates. In one study, a dispersion of carbon nanotubes (CNTs) in methanol was prepared and deposited onto carbon fiber (CF) prepregs using spray coating, as illustrated in Figure 2.4. Following the spray coating process, heat was applied to evaporate the solvent, ensuring precise control of the CNT network on the surface [66]. Similarly, another approach involved dispersing graphene nanoplatelets (GNPs) in acetone, which was subsequently sprayed onto carbon fiber. Acetone acted as a carrier medium for GNPs, and upon its evaporation, a uniform GNP-coated fabric was obtained [67]. Furthermore, researchers developed conductive Kevlar fibers by spray-coating them with graphene and CNTs through a layer-by-layer process. Polyurethane served as an intermediate layer, facilitating better adhesion between the nanomaterial coating and the Kevlar fiber surface [65]. Additionally, natural fiber fabrics were coated with CNT suspensions, and the resulting composites were fabricated using the Vacuum-Assisted Resin Transfer Molding (VARTM) technique, highlighting the efficacy of this method for various composite applications [68]. Ensuring the stability and uniform dispersion of CNTs in the suspension was crucial for achieving an even distribution on the fiber surface. Dispersing CNTs in a solution containing ethanol and water resulted in a stable suspension, leading to enhanced coating quality [68]. The research findings underscore the effectiveness of spray coating in depositing nanoparticles onto dry carbon fabrics, making it a promising approach for advanced composite applications.

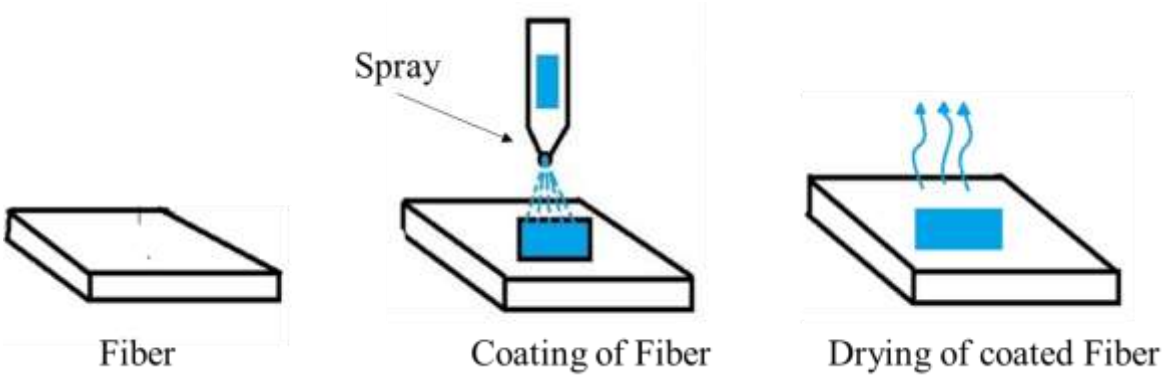

Figure 2.4. Spray Coating Method of nanoparticles on fibers

2.3.2.4 Chemical Grafting:

Chemical grafting as shown in Figure 2.5 is an effective technique for modifying fiber surfaces by covalently bonding nanomaterials through bridging agents. This method primarily follows two approaches: the graft-to and graft-from techniques. In the graft-to method, the substrate is pre-functionalized with specific chemical groups, allowing a pre-synthesized polymer to attach via a coupling reaction. This approach provides precise control over the polymer's structure and properties. Conversely, in the graft-from method, initiating groups are anchored to the polymer backbone, serving as macroinitiators for direct polymer chain growth. This enables high-density grafting and the formation of thicker polymer layers on the substrate [69]. Several chemical grafting techniques facilitate nanomaterial integration onto fiber surfaces. Ultraviolet (UV) radiation grafting, for instance, involves photosensitizing the textile substrate and exposing it to UV light in the presence of a monomer, inducing monomer grafting onto the surface [70]. Similarly, ozone treatment activates the textile surface by generating reactive sites, thereby enabling grafting [71]. A notable example is the chemical bonding of graphene oxide (GO) onto glass fiber (GF) via amidation to enhance the interfacial adhesion in GF/epoxy composites. Here, the GF surface is pre-treated with an amino-functionalized silane coupling agent, which facilitates covalent grafting of GO through an amidation reaction. Fourier-transform

infrared spectroscopy (FTIR) confirmed this covalent attachment [72]. Li et al. [73] investigated the grafting of GO onto carbon fiber (CF) using poly (amido amine) (PAMAM) as a bridging agent. The interaction between PAMAM and CF increased amino group density on the CF surface, allowing GO to be chemically bonded via PAMAM, thereby modifying the CF's surface properties. Another study employed a multi-step process where CF was initially oxidized using nitric acid, followed by acyl chloride treatment. The acyl chloride-modified CF was then covalently grafted with amino-functionalized GO in tetrahydrofuran (THF), forming a hierarchical structure with increased CF surface roughness. The GO sheets not only enhanced the composite interface but also contributed functional groups for epoxy resin interactions [74].

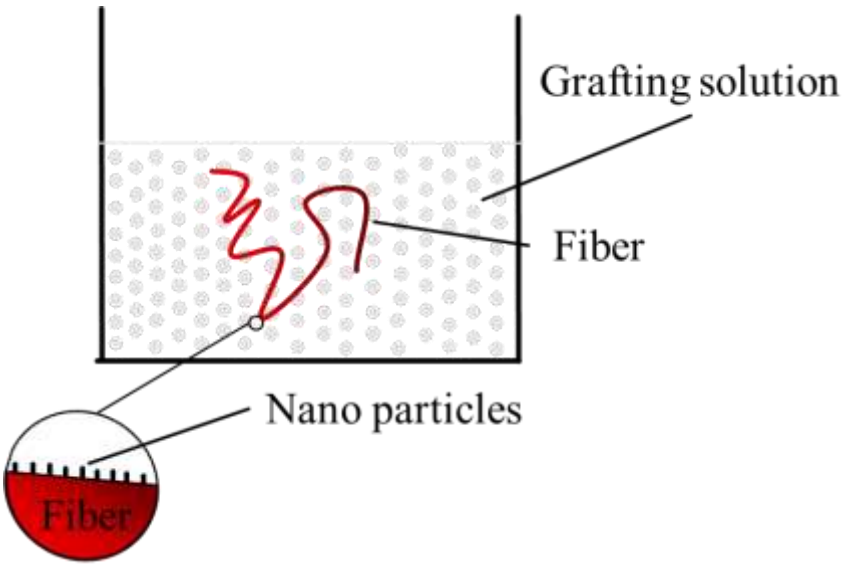

Figure 2.5. Chemical Grafting Method of nanoparticles on fibers.

2.4 Fabrication method of fiber-reinforced polymer composites.

This literature delves into different composite processing approaches employed for polymer matrix composite as shown in Figure 2.6. This section highlights various manufacturing techniques, including the hand lay-up method, open mold casting, and vacuum resin transfer molding, among others, utilized in the production of polymer matrix

composite materials as shown in Figure 2.7. The fabrication of thermoset and thermoplastic composites involves distinct industrial processes tailored to the unique characteristics of these materials. Various techniques are employed for composite component fabrication, ranging from conventional methods like injection molding to specialized approaches developed to address challenges posed by fiber-reinforced polymers. Selection of a specific fabrication method depends on factors such as the composite materials used, part design, and intended application. Molding is a crucial step in composite production, shaping the resin and reinforcement to achieve the desired form. In the realm of thermoset composites, a fundamental technique is hand layup, where layers of prepreg or dry textiles are manually stacked onto a tool. Following this, resin is applied to the dry plies through methods like resin infusion or wet layup, where each ply is coated with resin before being laid down and compacted through debulking. The choice of technique is influenced by the specific requirements of the composite part, including material composition, design intricacies, and intended functionality. Suresha et al. [75] used the open mold casting technique for the fabrication of an E-glass fiber-filled epoxy composite while using a cenosphere as a filler material with a particle size of 70-85 micrometers. The epoxy resin and hardener were blended in a weight proportion of 100:12 and homogeneously mixed. This amalgam was placed under a pressure of 0.5 MPa using a hydraulic press. Cenosphere particles were incorporated into the epoxy resin at concentrations of 2.5 and 5 wt.%. Following this, laminates were created, and specimens for the abrasion test were fashioned by cutting using a diamond-tipped cutter.

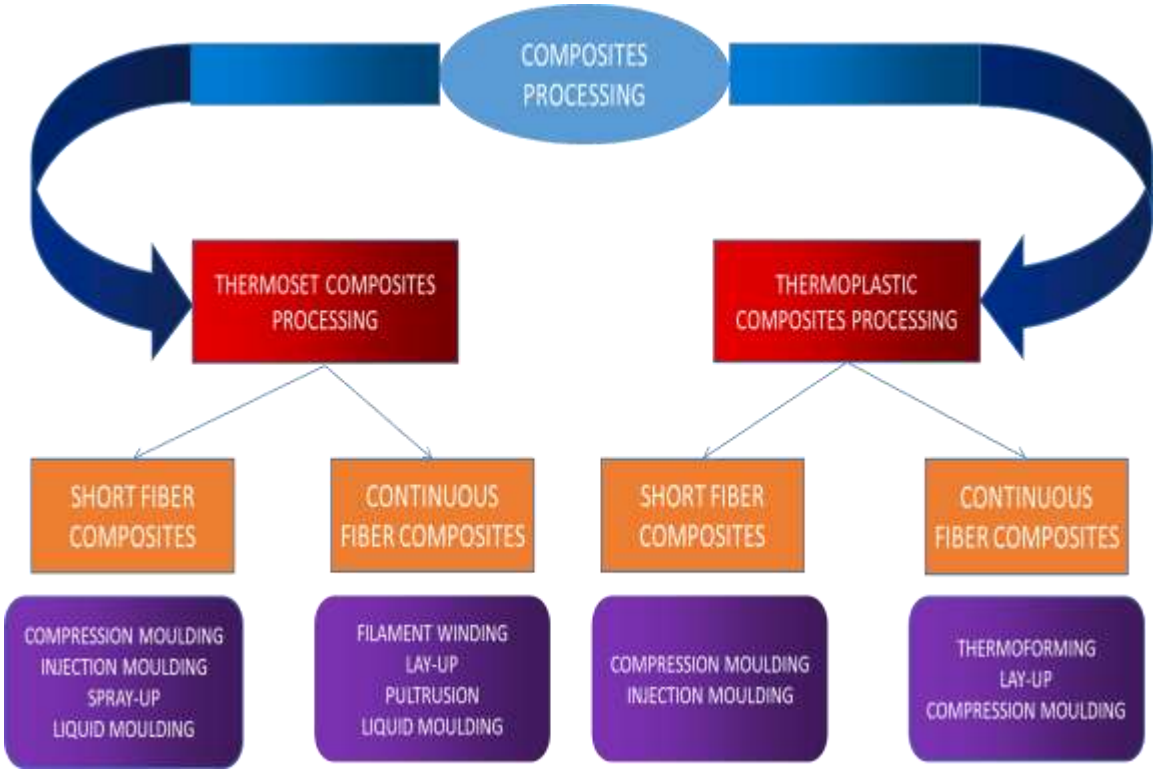

Figure 2.6. Classification of the polymer composite processing

However, Suresh et al. [76] used the open mold casting method for the fabrication of the glass fiber-reinforced vinyl ester composite. The synthesis of methyl ethyl ketone peroxide, resin, and n-dimethyl aniline involved their preparation through the application of a hydraulic press, maintaining a constant pressure of 0.5 MPa. The resulting samples were then manufactured with dimensions measuring 250 mm × 250 mm × 3 mm. Padhi et al. [77] used the injection moulding method and fabricated the short glass fiber reinforced polypropylene matrix composite. Utilizing blast furnace slag as a filler material in the range of 0-30 wt.%, the slag particulates underwent a preheating step at 80°C for 3 hours to eliminate surface moisture. The polypropylene (PP) matrix was introduced into the mold, subjected to a clamping force of 40 tons, and left to solidify before ejecting the samples using an ejection pin. Through this process, a total of eight sets of rectangular samples, measuring 25 mm x 150 mm x 3 mm, were successfully fabricated.

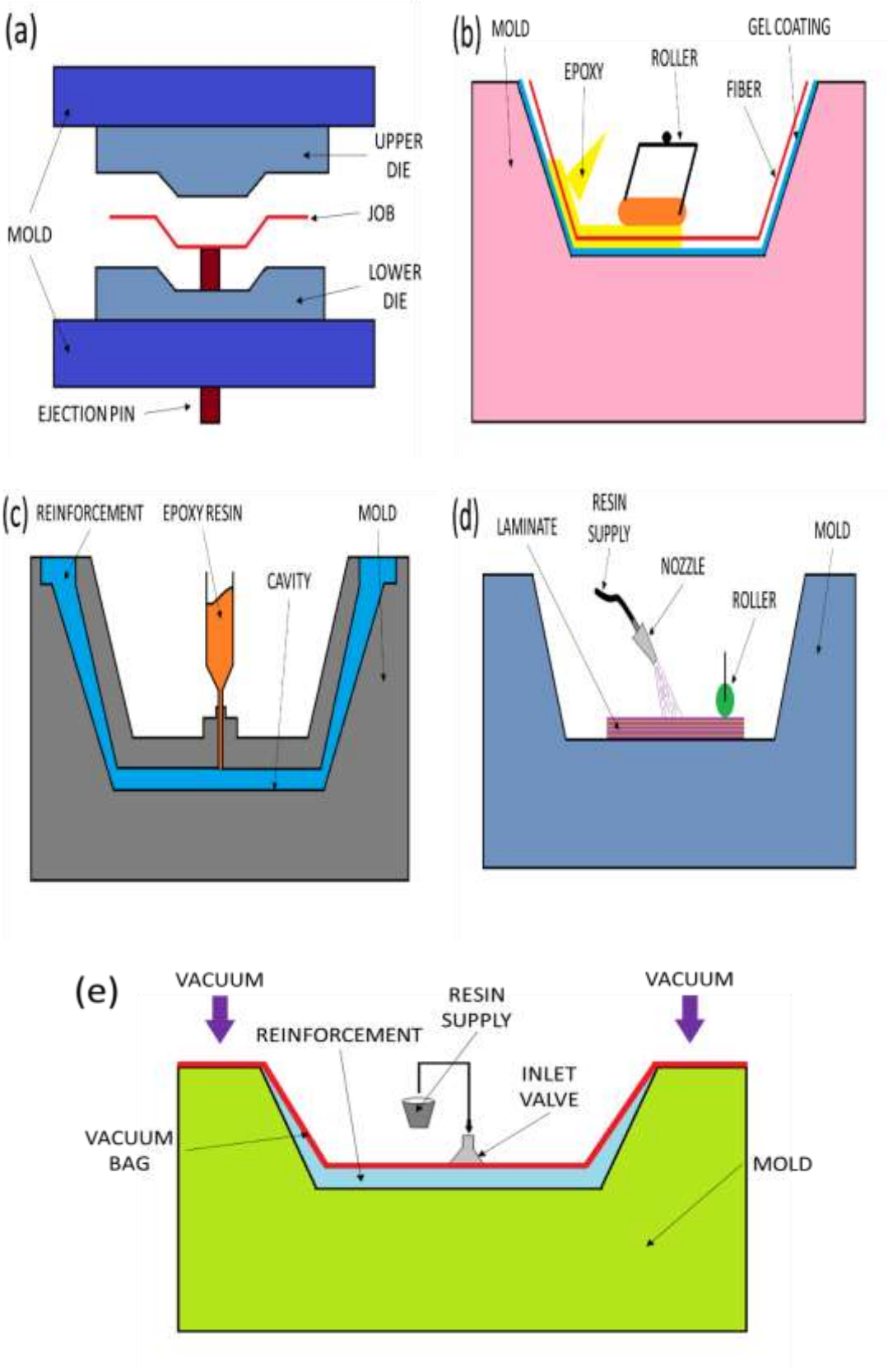

Figure 2.7. Fabrication method of polymer composite (a) Compression Molding, (b) Hand lay-up method, (c) Resin transfer molding, (d) Spray coating, and (e) Vacuum-assisted resin infusion.

Padhi et al. [78] focuses on producing composite materials incorporating chopped E-glass fiber reinforced epoxy resin matrices, featuring weight percentages ranging from 10 to 60. The compression molding technique is utilized for this purpose. Moisture removal from the fiber mats is accomplished through exposure to a hot air oven set at 150°C. Following this, the laminates are compressed within a mold and subjected to a curing process at 180°C for a duration of 3 hours. The cured composite material undergoes a gradual cooling phase, reaching room temperature to finalize the fabrication process. Conversely, Suresha et al. [79] fabricate glass fiber-reinforced polyurethane (PU) resin matrix composites, incorporating weight percentages varying from 10 to 40 (in increments of 10wt.%) using a twin-screw extruder operating at 280°C. The resin and fiber mixture is prepared through an extrusion process using a machine equipped with multiple nozzles, each set at distinct temperatures. Pellets obtained from this process are then subjected to injection at a pressure of 70 kg/cm^2 for the purpose of characterizations. In a separate investigation, Biswas et al. [80] employ the hand layup method to fabricate epoxy (LY-556) resin composites filled with 50wt.% glass fiber. Red mud is introduced as a filler in concentrations of 0, 10, and 20wt.%. The epoxy resin is mixed with a hardener in a weight ratio of 10:1. Effective curing is achieved by subjecting the mixture to a load for 24 hours at room temperature. Furthermore, Agarwal et al. [81] examine epoxy resin composites filled with 10 to 50wt.% long and short E-glass fibers using the open mold casting technique. The curing process extends for a duration of 48 hours at room temperature. Rout et al. [82] opted for the hand layup method to manufacture epoxy resin matrix composites containing 40wt.% glass fiber. Granite powder is incorporated as a filler in varying proportions, ranging from 0 to 20 wt.%. Curing is conducted under a 35 kg load for 24 hours at room temperature, with ten fabric layers forming a 5 mm thick laminate. Pawar et al. [83] adopt the vacuum resin transfer molding method to produce glass fiber-filled epoxy

resin matrix composites, with weight percentages ranging from 10 to 50 wt.%. Curing of the composite material is carried out for a 12-hour period under a load of 25 kg. Additionally, Kajorncheappunngam et al. [84] utilize the vacuum resin transfer method for the manufacturing of glass fiber-filled epoxy resin matrix composites. The curing process involves placing the fiber and resin mixture between two layers of Teflon-coated material, each having a thickness of 0.32 cm. This composite undergoes curing for 3 days, and surplus resin is removed using rollers. The final fabricated composite achieves a thickness of 1.5 mm. Among all the methods, the hand lay-up method is the simplest, cost-effective, and widely used fabrication technique for composite materials [85]. It involves manually placing fiber reinforcement in a mold and impregnating it with resin using rollers or brushes. This method requires minimal equipment, making it ideal for small-scale production and prototyping. Although labor-intensive, it allows flexibility in fiber orientation and thickness control, making it suitable for fabricating large and complex composite structures.

2.5 Physical and Mechanical properties of fiber-reinforced polymer composites.

This review highlights the impact of reinforcement on the physical and mechanical characteristics of polymer matrix composites. Various reinforcement types, ratios, and particle sizes are examined to assess their influence on these properties. The spatial distribution and orientation of micro- and nano-scale reinforcements play a critical role in determining the mechanical performance of polymer composites, affecting parameters such as strength, stiffness, and durability.

Bazrgari et al. [86] investigated the mechanical behavior of Al_2O_3 nanoparticle-reinforced epoxy (EP) matrix composites, incorporating 20 wt.% reinforcement.

Mechanical characterization was conducted using a three-point bending test, notched Izod impact test, and hardness test, employing Zwick universal testing machines, impact testers, and durometers, respectively. The findings indicated that flexural strength improved with reinforcement, while impact resistance was optimal at lower reinforcement levels. Additionally, a 1 wt.% reinforcement led to an increase in hardness. Aslan et al. [87] analyzed the mechanical properties of polypropylene (PP) composites reinforced with sisal fiber, glass fiber, and carbon fiber at varying concentrations (25, 50, and 75 wt.%). The study concluded that carbon fiber exhibited lower density, whereas a 25/75 wt.% ratio of sisal/glass and sisal/carbon fibers yielded superior mechanical performance.

Yuan et al. [88] examined the effect of carbon nanotubes (CNTs) on the mechanical properties of polydopamine (PDA)/polyethylene-imine (PEI) hybrid matrices. The results revealed improvements in tensile strength, Young's modulus, failure strain, and interfacial bonding strength with CNT reinforcement. Similarly, Li et al. [89] investigated graphene-reinforced polymer matrices, reporting increases in Young's modulus (150%), shear modulus (27.6%), and hardness (35%). Kawaz et al. [90] explored the mechanical performance of multi-walled carbon nanotube (MWCNT)-reinforced poly(methyl methacrylate) (PMMA) composites, demonstrating a direct correlation between MWCNT content and Young's modulus. Chen et al. [91] investigated graphene oxide (GO) and MoS_2 nanoparticle-reinforced bismaleimide (BMI) matrices at different loadings (0.2–1.0 wt.%), noting that 0.6 wt.% exhibited maximum impact and flexural strength.

Yan Li et al. [92] observed that the incorporation of 1.0 wt.% CNTs demonstrated the most effective reinforcement. This enhancement is attributed to the improved mechanical interlocking between the fiber and matrix, where CNTs function as nanoscale "anchors," strengthening the fiber-matrix adhesion. Omrani et al. [93] studied bio-based epoxy reinforced with carbon fiber (CF), concluding that CF reinforcement improved the

composite's modulus and strength. Hunke et al. [94] evaluated plasma-modified polytetrafluoroethylene (PTFE) micro-powders (10 wt.%) in polyethersulfone (PESU) matrices, revealing superior mechanical properties in plasma-treated PTFE composites compared to pristine PTFE. Liu et al. [95] investigated hybrid reinforcements of graphite nanoplatelets (GNPs) and graphite nanofibers (GNFs) in high-density polyethylene (HDPE), demonstrating that combined GNF/GNP reinforcements exhibited superior mechanical properties. Sudheer et al. [96] examined the effects of ceramic whiskers (PTW) (7.5 wt.%) and solid lubricant graphite (2.5 wt.%) on epoxy (EP) matrices, reporting enhanced density, hardness, tensile strength, flexural strength, and impact resistance. Huang et al. [97] analyzed the tribological properties of phenylethynyl-terminated ether-imide (PTEI)-reinforced polyetherimide (PEI) matrices, noting reduced wear rates upon reinforcement. Chang et al. [98] investigated zeolite-reinforced ultra-high molecular weight polyethylene (UHMWPE) composites (10 and 20 wt.%), showing increased modulus but reduced tensile strength and elongation at break.

Namdev et al. [99] observed that the incorporation of GNP into carbon fiber/epoxy composites resulted in enhanced tensile and flexural strength, also significantly improving the sliding wear behavior of the polymer composites. Lin et al. [100] examined carbon fiber (CF) and nano-ZrO_2-reinforced PEEK matrices (10–20 wt.%), finding enhancements in tensile strength and Young's modulus with 10 wt.% reinforcement. Aderikha et al. [101] studied RF plasma-treated poly-oxa-diazole (1.0–4.0 wt.%) reinforced PTFE matrices, reporting increased tensile strength and elongation at break. Another study by Aderikha et al. [102] on carbon black (0–10 wt.%)-reinforced PTFE showed peak ultimate tensile strength and elongation at 0.5–1.0 wt.% filler content. Suresha et al. [103] analyzed polyamide 66/polypropylene (PA66/PP) composites reinforced with graphite (2.5 and 5 wt.%), nanoclay (NC) (2 and 3 wt.%), and NC/short carbon fiber (NC/SCF) (10 wt.%),

concluding that 2 wt.% NC and 10 wt.% SCF offered optimal tensile and flexural strength, while 5 wt.% graphite exhibited the highest impact resistance. Zhang et al. [104] investigated nano-SiO_2 (0.5–4 wt.%)-reinforced PEEK composites, reporting increased Young's modulus and reduced elongation at break. Aramide et al. [105] evaluated glass fiber (5–30 wt.%)-reinforced polyester matrices, showing increased strength and modulus, with a 25% decrease in impact energy at higher fiber content. The highest tensile and flexural strengths were observed at 30 wt.% GF. Al-Alkawi et al. [106] examined the fracture toughness of glass fiber-reinforced polyester composites, finding that at 33 wt.% fiber content, tensile strength and fracture toughness decreased with increasing temperature up to 60°C.

Chen et al. [107] studied glass fiber (5–30 wt.%)-reinforced PA66/polyphenylene sulfide (PPS) blends, reporting maximum tensile and flexural strength at 30 wt.% and 25 wt.% fiber loading, respectively. Mohbe et al. [108] analyzed glass fiber and montmorillonite (Na-MMT)-reinforced polyester composites, achieving maximum tensile strength (130.03 MPa), impact strength (153.50 KJ/m²), and flexural strength (205.152 MPa) at 3 wt.% Na-MMT. Faizal et al. [109] investigated glass fiber-reinforced polyester composites, highlighting the significant influence of curing pressure on tensile modulus and ductility. Leonard et al. [110] studied mat glass fiber (12–60 wt.%)-reinforced polyester matrices, reporting peak tensile strength (325 MPa), Young's modulus (13.9 GPa), and fracture toughness at 60 wt.% GF. Alam et al. [111] evaluated the impact of fiber orientation (0°, 45°, 90°) on chopped and roving GF-reinforced polyester composites, identifying 90° orientation as yielding the highest tensile strength. Hossain et al. [112] examined woven glass fiber (E-GF) and carbon nano-filler (CNF) (0.1–0.4 wt.%)-reinforced polyester matrices, showing optimal compressive strength, modulus, and interfacial bonding at 0.2 wt.% CNF. Iba et al. [113] reported that tensile strength and

Young's modulus increased with unidirectional continuous glass fiber (0.25–0.45 wt.%) loading, with peak performance at 0.45 wt.% and 18 μm fiber diameter. Araujo et al. [114] analyzed glass fiber (20–60 wt.%)-reinforced polyester composites, observing maximum mechanical performance at 40 wt.% GF.

Gupta et al. [115] investigated glass fiber, fly ash (FA), and calcium carbonate ($CaCO_3$)-reinforced epoxy matrices, finding $CaCO_3$ composites exhibited superior compressive and impact strengths compared to FA-based composites. Kumar et al. [116] studied nano-clay (2 wt.%) and short carbon fiber (10 wt.%)-reinforced PA66/PP composites, noting optimal tensile properties. Reddy et al. [117] compared jute fiber, pineapple leaf fiber, and GF-reinforced epoxy and polyester matrices, concluding that polyester matrices exhibited superior mechanical properties. Gopinath et al. [118] evaluated jute, E-glass, and coconut fiber-reinforced epoxy and polyester composites, reporting superior mechanical performance for epoxy/glass fiber composites. Prakash et al. [119] examined silane-treated E-glass fiber (25–40 wt.%), Al-6061, and SS-304-reinforced epoxy composites, observing enhanced mechanical performance over untreated matrices. Maciel et al. [120] reported that curaua fiber (30 wt.%) and GF-reinforced epoxy composites demonstrated improved mechanical properties, with curaua fiber composites exhibiting superior strength.

Chao et al. [66] reported that CNTs improved the tensile properties of composites by enhancing interfacial bonding between carbon fibers and high-density polyethylene (HDPE), thereby improving stress transfer and reducing debonding. Pin-Ning et al. [121] investigated the effect of CNTs/GNPs hybrid reinforcement (0.5–1.5 wt.%) on interlaminar shear strength (ILSS). The study revealed that ILSS exhibited a notable enhancement up to 1 wt.% loading, beyond which a marginal decline was observed at 1.5 wt.%, likely due to agglomeration-induced stress concentrations. Kumar et al. [122] observed that 1 wt.%

addition of MWCNTs in the epoxy matrix improved the tensile and flexural strength of cured specimens compared to neat specimens due to better interfacial bonding between fiber and matrix. Zhang et al. [123] reported that the introduction of GO improved the interfacial properties between carbon fiber and the matrix, leading to a significant enhancement in interfacial shear strength (IFSS), interlaminar shear strength (ILSS), and tensile properties of the composites.

2.6 Thermal and thermo-mechanical properties of fiber-reinforced polymer composites.

This study investigates the effect of reinforcement on the thermal properties of polymer matrix composites, considering different reinforcement types, ratios, and sizes. Thermogravimetric Analysis (TGA) measures weight changes with temperature, assessing material composition and thermal stability. Weight reduction occurs as components decompose, with TGA ensuring quality control by quantifying base polymers, fillers, and plasticizers. Dynamic Mechanical Analysis (DMA) evaluates viscoelastic behavior, determining modulus variations and glass transition temperature under sinusoidal stress. Additionally, thermal conductivity is crucial for heat dissipation, enhancing performance and durability in applications like electronics and aerospace. Efficient thermal conductivity prevents thermal degradation, making it a key factor in composite material optimization for high-performance applications.

Husic et al. [124] investigated the thermal characteristics of glass fiber-reinforced polyurethane matrices derived from soybean oil and petrochemical polyol Jeffol. The study revealed that soy-based polyurethanes exhibited superior thermal stability compared to their petrochemical counterparts. Similarly, Budai et al. [125] analyzed the thermal properties of chopped glass fiber (E-GF) reinforced polyester composites, demonstrating

that increased reinforcement content delayed thermo-oxidative degradation. Lopez et al. [126] further examined E-GF/polyester composites, reporting that TGA analyses indicated mass loss increased with degradation temperature. Chen et al. [127] evaluated the thermal behavior of amino-modified graphene oxide (AMG) reinforced polyamide (PA 6), observing enhanced thermal stability and uniform dispersion of the reinforcement. Qiao et al. [128] investigated halloysite nanotube (HNT)-reinforced UHMWPE composites, noting that well-dispersed reinforcement improved thermal stability and wettability.

Zhao et al. [129] studied nano-SiO_2-reinforced polyimide composites, establishing that 5 wt.% reinforcement provided optimal thermal stability and heat resistance. Similarly, Li et al. [130] examined solvent-free graphene oxide nano-ribbons colloids (GONRM2070) in epoxy matrices and reported enhanced thermal properties at 0.6 wt.% reinforcement content. Lin et al. [131] assessed the thermal properties of PEEK matrices reinforced with short carbon fiber (SCF), solid lubricants, and submicron nanoparticles. SCF reinforcement provided superior thermal stability and wettability. Samad et al. [132] explored the thermal performance of plasma-treated single-walled carbon nanotubes (SWCNTs) in UHMWPE matrices, demonstrating improved bonding, hardness, elastic modulus, and scratch resistance. Garcia et al. [133] examined the thermal behavior of graphite and graphite oxide (GO)-reinforced polyester (PP-70), concluding that both reinforcements improved thermal properties, with GO outperforming graphite. Tiqah et al. [134] studied sugar palm (SP) and glass fiber-reinforced polyurethane composites, employing TGA and DMA to reveal that hybrid reinforcement enhanced thermal properties for automotive applications.

Shen et al. [135] analyzed glass fiber and CNT-reinforced polyamide 6 composites, noting that thermal stability increased with CNT loading, peaking at 2 wt.%. Yasmin et al. [136] investigated graphite platelet-reinforced epoxy composites, measuring the coefficient of thermal expansion via the strain gauge technique and concluding that reinforced

composites exhibited greater thermal stability than pure matrices. Nair et al. [137] examined the thermal properties of treated and untreated sisal fiber-reinforced polystyrene composites via TGA and DMA, reporting that treated fiber composites exhibited superior thermal stability. Finally, Kim et al. [138] assessed basalt fiber and natural graphite flake powder (NGF)-reinforced epoxy matrices, determining that 20 wt.% NGF yielded maximum thermal stability, while 40 wt.% provided the most efficient heat transfer pathway. Furthermore, incorporating CNTs improved both axial and transverse thermal conductivity in GF-reinforced hybrid nanocomposites [139].

Zahra et al. [140] presented the maximum degradation temperatures at each stage, demonstrating that the thermal stability of nanocomposites improved with the incorporation of MWCNTs up to 1 wt.% which result a 35°C increase in degradation temperature. However, beyond this concentration, thermal stability declined. This behavior is attributed to the intrinsic thermal conductivity of MWCNTs, which facilitates uniform heat dissipation across the phenolic matrix, thereby preventing localized overheating. Chen et al. [127] systematically investigated the thermal behavior of a polyamide 6 (PA6) matrix reinforced with amino-modified graphene oxide (AMG) at varying weight fractions (0–1 wt.%). Their findings revealed that increasing AMG content led to improved thermal stability and enhanced dispersion within the polymer matrix. Garcia et al. [133] analyzed the thermal properties of a polyester (PP-70) matrix incorporating graphite and graphite oxide (0.1–0.5 wt.%), revealing that both reinforcements enhanced thermal performance, with graphite oxide exhibiting superior stability. Shen et al. [135] conducted an extensive study on polyamide matrices reinforced with glass fiber and carbon nanotubes across a wide range of weight fractions (0.5–4 wt.%). Their analysis demonstrated a direct correlation between CNT content and thermal stability, with the highest improvement recorded at 2 wt.% CNT loading.

2.7 Tribological Properties of fiber-reinforced polymer composites

Abrasive wear in polymers is commonly classified into (a) two-body and (b) three-body wear. Two-body abrasion occurs when hard particles embedded in a surface cause material removal, which can transition into three-body abrasion, where wear debris acts as abrasive particles between contact surfaces, facilitating rolling and sliding motion [141]. This study examines the influence of reinforcement on the abrasive wear resistance of polymer matrix composites. Various nanoparticles, differing in type, size, and concentration, are analyzed for their tribological effects. Key parameters governing material wear include applied load, sliding distance, and abrasive size, all of which significantly impact real-time tribological performance and service life assessment.

Pang et al. [142] investigated the tribological characteristics of graphene oxide (GO) (0.1, 0.5, and 1.0 wt.%) reinforced UHMWPE matrix, revealing that GO incorporation enhanced strength and hardness while reducing the wear rate and friction coefficient. Similarly, Yu et al. [143] studied functionalized cubic boron nitride (FC-BN) and functionalized hexagonal boron nitride (FH-BN) (0–1 wt.%) reinforced epoxy composites, concluding that FC-BN exhibited superior tribological performance by lowering both wear rate and friction coefficient. A separate study [144] examined graphene, graphite, and perfluoropolyether (PFPE) (10 wt.%) reinforced epoxy composites, reporting that graphene-filled composites demonstrated the lowest wear rate, with friction increasing at velocities up to 0.42 m/s. Li et al. [89] analyzed graphene (0.1–1.0 wt.%) reinforced nylon 6 matrix composites, whereas Youssef et al. [145] examined carbon nano-filler (0.5–2.0 wt.%) and paraffin oil (2 wt.%) reinforced UHMWPE composites, noting that 1.0 wt.% reinforcement significantly improved wear resistance. Similarly, a study [146] assessed MoS_2 (0.25–2 wt.%) reinforced graphene oxide composites, indicating a reduction in both wear rate and friction coefficient.

He et al. [147] investigated nano-SiO_2 reinforced PTFE composites, observing a decrease in average friction coefficient with reinforcement. Golchin et al. [148] studied CNT (0.5 wt.%) and GO (0.5 wt.%) reinforced polyethylene composites, demonstrating reduced friction and wear rate. Another investigation [149] assessed carbon fiber (10 wt.%), glass fiber (10 wt.%), graphite (5 and 8 wt.%), and SiO_2 nanoparticles reinforced epoxy composites using block-on-ring tribological tests. Zhao et al. [150] examined short glass fibers (SGF) (5–15 wt.%), silica nanoparticles (3 wt.%), and graphite (3–8 wt.%) reinforced epoxy composites, finding that SGF reduced wear rate. Yan et al. [151] evaluated 3-aminopropyltriethoxysilane (APTES) (0.1–1.0 wt.%) and GO reinforced polyethersulfone (PES) composites using a universal micro-tribometer (UMT-3MT0), identifying 1.0 wt% APTES-GO as the optimal reinforcement for minimizing wear and friction. Zhang et al. [152] assessed CNT (0.2–0.4 wt.%), SCF (10 wt.%), SiO_2 (1–3 wt.%), and SGF (10 wt.%) reinforced epoxy composites, concluding that SiO_2 and SCF yielded superior tribological performance, while silica in CNT composites improved wear resistance. Zang et al. [153] analyzed monodisperse SiO_2 (5 wt.%), SCF (10 wt.%), and graphite (8 wt.%) reinforced epoxy composites using pin-on-disc tribometer, confirming that SiO_2 reduced wear and friction.

Zalazink et al. [154] investigated micro- and nano-sized MoS_2 and WS_2 (0.5–5 wt.%) reinforced PEEK composites, reporting decreased wear rates for both reinforcements. A study [155] explored (0.1–0.2 wt.%) reinforced UHMWPE composites using a ball-on-disc wear tester, with 0.2 wt.% reinforcement at 9 N load and 0.5 m/s sliding speed yielding the lowest wear and friction. Liu et al. [130] investigated functionalized fullerene C_{60} (FC60) (0.5 wt.%) and functionalized graphene (FG) (0.5 wt.%) coated epoxy composites, reporting reduced wear and friction coefficients. Mohammed et al. [156] analyzed SCF (10 wt.%), SiO_2 (5 wt.%), and graphite (8 wt.%) reinforced epoxy

composites, identifying micro-SCF and nano-SiO_2 as the most effective reinforcement combination. Song et al. [157] studied chopped carbon fiber (20 wt.%), glass fiber (5 wt.%), and MoS_2 (5 wt.%) reinforced PTFE composites, reporting optimal tribological performance with MoS_2 and glass fiber. Theiler et al. [57] investigated sliding behavior of graphite (15 wt.%), CNT (6.8 wt.%), and TiO_2 (14 wt.%) reinforced PEEK composites, determining that graphite and CNT minimized friction, while TiO_2 reduced wear. Yang et al. [158] examined GO and multi-walled CNT reinforced phenolic resin composites, confirming improved tribological performance with polydopamine functionalization. Similarly, a study [159] analyzed fluorinated graphene (FG) (0–1 wt.%) reinforced UHMWPE composites using a high-speed reciprocating friction tester, demonstrating enhanced micro-hardness and superior tribological properties at higher FG content.

Anurag et al. [99] reported that the incorporation of graphene nanoplatelets into carbon fiber-reinforced epoxy composites significantly enhances their sliding wear performance. Beibei et al. [143] observed that the wear rate of paper-based composites incorporating a synergistic combination of MWCNTs and GNPs was reduced by 65%, demonstrating superior anti-wear performance compared to composites lacking carbon nanomaterials. Z. Lin et al. [160] observed that initially, the addition of MWCNTs increased the friction coefficient (COF); however, as the MWCNT content in the sizing agent increased from 0.05 wt.% to 1 wt.%, COF decreased due to the formation of a stable, load-carrying tribo-film at the fiber-matrix interface. Zhang et al. [161] applied 1 wt.% carbon nanofibers (CNF) and multi-walled carbon nanotubes (MWCNT) to glass fiber mats before epoxy composite fabrication, followed by erosion testing. MWCNT-reinforced composites exhibited significantly lower mass loss (0.014 ± 0.003 g) than CNF-based composites (0.078 ± 0.004 g) under 30 seconds of particle erosion, demonstrating that MWCNT reinforcement effectively enhances the erosion resistance of GF/epoxy

composites. Sarah et al. [162] investigated the influence of erodent velocity, impact angle, and nanoparticle (NP) reinforcement on erosion resistance (ER). The addition of silica and alumina NPs significantly altered the erosion behavior from brittle to ductile, with hybrid nanocomposites (NCs) demonstrating superior wear resistance compared to single NP-based coatings.

Control factors and their respective levels play a crucial role in analyzing the wear behavior of polymer composites. Table 2.2 presents key machine parameters and their corresponding levels. Figure 2.8 illustrates the industrial applications of polymer composites. Finally, it was seen from various studies that composite materials, formed by combining two distinct materials, exhibit superior properties compared to conventional materials.

Table 2.2

Various predicted governing factors for different wear evaluations of polymer composites.

Control Factor	Levels				Units
	I	II	III	IV	
Coating material	C1	C2	C3	C4	unit less
Nanoparticles content	W1	W2	W3	W4	Wt.%
Normal Load	L1	L2	L3	L4	N
Sliding frequency	F1	F2	F3	F4	Hz
Discharge rate	D1	D2	D3	D4	g/min
Temperature	T1	T2	T3	T4	°C
Impact velocity	V1	V2	V3	V4	m/s
Impingement angle	A1	A2	A3	A4	degree

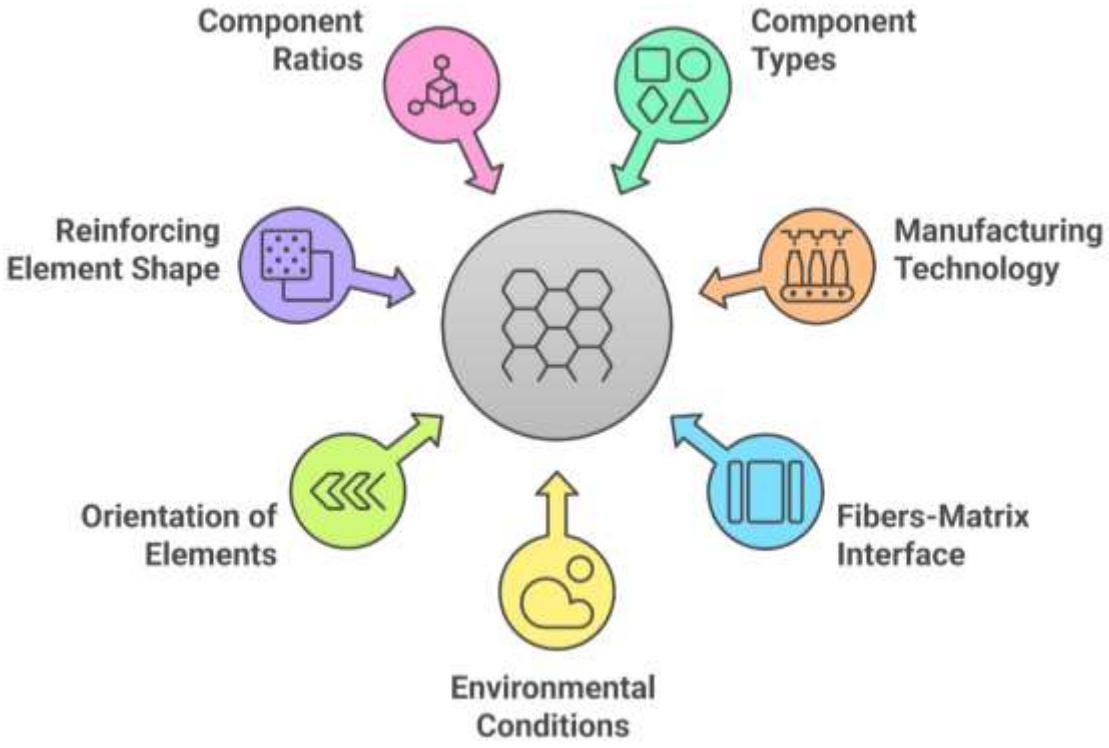

Figure 2.8 Various components and aspects of polymer composite materials.

2.8 Analysis of the Frictional Properties of Fiber-reinforced Polymer Composites Using Machine Learning Techniques.

Recent advancements in computational techniques have facilitated the analysis and interpretation of experimental data to predict the complex mechanical, tribological, and thermal properties of materials [163]. Machine learning (ML)-based data-driven models utilize existing experimental datasets and apply sophisticated mathematical algorithms to derive predictive insights. This computational approach involves extensive calculations, often requiring high-performance computing systems. Consequently, ML models can efficiently forecast material behavior under similar environmental and physical conditions, eliminating the need for repetitive experimental procedures, thereby conserving time and resources. Modern experimental methodologies integrated with predictive models exhibit strong correlations with actual experimental data, streamlining research processes and

reducing associated costs [164]. ML models play a crucial role in reducing experimental efforts and costs by leveraging existing data for predictive analysis. These models optimize design parameters, identify trends, and capture complex, nonlinear relationships more effectively than traditional methods, ensuring accurate and efficient problem-solving. Their ability to process large datasets and dynamically adapt to new information significantly accelerates research and development while enhancing material design and performance [165].

Borjali et al. [166] developed an ML-based model to predict the wear rate of polyethylene, employing four different ML algorithms. The achieved coefficient of determination (R^2) values were 75% for the random forest (RF), 72% for the gradient boosting machine (GBM), 73% for the artificial neural network (ANN), 69% for the support vector machine (SVM), and 91% for the K-nearest neighbor (KNN) model. Similarly, Kong et al. [167] proposed a predictive model based on decision theory, achieving an R^2 value of 90% for capability forecasting. The R^2 metric is widely adopted for evaluating model performance, as it quantifies the proportion of variance explained by the model, indicating its predictive accuracy. Unlike metrics such as mean absolute error (MAE), mean squared error (MSE), and root mean square error (RMSE), which assess prediction errors, R^2 provides a normalized score, enabling direct model comparisons across different scales [168].

Mechanical properties such as modulus of elasticity, tensile strength, interlaminar shear strength, fracture toughness, and hardness, along with tribological parameters including sliding distance, normal load, and speed, collectively govern the tribological performance of fiber-reinforced polymer (FRP) composites. Although extensive studies have been conducted on two-variable interactions, the influence of multiple varying parameters remains underexplored due to the complexity of the variables affecting the

tribological behavior of these composites [169]. The advent of data-driven methodologies in ML and artificial intelligence (AI) has facilitated the investigation of intricate higher-order correlations among multiple parameters, surpassing the limitations of traditional statistical methods. These advancements have led to the emergence of a novel research domain in tribology, known as “intelligent tribology” or “triboinformatics” [170].

2.9 After thorough literature review it is observed that still possibility to the explore the research in this areas based on the following research gap:

- The inherently smooth surface of synthetic fibers results in weak interfacial adhesion with the polymer matrix, leading to inadequate stress transfer. Advanced surface modification techniques, including functionalization and nanoparticles coating, are required to enhance mechanical interlocking and adhesion properties.
- Most existing studies focus on modifying the polymer matrix using nanoparticle reinforcements, while direct fiber surface modifications using nanoparticles remain largely unexplored. The potential of nanoparticle coatings in improving fiber-matrix interfacial bonding and load transfer efficiency requires systematic investigation.
- Chemical treatments for the uniform deposition of nanoparticles onto fiber surfaces remain underexplored. Optimizing chemical functionalization methods can facilitate uniform nanoparticle adhesion, thereby improving interfacial bonding, mechanical integrity, and durability of fiber-reinforced polymer composites.
- Research on hybrid nanoparticle reinforcement is limited, with most studies concentrating on single-nanoparticle systems. The synergistic effects of multiple nanoparticles in enhancing mechanical, thermal, and tribological properties of

polymer composites require comprehensive study, including interactions between different nanoparticle types.

- Most previous studies on synthetic fiber-reinforced polymer composites (SFRPCs) have primarily focused on evaluating their mechanical and tribological properties through various approaches such as fiber hybridization, fiber volume fraction optimization, and matrix modification. However, there is a significant lack of research on the mechanical and tribological performance of composites incorporating fiber modification through chemical treatments and nanoparticle coatings.
- Despite advancements in ML-based modeling, the tribological behavior of FRP composites remains underexplored, particularly in multi-variable interactions. The complex relationship between mechanical, thermal, and frictional properties requires further investigation within intelligent tribology frameworks.

2.10 Objectives of the present work

The identified research gaps in the available literature have contributed to defining the objectives of this study, which are discussed below:

- To modify the surface of synthetic fibers and functionalize CNTs and GO using chemical treatments.
- To coat CNTs and GO on fiber surfaces and characterize them using SEM, FTIR, and TGA.
- To fabricate coated and uncoated fiber-reinforced epoxy composites.
- To evaluate their physical, mechanical, thermal, and tribological properties.
- To analyze and predict frictional behavior using machine learning techniques.