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Advanced Polymer Composite Materials: Fabrication Techniques, Mechanics and Diverse Applications

Saeideh Alipoori *

UNAM - Institute of Materials Science and Nanotechnology, Bilkent University, Ankara 06800, Türkiye

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ABSTRACT

Advanced polymer composite materials have attracted significant attention across a broad range of industries, such as aerospace and automotive, electronics, biomedical fields, and construction, due to their superior mechanical properties, thermal stability, and lightweight nature. These materials are prepared by combining polymer with reinforcing agents such as fibers, nanoparticles, or fillers, which increase properties like tensile strength, durability, and stretchability. In addition to enhancing mechanical performance, the integration of fillers and nanoparticles also improves thermal conductivity, which is critical for applications requiring efficient heat dissipation. Fabrication techniques of polymer composites, ranging from traditional methods such as injection molding and extrusion to modern techniques like additive manufacturing, help to have precise control over material properties to enhance the performance of nanomaterials like carbon fibers, carbon nanotubes, and graphene. The mechanical performance of polymer composites, such as tensile strength, stiffness, and fatigue resistance, is closely related to the type of reinforcement, polymer, and processing technique. For future research and more development of polymer composites, sustainability, recyclability, and large-scale production are the remaining critical challenges.

Keywords: Polymer composites, Nanomaterials, Mechanical Properties, Thermal Properties, Applications.

1. Introduction

Polymer composite materials (PCMs) have attracted considerable attention in materials science, where lightweight, durable, and multifunctional materials have shown crucial need in the development of various industries (Sarde et Patil 2019; El-Aouni et al. 2020; Siakeng et al. 2019; Sajan et Selvaraj 2021). The foundation of PCMs lies in the effective combination of polymer matrices with reinforcing agents to produce materials with high mechanical, thermal, and electrical properties. This versatility has led to the widespread application of PCMs from aerospace engineering to consumer electronics and biomedical devices (Naheed Saba et al. 2016; N Saba et Jawaid 2018; Friedrich et Almajid 2013). One of the key advantages of PCMs is their ability to integrate a wide range of reinforcing materials, such as fibers, nanoparticles, and other advanced materials. For high-performance applications, the flexibility of PCMs allows for the development of materials with specific mechanical properties, such as tensile strength, stiffness, and impact resistance (Kang et al. 2019; R.K. Sinha et al. 2020; Zakaria et al. 2019; Chawla 2012; Sajan et Selvaraj 2021). Additionally, polymers provide other functionalities for PCMs, including electrical conductivity, thermal management, and even self-healing capabilities, which further enhance the applicability of PCMs (Takagi 2019; Safri et al. 2018; Gurjar, Sharma, et Sarkar 2018).

The ongoing advancements in fabrication techniques of PCMs, such as additive manufacturing, hot pressing, and thermal fiber drawing, have further expanded the potential of polymer composites, enabling the creation of complex structures with enhanced properties in terms of material properties, cost-effectiveness, and scalability (Valino et al. 2019; Zindani et Kumar 2019; Van de Werken et al. 2020). Polymer composites can be defined as the assembly of two or more materials the final structure has each component's properties. Polymer composite materials are now commonly called reinforcement materials (fillers) embedded in a polymer matrix (Sanjay et al. 2019; Nobile 2011; Venkateshwaran et Elayaperumal 2010; Devnani et Sinha 2019; Hsissou et al. 2021). The continuous phase and discontinuous phase are called the matrix and the reinforcement materials, respectively. The interfacial interaction between polymer and filler, the type of filler, and the fabrication method are largely influenced by the mechanical properties of polymer composites (Zhou et al. 2019; M Asim et al. 2018; Qian Cheng, Jiang, et Li 2020). The optimal interfacial bonding between the polymer matrix and filler is one of the critical challenges in the design of polymer composites in which the insertion of fillers with good tensile strength and high modulus makes the polymer matrix with high

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* Corresponding author.
E-mail address: saeideh@unam.bilkent.edu.tr (Saeideh Alipoori).

mechanical and thermal qualities (Yan Li, Yi, et al. 2018; Ahmadijokani et al. 2020; Arabpour et al. 2020; De et al. 2020; Hsissou et al. 2021).

A comprehensive understanding of the interplay between the fabrication methods, mechanical properties, and the performance of PCMs in various applications is still needed (Tarhini et Tehrani-Bagha 2019; Vaggar et Kamate 2020; Thomason 2020; Naheed Saba et al. 2016; Hsissou et al. 2021). This review aims to address this gap by providing detailed information about the latest fabrication techniques, the mechanical behavior of advanced polymer composites, and their diverse applications across various industries for future research and development. The objective of the present review is to equip researchers, engineers, and industry professionals with a thorough understanding of the fabrication, mechanics, and applications of polymer composites, thereby fostering further innovation and application of these versatile materials. By addressing the challenges and opportunities associated with PCMs, this review seeks to contribute to the ongoing advancement of composite materials and their applications in modern technology.

2. Different Types of Polymer Composite Materials (PCMs)

Polymer Composite Materials (PCMs) represent a class of advanced materials combining polymers with other materials to develop composites with enhanced properties for various applications (Hsissou et al. 2021; Sajan et Selvaraj 2021; Nambiar et Yeow 2012). PCMs are made of a polymer matrix (thermoplastic or thermosetting) and a reinforcing material essentially materials made from a polymer matrix, which can be thermoplastic or thermosetting, and a reinforcing phase such as nanofillers, glasses, fibers, and ceramics etc. Polymer composites consist of the unique properties of both the polymer and the reinforcing agent, resulting in a composite with excellent thermal, electrical, and mechanical properties which have become a crucial component in diverse applications, including aerospace, automotive, electronics, and biomedical industries (Hsissou et al. 2021; Prabhakar et al. 2018; Bhong et al. 2023).

The PCMs can be classified into three different categories: fiber-reinforced composites, particle-reinforced composites, and hybrid composites (Sajan et Selvaraj 2021; Sonar et al. 2015). Figure 1 shows the different types of PCMs.

Among them, fiber-reinforced polymer composites (FRPCs) are the most commonly used composite. In this type of composite, the fiber acts as the reinforcing agent, supplying high stiffness, high tensile strength, and high fatigue resistance; however, the polymer provides flexibility, ease of fabrication, and corrosion resistance. The used fibers can be classified into natural fibers and synthetic fibers (Hsissou et al. 2021; Dixit et al. 2017; Kamath, Sampathkumar, et Bennehalli 2017). Natural fibers have gained much attention compared to synthetic fibers such as flax, jute, hemp, and sisal, which are incredibly used in industries like automotive and packaging due to their good mechanical properties, biodegradability, and low cost. Although natural fibers may not match the high-performance properties of synthetic fibers, they offer more environmentally friendly alternatives by maintaining desirable mechanical properties (Hsissou et al. 2021; Arteiro et al. 2020; Dixit et al. 2017). However, in applications that do not need high mechanical properties, the use of natural fibers is expected to increase due to the growing environmental concerns. In high-performance applications where durability, stiffness, and strength are critical, synthetic fibers such as aramid fibers, carbon, and glass are broadly used. For instance, carbon fiber-reinforced polymers (CFRPs) are well-known for their remarkable strength-to-weight ratio, making them ideal for use in the aerospace and automotive industries. Due to their high performance and lightweight, CFRPs are widely used in racing cars, sporting goods, and aircraft components (Hsissou et al. 2021; Dixit et al. 2017; Sonar et al. 2015; Yuhazri, Zulfikar, et Ginting 2020). Yuan et al. (X. Yuan et al. 2023) developed a temperature-dependent micromechanical model to predict the transverse mechanical properties of carbon fiber-reinforced polymer (CFRP) composites. The model incorporates temperature-dependent Young's modulus, a polymer plasticity model, and a cohesive zone model for the fiber/polymer interface. Validated against experimental data, the model accurately estimates Young's modulus and strength at various temperatures. Results show that transverse tensile and compressive strengths decrease by 9.1% and 4.8% at 80°C, while at −196°C, they increase by 16.1% and 8.8%. Parametric analysis reveals that interface strength significantly affects mechanical behavior, while stiffness and fracture energy have minimal influence. The study also highlights limitations due to unavailable damage evolution data for polymer matrices at different temperatures, but the proposed model offers a reliable method for assessing CFRP composite behavior under varying thermal conditions(X. Yuan et al. 2023).

Glass fiber-reinforced polymers (GFRPs) are another type of FRPC that have good mechanical properties and lower cost compared to CFRPs (Sajan et Selvaraj 2021; Sonar et al. 2015). In applications such as bridge construction, wind turbine blades, and boat hulls where high durability and high strength are required, the GFRPs are extensively used in such applications (Hsissou et al. 2021; Dixit et al. 2017; Kamath, Sampathkumar, et Bennehalli 2017). On the other hand, aramid fiber-reinforced polymers are commonly used in ballistic applications such as body armor for their superior impact resistance (Dixit et al. 2017; More et al. 2021). Xian et al. (Xian, Guo, et Li 2022) developed two carbon/glass fiber hybrid plates-random hybrid (RH) and core-shell hybrid (CH) polymer composites and subjected them to bending loads and water immersion for 360 days to examine their durability. Results revealed that the RH plates exhibited better synergetic effects between fibers, leading to a 51.3% and 39.7% increase in tensile and flexural strength, respectively, compared to CH plates. Additionally, the RH plate showed superior corrosion resistance, retaining 30-40% of tensile strength and 50-60% of flexural strength over five years in typical bridge environments. High bending loads accelerated microcrack formation, resin hydrolysis, and fiber/resin interface debonding. Overall, the RH plate's superior performance provides insights into designing durable composites for engineering applications (Xian, Guo, et Li 2022).

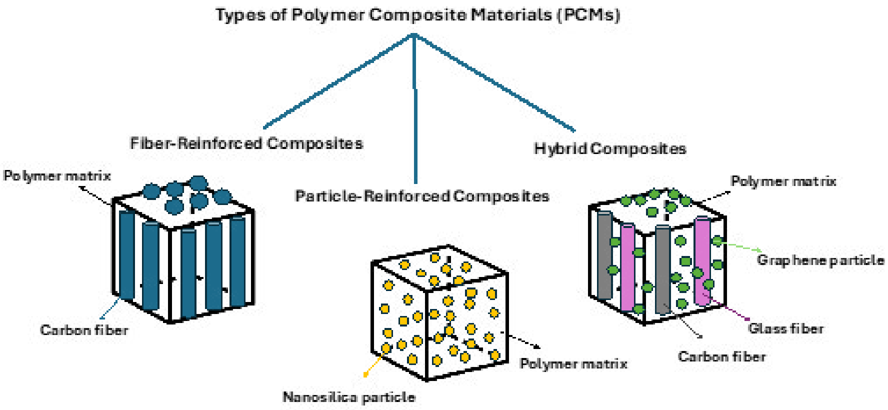


Fig. 1. Different types of polymer composite materials (PCMs).

Particle-reinforced composites are another key type of PCMs in which the small particles are dispersed throughout the polymer matrix to improve its mechanical, thermal, or electrical properties. Materials such as metals, ceramics, or carbon-based materials like graphene or carbon nanotubes are the common categories of reinforcing material (More et al. 2021; D.W. Lee et Yoo 2016; El Kadi 2006). Particle-reinforced composites can be used in different applications where high wear resistance, thermal stability, or electrical conductivity is required. For instance, due to their superior thermal conductivity and electrical properties, metal particle-reinforced polymer composites are commonly used in electronic packaging and heat sinks (Hsissou et al. 2021; Yadav et al. 2023). Azimpour-Shishevan et al. (Azimpour-Shishevan, Akbulut, et Mohtadi-Bonab 2020) investigated the effects of adding carbon-based nanoparticles, specifically Multi-Wall Carbon Nanotubes (MWCNTs) and Graphene Nanoplatelets (GNPs), on the mechanical and thermal properties of Carbon Fiber Reinforced Polymer Composites (CFRPs). The aim was to enhance the weak interface behavior between carbon fibers and polymers by incorporating nanoparticles. Experimental results showed that the addition of MWCNTs and GNPs improved mechanical properties such as elasticity modulus, tensile strength, flexural modulus, and buckling load. Additionally, modal tests indicated an increase in natural frequency and a decrease in damping ratio. Thermal properties, including storage modulus, thermal stability, and conductivity, were also enhanced. Notably, MWCNTs outperformed GNPs in improving CFRP performance. Hydrophobicity tests revealed that MWCNTs increased hydrophobicity, while GNPs made the material more hydrophilic. Overall, MWCNTs demonstrated superior performance in mechanical, thermal, and modal properties compared to GNPs, making them more effective for CFRP enhancement (Azimpour-Shishevan, Akbulut, et Mohtadi-Bonab 2020).

Developing nanometer-sized particles in particle-reinforced composites is one of the most significant advancements in nanocomposites. Due to the high surface are-to-volume ratio of the nanoparticles, they offer significant improvements in material properties, resulting in strong interfacial interactions between the polymer and the nanoparticles (Sajan et Selvaraj 2021; X. Sun et al. 2013). The most common types of nanomaterials are carbon nanotubes (CNTs), nano silica, and graphene, which exhibit superior thermal stability, electrical conductivity, and mechanical properties (Hsissou et al. 2021; X. Sun et al. 2013; Lau, Gu, et Hui 2006). For example, graphene-based nanocomposites have indicated tremendous potential in applications such as energy storage, energy harvesting, sensors, and flexible electronics due to their excellent electrical and mechanical properties (X. Sun et al. 2013; Lau, Gu, et Hui 2006).

Carbon nanotubes have superior tensile strength and modulus, as well as remarkable electrical conductivity, making them ideal for high-performance applications (Arteiro et al. 2020; X. Sun et al. 2013). Carbon nanotube-reinforced polymer composites have also attracted significant interest in the aerospace and automotive industries because of their unique lightweight, electrical, and mechanical characteristics (Sajan et Selvaraj 2021; Lau, Gu, et Hui 2006). Furthermore, CNT-reinforced composites have exhibited promise in the field of electronics, where flexible and conductive materials can be developed for applications such as wearable electronics and sensors (Hsissou et al. 2021; X. Sun et al. 2013). Luo et al. (X. Luo, Yang, et Schubert 2022) explored the incorporation of pristine carbon nanotubes (CNTs) and functionalized CNTs (f-CNTs) into poly(methyl methacrylate)/graphene nanoplatelet (PMMA/GNP) composites to enhance conductivity and lower the percolation threshold by forming a 3D hybrid structure. The electrical properties in both in-plane and perpendicular directions were analyzed. Synergistic effects in the in-plane direction depended on total filler loading, while those in the perpendicular direction were influenced by GNP/CNT or GNP/f-CNT ratios. A schematic diagram illustrating the evolution of 3D conductive pathways explained this behavior. Figure 2 shows the logarithmic value of in-plane conductivity of PMMA/GNP/f-CNT composite and PMMA/GNP/CNT composite versus filler volume fraction. Type 3 synergy in ternary composites occurs when their conductivity exceeds that of binary composites. This effect was observed in PMMA composites with filler fractions below 0.01, with the strongest synergy at a 0.003-0.005 filler fraction and a GNP/f-CNT ratio of 1/1. At this ratio, the conductivity was significantly higher than in binary systems (Figure 2a). For PMMA/GNP/CNT composites, type 3 synergy occurred at higher filler fractions, over 0.01, highlighting the critical role of filler ratios in conductivity improvement (Figure 2b). Figure 2c indicates the optical image results. The synergy in percolation is attributed to the improved distribution of hybrid fillers in PMMA composites. In the GNP/f-CNT system, GNP segregation disappeared, forming more continuous networks than binary composites. Functionalized CNTs (f-CNTs) enhanced the dispersion of GNPs, improving filler connectivity due to their large aspect ratio. In contrast, binary PMMA/f-CNTs showed poorer electrical properties than PMMA/CNTs due to the adverse effects of functionalization. Ternary

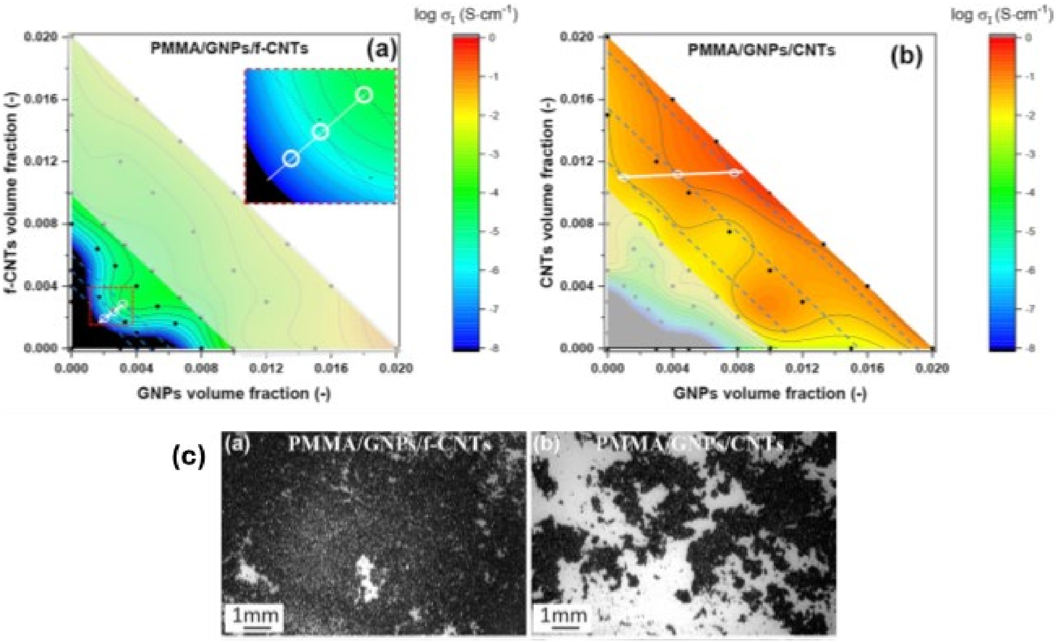


Fig. 2. The logarithmic value of in-plane conductivity of (a) PMMA/GNP/f-CNT composite and (b) PMMA/GNP/CNT composite versus filler volume fraction of two hybrid fillers in a contour plot diagram showing synergy region and strongest synergy points (white circles and white line). The contour interval is 0.5. The inset is a magnified view of the strongest synergy points. (c) Optical images of the surface of the PMMA/GNP/f-CNT and b PMMA/GNP/CNT composite films at 0.005 total filler loading (X. Luo, Yang, et Schubert 2022).

PMMA/GNP/CNT composites exhibited lower conductivity at filler fractions below 0.01 due to smaller aggregation. The study achieved tunable conductivity anisotropy (the ratio of in-plane to perpendicular conductivity) ranging from 0.01 to 1000 by adjusting filler loadings and ratios. The f-CNT composites exhibited synergy below 0.01 filler fraction, while CNT composites showed synergy beyond this level. The findings offer new insights into designing highly anisotropic or isotropic conductive polymer composites (CPCs) with significant applications in advanced materials (X. Luo, Yang, et Schubert 2022).

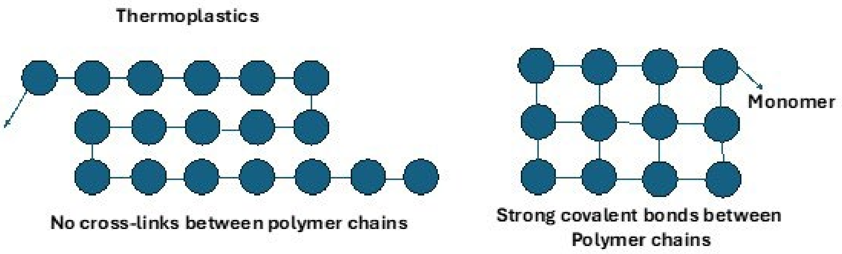
Hybrid polymer composites represent another prominent type of PCMs, where two or more various categories of reinforcing materials are combined within the same polymer matrix. There is a balance between the performance, cost, and weight of each type of component in hybrid composites (Sajan et Selvaraj 2021; Prabhakar et al. 2018). For example, a single composite containing both carbon fibers and glass fibers results in a composite with high strength and stiffness while also having good impact resistance and low cost compared to only carbon fibers. Similarly, combining both natural fibers and synthetic fibers in a hybrid composite can provide a more sustainable solution without compromising mechanical performance (Hsissou et al. 2021; More et al. 2021). Hybrid composites are increasingly being used in automotive, aerospace, and sporting goods industries where the optimization of material properties is necessary (El Kadi 2006; Gibson 2010).

Thermoplastic and thermosetting polymers also play a crucial role in the performance of PCMs (Figure 3). Epoxy, polyester, and phenolic resins as thermosetting polymers are commonly used in high-performance composites because of their excellent chemical resistance, high strength, and thermal stability (Hsissou et al. 2021; Rajeshkumar et al. 2021). After curing, thermoset polymers form a cross-linked structure, providing strong interfacial interaction with the reinforcing agent. Epoxy-based composites are broadly used in aerospace and automotive applications owing to their excellent strength and durability. Nevertheless, thermosetting composites can not be recyclable, which poses environmental challenges (Sajan et Selvaraj 2021; Arteiro et al. 2020).

On the other hand, thermoplastic polymer composites such as polypropylene, polyamide, and polyethylene are commonly used in automotive, construction, and consumer goods applications due to their recyclable and re-moldable ability, making them an attractive option for applications where sustainability is a key consideration (Sajan et Selvaraj 2021; Prabhakar et al. 2018). Thermoplastic polymers can be melted and reshaped, which makes them easier to process and recycle compared to thermosetting polymers (Hsissou et al. 2021; Gibson 2010).

Recently, bio-based polymer composites have also been developed to decrease the environmental impact of traditional petroleum-based polymers (Ramakrishna et al. 2001; Sajan et Selvaraj 2021). Bio-based polymers, which are derived from renewable resources such as polylactic acid (PLA), polyhydroxyalkanoates (PHA), and starch-based polymers, can be used as matrix material in composite systems (Arteiro et al. 2020; Omran et al. 2021). When the biopolymer combines with a reinforced agent like natural fibers, it offers a more sustainable alternative to conventional PCMs while maintaining good mechanical properties (Hsissou et al. 2021; Kamath, Sampathkumar, et Bennehalli 2017). These biocomposites are being used in biodegradable consumer products, packaging, and automotive interiors, where environmental concerns are driving demand for more sustainable materials (Ramakrishna et al. 2001; Gibson 2010; Kamath, Sampathkumar, et Bennehalli 2017). Polylactic acid (PLA), a biodegradable and renewable thermoplastic, shows potential as a substitute for fossil fuel-derived polymers but suffers from poor thermal, electrical, and mechanical properties. Incorporating carbon nanofillers like graphene nanoplatelets (GNPs) and multiwall carbon nanotubes (MWCNTs) into PLA improves these properties (Botta et al. 2017; Y. Luo, Cao, et Guo 2018). Batakliev et al. (Batakliev et al. 2021) studied the physico-chemical properties of GNPs and MWCNTs using Raman spectroscopy and analyzed the impact of these carbon nanofillers at 6wt% loading on the structure and homogeneity of PLA-based nanocomposites. Raman spectroscopy, X-ray diffraction (XRD), and differential scanning calorimetry (DSC) confirmed the homogeneous dispersion of nanofillers, leading to enhanced crystallinity and thermal stability. Thermo-gravimetric analysis (TGA) outlined the nanocomposites' improved thermal properties, while tensile tests demonstrated a significant increase in tensile strength and resistance to strain, suggesting a synergistic effect. The use of Raman spectroscopy allowed for precise analysis of molecular morphology, revealing high structural uniformity. GNPs and MWCNTs acted as nucleating agents, enhancing the mechanical and thermal properties of the nanocomposites. The low-cost melt blending method proved effective in achieving fine dispersion of the nanofillers, resulting in superior 3D-printed PLA-based composites (Batakliev et al. 2021).

The combination of novel polymer matrices with advanced reinforcing materials has led to the fabrication of smart composites responding to external stimuli such as temperature, pressure, or electrical fields, making them suitable for applications in sensors, actuators, and self-healing materials (Sajan et Selvaraj 2021; More et al. 2021). For instance, when the shape-memory polymer composites are exposed to specific stimuli such as heat or an electrical field, they can be deformed and, after removal, returned to their original shape. These materials have potential applications in biomedical devices, aerospace components, and deployable structures(Hsissou et al. 2021; Thevenot et al. 2013; Bhaskar et al. 2020).



Themoplastic Materials	Thermoset Materials
Polyethylene	Polyester
Polystyrene	Melamine
Teflon	Silicone
Polyvinyl chloride	Vulcanized rubber
Nylon	Polyurethane
Acrylic	Vinyl etser resin
Polycarbonate	Epoxy resin

Fig. 3. Structure of Thermoplastic and Thermoset Polymers.

Self-healing polymer composites are another emerging type of polymer composites, where composites are designed to repair themselves after damage (Sajan et Selvaraj 2021; Arteiro et al. 2020). By incorporating the healing agents as microcapsules or vascular networks into the polymer matrix, these composites can autonomously heal cracks and prevent propagation, which extends the material's lifespan (Ramakrishna et al. 2001; Omran et al. 2021). In aerospace and automotive industries, where material failure can have serious safety implications, self-healing composites are particularly attractive. These types of PCMs could lead to more durable, reliable materials that require less maintenance and longer service lives (Hsissou et al. 2021; Arteiro et al. 2020).

3. Processing of Polymer Composites

Polymer composites are broadly used in diverse areas such as aerospace, healthcare, automotive, and electronics due to their excellent thermal, mechanical, lightweight nature, and electrical properties. The processing method of polymers plays a critical role in the final properties of the composite, such as strength, thermal stability, toughness, and electrical conductivity (Mohammad Asim et al. 2017; Mittal et al. 2018). Various processing techniques have been developed over time, ranging from traditional methods like injection molding to more advanced methods such as additive manufacturing (Figure 4). It is essential to understand the influence of the processing parameters for optimizing the performance of polymer composites in specific applications (Mallick 2017; S. Yuan et al. 2021; Fu et al. 2020).

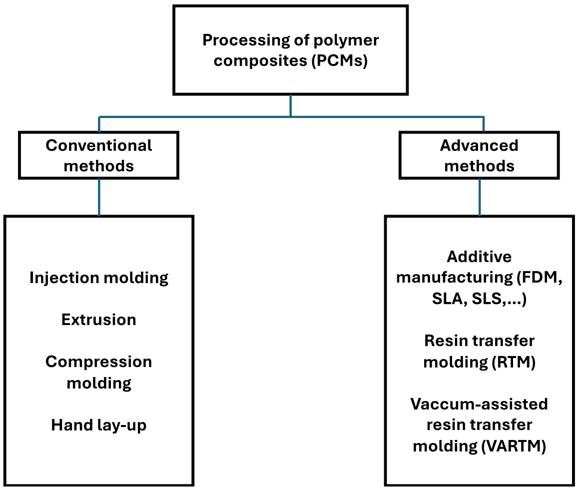


Fig. 4. Various processing techniques of polymer composite materials.

Conventional processing techniques for the fabrication of PCMs, such as injection molding, extrusion, compression molding, and hand lay-up, have been extensively used (Fu et al. 2020; Amar, Kumar, et Yadav 2024). Among them, injection molding is one of the most common techniques for processing thermoplastic composites. In this technique, the polymer heats to the molten state and is then injected into a mold cavity, including the reinforcing agents (Mohammad Asim et al. 2017; Mallick 2017; Fu et al. 2020). Once it is cooled, the composite part solidifies and then is ejected from the mold. Complex shapes with high dimensional consistency and accuracy are produced in this method, making it ideal for mass production. In this method, the process is highly automated, which produces parts with low human intervention. However, the resilience problem is one of the limitations of injection molding, which restricts its use with certain thermosetting polymers that require curing during processing (Fu et al. 2020; Mohammad Asim et al. 2017; Turng 2001). Wood-plastic composites (WPC), made from wood fiber (WF) and polypropylene (PP), are eco-friendly materials widely used in construction, automotive, and furniture industries. However, their mechanical limitations restrict broader structural applications (Yam et al. 1990; Kazayawoko, Balatinecz, et Matuana 1999). Guo et al. (G. Guo et Kethineni 2020) explored enhancing WPC properties by adding glass fiber (GF) and carbon fiber (CF) through one-step direct injection molding. The tensile stress vs. strain curve in Figure 5a shows that adding CF and GF to PP increases its ultimate tensile strength. Introducing WF slightly decreases the tensile strength but increases the tensile modulus compared to pure PP. GF composites show similar tensile strength to CF composites but have a lower tensile modulus. Hybrid composites outperform WF composites in tensile strength. However, all composites exhibit reduced ductility, with pure PP showing local necking, while others exhibit sharp fractures (Figure 5b). Thus, the tensile strength and modulus improved significantly up to 38% and 78% for PP/WF/CF composites. Additionally, hybrid WPCs demonstrated improved flame-retardant properties, reducing fire spread and dripping during combustion. Water absorption tests revealed GF composites were more resistant to moisture than CF or WF composites. While WF serves primarily as a cost-reducing filler, GF and CF substantially increased tensile properties without needing coupling agents. Though elongation at break decreased, the study suggests that hybrid WPCs could find broader structural uses, balancing performance and cost, particularly in applications requiring flame resistance, such as CF/WF composites (G. Guo et Kethineni 2020).

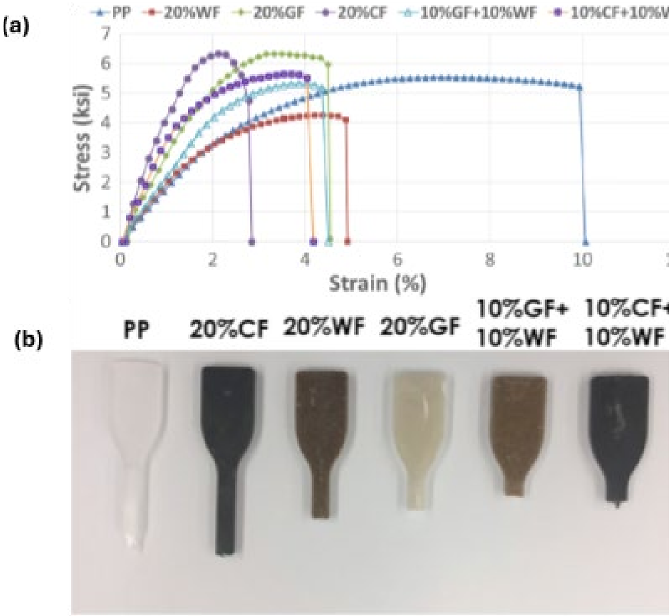


Fig. 5. (a) Typical engineering stress vs. strain before water absorption. (b) Typical fractured specimens (G. Guo et Kethineni 2020).

Another well-established technique is extrusion (Figure 6). Pipes, sheets, or films can be produced with this technique in which the polymer and filler are melted by force through a die to form continuous products. The produced composites are long and uniform, with consistent cross-sections (Zhuo et al. 2021; Kosmalska et al. 2022; Formela et al. 2018). Extrusion techniques are useful for making large quantities of PCMs like building materials, electrical cables, and automotive components. One of the main advantages of this method is its simplicity, which produces a wide range of materials with low cost. Nevertheless, extrusion does not apply to the production of continuous profiles and complex three-dimensional shapes (Mallick 2017; Sharafi et al. 2021; Raquez, Narayan, et Dubois 2008).

Compression molding is a conventional technique for processing thermoset polymer composites. In this technique, heat and pressure are applied after placing the polymer matrix and reinforcement in a mold, which cures the material and consolidates the composite (Saunders, Lekakou, et Bader 1999, 1998; Jaafar et al. 2019). Compression molding produces large, structurally sound parts with minimal waste. In the automotive and aerospace industries, it is used for manufacturing products with high strength and rigidity, such as aircraft panels, bumpers,

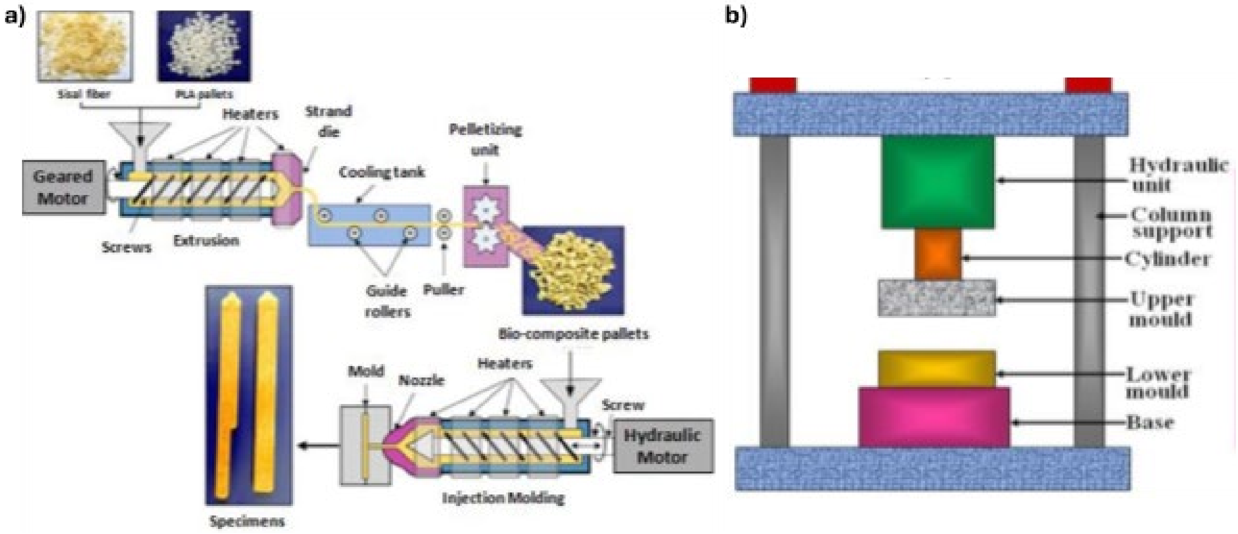


Fig. 6. a) Injection molding versus Extrusion molding (Rabbi, Islam, et Islam 2021). b) Compressing molding (Sathish et al. 2021).

and fenders. High-performance composites can be effectively produced in this method as the applied pressure eliminates voids during molding and improves the overall quality of the material(Mohammad Asim et al. 2017; Mallick 2017; M. Singh, Verma, et Zafar 2020). Mirzazadeh et al. (Mirzazadeh, Sherafat, et Bagherzadeh 2021) focused on the synthesis and characterization of sodium-potassium niobate (KNN) as a lead-free piezoelectric compound integrated with polyvinylidene fluoride (PVDF) to form KNN/PVDF composites through hot compression molding. KNN was synthesized using a solid-state reaction with two calcination steps, and its structural properties were examined via X-ray diffraction (XRD). The composites were created at various KNN to PVDF weight ratios and exhibited high density (97.44% to 99.11% of theoretical density). Thermogravimetric analysis revealed enhanced thermal stability with increased KNN content. Mechanical testing showed that composites with higher KNN percentages had elevated Young's modulus and yield strength. Electrical properties indicated that dielectric constant and piezoelectric coefficients improved with KNN content, with the composite containing 80 wt% KNN demonstrating significant ferroelectric behavior, a remanent polarization of 0.255 μC/cm^2, and coercivity of 20.5 kV/cm. The findings suggest that KNN/PVDF composites have promising applications in energy generation and biocompatibility (Mirzazadeh, Sherafat, et Bagherzadeh 2021).

Hand lay-up is a commonly used technique in the production of large and low-volume composite structures for aircraft components, wind turbine blades, and boat hulls (Kim et al. 2014; M. Rahman, Jasani, et Ibrahim 2017). Layers of the reinforcing agent are placed in a mold, and then the polymer matrix is applied through resin infusion or brushing (Mohammad Asim et al. 2017; Marouani, Curtil, et Hamelin 2008; Amar, Kumar, et Yadav 2024). Vacuum bagging or rolling are then consolidated the layers, and the composite is allowed to cure. It is a simple and cost-effective process but highly dependent on the operator's skill (Mallick 2017; Roopa et al. 2015).

In recent years, more sophisticated techniques such as additive manufacturing, resin transfer molding (RTM), and vacuum-assisted resin transfer molding (VARTM) have been developed (Balla et al. 2019; S. Yuan et al. 2021; Hsiao et Heider 2012; Goren et Atas 2008). These advanced methods offer prominent control over the microstructure and properties of polymer composites for producing PCMs with tailored properties for specific applications. Additive manufacturing or 3D printing has developed complex and customized parts of polymer composites with minimal material waste. There are different types of 3D printing technologies, such as fused deposition modeling (FDM), stereolithography (SLA), or selective laser sintering (SLS) (Figure 7) (Mohammad Asim et al. 2017; El Moumen, Tarfaoui, et Lafdi 2019; Kafle et al. 2021; S. Singh, Ramakrishna, et Berto 2020). Additive manufacturing provides the opportunity to produce geometrically complex structures that would be difficult or impossible to create using conventional methods. Furthermore, this method enhances the mechanical properties by allowing precise control over the orientation and distribution of reinforcement materials within the composite. Recent research works have been focused on optimizing the 3D printing process by exploring new reinforcement materials, such as carbon nanotubes and graphene, and developing advanced printing techniques that improve the quality and performance of the printed parts (Mallick 2017; Balla et al. 2019; Spitalsky et al. 2010; S. Singh, Ramakrishna, et Berto 2020).

Yang et al. (Yang et al. 2020) introduced a novel method for covalently functionalizing graphene oxide (GO) using poly(aryl ether ketone) with pendant carboxyl groups to create functionalized graphene oxide (LFG). LFG was incorporated into poly(ether ether ketone) (PEEK) composites via melt blending, resulting in improved interface adhesion. Figure 8a indicates the preparation of LFG/PEEK composites involved in mixing PEEK powder with LFG nanosheets using ultrasonic dispersion and mechanical stirring, followed by melt blending. The covalent grafting of PEK-L on modified GO improved interfacial adhesion with PEEK. The mechanical properties were analyzed (Figure 8b and 8c), showing that while GO enhances tensile strength and modulus when added above 0.3 wt%, it reduces tensile toughness. In contrast, LFG significantly improves tensile strength and toughness, with a 0.5LFG/PEEK composite showing increases of 6.8%, 7.0%, and 31.6% in tensile strength, modulus, and elongation, respectively. Moreover, composites containing just 0.1 wt% LFG showed tensile and impact strength enhancements of 5.7% and 20.5%, respectively, compared to neat PEEK. Additionally, a 0.5 wt% LFG composite demonstrated excellent friction and wear properties, with reductions of 27.3% in friction coefficient and 18.3% in specific wear rate. These composites are suitable for high-performance additive manufacturing, particularly through fused deposition modeling (FDM). The LFG/PEEK composites maintained enhanced mechanical performance, with tensile strength and breaking elongation improvements of 16.7% and 44.6%, respectively, compared to standard PEEK. This advancement broadens the potential applications of FDM parts in various engineering fields (Yang et al. 2020).

Another advanced processing technique of PCMs is resin transfer molding (RTM). In this process, the dry reinforcing agents such as glass fiber or graphene are placed in a mold, and then, under pressure, the liquid resin is injected into the mold to impregnate the fibers, followed by curing of the resin to form a solid structure (Laurenzi et Marchetti 2012; Sozer, Simacek, et Advani 2012; Haider, Hubert, et Lessard 2007). RTM can be used to produce large and complex parts with excellent surface finish and mechanical properties compared to conventional processing methods (Mohammad Asim et al. 2017; Mallick 2017; Balla

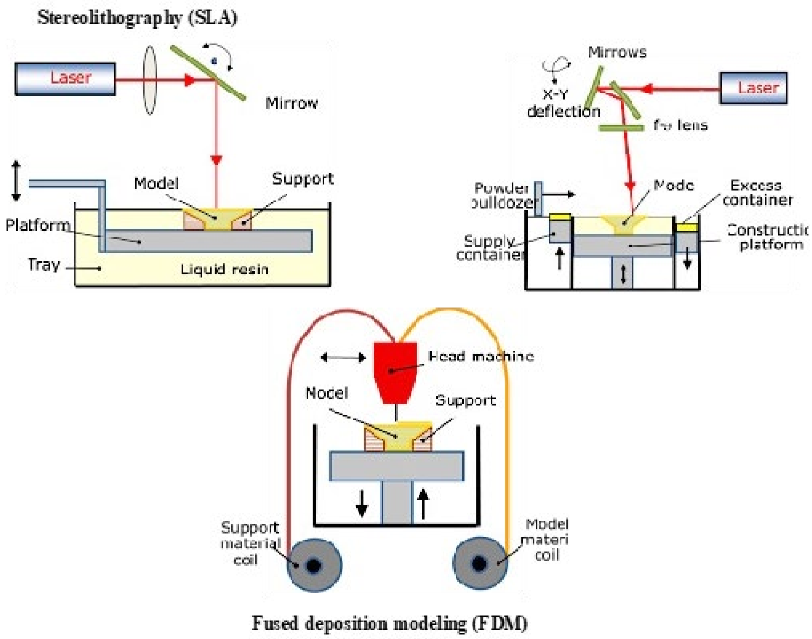


Fig. 7. Different types of additive manufacturing or 3D-printing technologies (Jiménez et al. 2019).

et al. 2019). This process is broadly used to manufacture components that require high strength-to-weight ratios, such as aerospace, automotive, and marine industries. One of the main challenges of the RTM is the resin impregnation of the reinforcement materials, such as voids or incomplete wetting, affecting the mechanical performance of the composite. To address this problem, vacuum-assisted resin transfer molding (VARTM) has been developed, which uses vacuum pressure to assist resin flow and improve fiber wetting (Laurenzi et Marchetti 2012; Sozer, Simacek, et Advani 2012; Rouison, Sain, et Couturier 2006; Shojaei, Ghaffarian, et Karimian 2003).

The influence of processing parameters such as pressure, temperature, reinforcement alignment, and curing time play a crucial role in determining the final properties of the composite. In injection molding, for example, factors such as injection temperature, mold temperature, and cooling rate can remarkably affect the crystallinity, fiber orientation, and residual stresses in the composite (Mittal et al. 2018; Mallick 2017; Abliz et al. 2013; Ramesh, Rajeshkumar, et Balaji 2021). Recent studies have shown that optimizing these parameters can lead to improved mechanical properties, such as increased tensile strength, flexural modulus, and impact resistance (Mohammad Asim et al. 2017; Chung et Kwon 2002). Similarly, in extrusion, the shear forces have a significant impact on the dispersion and alignment of reinforcement materials, which influences the mechanical and thermal properties of the composite. For instance, poorly dispersed fibers or particles can cause agglomeration, which leads to stress concentrators and reduces the strength of the composite (Gopal, Adali, et Verijenko

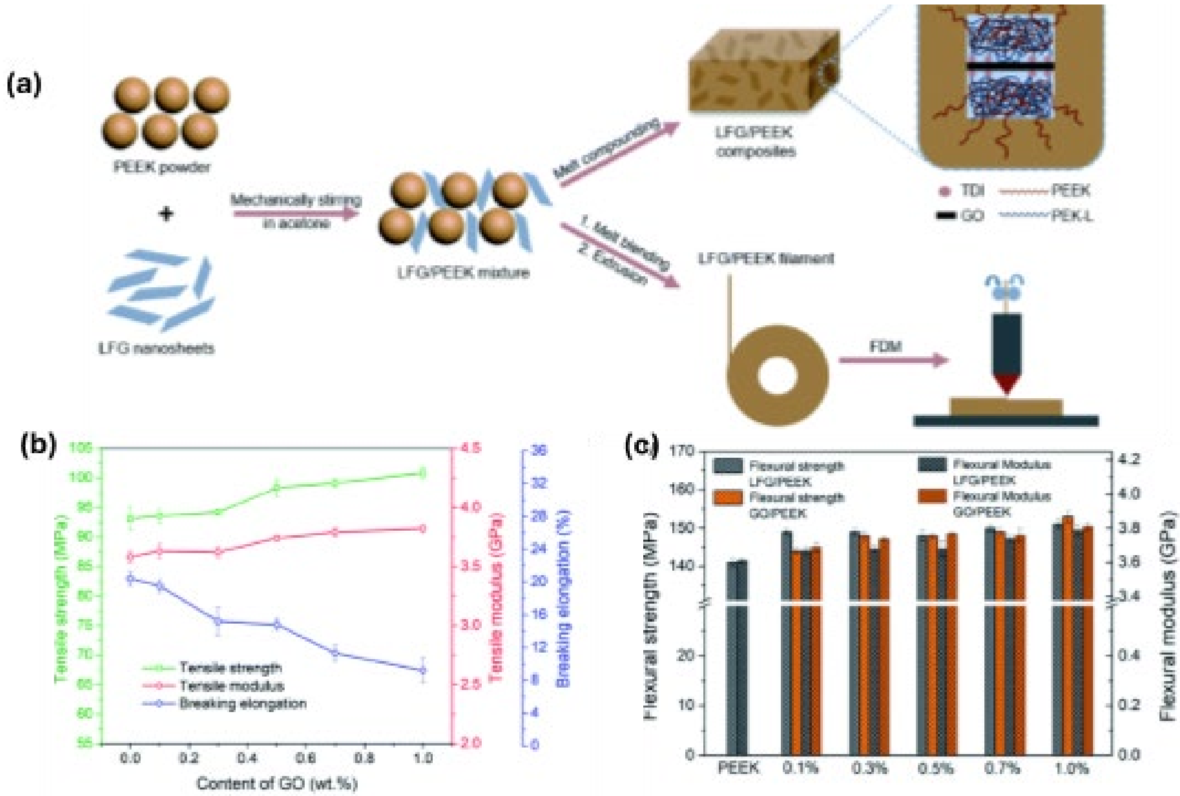


Fig. 8. (a) Preparation of LFG/PEEK composites and FDM process. Mechanical properties of GO/PEEK and LFG/PEEK composites, (b) tensile properties of GO/PEEK composites, (c) tensile properties of LFG/PEEK composites (Yang et al. 2020).

2000; Turng 2001; Saalbrink, Lorteije, et Peijs 1998). On the other hand, well-dispersion of the nanomaterial and aligned reinforcements can improve load transfer between the polymer matrix and the reinforcement, leading to enhanced mechanical performance. The applied pressure during the molding process in compression molding is critical for ensuring proper consolidation of the composite material (Mohammad Asim et al. 2017; Raquez, Narayan, et Dubois 2008; Y. Guo et al. 2020). Insufficient pressure can make void and incomplete wetting of the reinforcement, leading to reduced mechanical properties. Conversely, excessive fiber breakage and resin-rich areas caused by excessive pressure have negatively impacted the composite's performance. Therefore, careful control of molding pressure, temperature, and curing time is essential for producing high-quality polymer composites (Gopal, Adali, et Verijenko 2000; QF Cheng et al. 2010; Palanikumar, Karunamoorthy, et Karthikeyan 2006).

In advanced processing techniques such as RTM and VARTM, there are important parameters such as the resin flow rate, injection pressure, and vacuum level that influence the degree of fiber impregnation and the overall quality of the composite (El Moumen, Tarfaoui, et Lafdi 2019; S. Yuan et al. 2021; Shojaei, Ghaffarian, et Karimian 2003; Hsiao et Heider 2012). The presence of voids can remarkably reduce the strength and stiffness of the composite, but the excessive amount of resin can lead to weight penalties and reduced performance in lightweight applications. In additive manufacturing, the printing speed, printing temperature, and layer thickness are key factors that affect the microstructure and properties of the printed composite (Mohammad Asim et al. 2017; QF Cheng et al. 2010; Ramesh, Rajeshkumar, et Balaji 2021). For instance, thin layers and slow printing speeds can improve the surface finish and resolution of the printed part but may lead to increased printing times and higher costs. However, poor interlayer adhesion and mechanical properties can be the result of fast printing speeds and thicker layers. Furthermore, the type of reinforcement material and its distribution within the printed part can effectively affect its performance. Recently, researchers have shown that the incorporation of polymers with carbon nanotubes or graphene can significantly improve the mechanical, thermal, and electrical properties of 3D-printed composites (Spitalsky et al. 2010; S. Singh, Ramakrishna, et Berto 2020; Y. Guo et al. 2020). Robles et al. (Robles et al. 2021) evaluated the properties of two-part epoxy resin and glass fiber-reinforced polymer (GFRP) laminates enhanced with high graphene content. The impact of graphene on thermomechanical and tensile properties was examined, with results indicating a 16% improvement in flexural properties and a 52% increase in thermal conductivity, although impact performance decreased by 22%. Microscopy revealed graphene agglomerates, which contributed to a lack of electrical conductivity improvement. The research established that adding graphene significantly enhances storage modulus and glass transition temperature, while higher content leads to reduced tensile strength and increased viscosity, complicating resin infusion during processing. Laminates produced via resin transfer molding (RTM) showed improved flexural modulus and thermal conductivity, but the impact properties declined with increasing graphene content, particularly in neat resin. The study highlights a scalable, environmentally friendly mixing process for high graphene content composites, offering design flexibility for complex, cost-effective parts without requiring intricate procedures (Robles et al. 2021).

4. Mechanical Properties of Polymer Composites and influencing factors

Polymer composites have desirable properties such as superior mechanical properties, lightweight nature, and ease of fabrication. Additionally, the mechanical properties can be remarkably enhanced by combining the polymers with other materials, including nanoparticles and fibers (A. Kumar, Sharma, et Dixit 2021; Yunlong Li, Wang, et al. 2018). In this section, the mechanical properties of polymer composites, such as tensile, impact resistance, compressive, toughness, fatigue, fracture, and flexural properties, are considered. Moreover, the factors affecting the mechanical properties, including the type of polymer and reinforcement, filler concentration, processing conditions, and interfacial bonding, are also explored (Naheed Saba et al. 2016; A.K. Sinha, Narang, et Bhattacharya 2017; Arash, Wang, et Varadan 2014).

The tensile properties define the ability of materials to resist forces, which is critical for structural applications. Tensile strength, tensile modulus, and elongation at break are essential properties that need to be optimized (Pukanszky 1990; R. Rahman et Putra 2019). Generally, polymer composites indicate excellent tensile strength and tensile modulus compared to neat polymer due to the reinforcing effect of fibers or fillers. The fiber's alignment in a polymer matrix has a significant impact on tensile properties that the tensile strength and modulus along the fibers in unidirectional fiber composites can be much higher than in other directions, where the load is borne by the polymer (Ku et al. 2011; T. Wang et Schonhorn 1969; Feih et Mouritz 2012). On the other hand, the elongation at break of polymer composites is lower than that of the pure polymer. The particles or fibers restrict the mobility of the polymer chains, resulting in plastic deformation before failure (Ain et al. 2016; M.Z. Khan, Srivastava, et Gupta 2018).

Compressive strength is the ability of a substance to withstand loads that reduce its size, which resists elongation. The compressive properties are also enhanced by the presence of reinforcing agents. It depends on the type, volume, and also orientation of fibers within the matrix as the fibers act as load-carrying components, they provide additional resistance to compressive loads (Kousourakis, Bannister, et Mouritz 2008; Tsai et Sun 2004; Sapiai, Jumahat, et Hakim 2014). Nevertheless, the compressive strength in composites with unidirectional fibers can be lower than the tensile strength due to the buckling effect of the fibers under compression. Therefore, the polymer matrix plays a crucial role in compressive strength because it supports the fibers and prevents buckling. For instance, thermosetting polymers provide better compressive strength than thermoplastic polymers due to the cross-linked structure that offers greater rigidity (Yousaf et al. 2020; Ohayon-Lavi et al. 2020; K. Yu, Ding, et Zhang 2020; A. Jain et al. 2023; Krishnappa et Gururaja 2024).

Flexural strength and modulus are vital mechanical properties where materials experience bending or out-of-plane loading (A. Jain et al. 2024; Benkhelladi, Laouici, et Bouchoucha 2020). It measures the ability of a composite to resist deformation under bending forces. The fibers or fillers within a polymer composite act as load-bearing structures that carry the tensile stresses on the opposite sides of the bending plane. The flexural strength is significantly increased in the fiber-reinforced composites where the fibers are unidirectional to the applied load compared to the perpendicular situation (A.K. Sinha, Narang, et Bhattacharya 2020; K. Prakash et al. 2021; A. Kumar, Sharma, et Dixit 2021). Flexural modulus, which measures the stiffness of the material under bending, is higher for stiffer reinforcement such as carbon or glass fibers. Typically, the addition of reinforcement reduces the ductility of the composite under bending, resulting in a more brittle failure (A. Kumar, Sharma, et Dixit 2021; Z. Zhang et al. 2020).

Impact resistance is another crucial mechanical property to withstand dynamic loads or impact forces, which is the ability of a material to absorb and dissipate energy during sudden loading. Absorbing energy before fracturing is called toughness (Gupta et Srivastava 2016b; N Saba, Paridah, et Jawaid 2015). The reinforcement's ability to absorb energy during deformation affects the toughness of a polymer composite. The common energy dissipation mechanisms in composites are polymer matrix cracking, fiber pull-out, and fiber breakage. Strong interfacial bonding between the polymer and reinforcing agent can increase toughness by preventing premature failure at the interface (Senthilkumar et al. 2018; Sathishkumar, Naveen, et Satheeshkumar 2014).

Fracture behavior explains how the material behaves when a crack forms and propagates, while fatigue refers to the progressive weakening of a material when subjected to cyclic or repeated loading (Niaki 2023;

Pappa et al. 2021). Due to the great distribution of the applied stresses through the polymer matrix by the reinforcing agent in a polymer composite, it shows better fatigue resistance than pure polymers. However, the type and orientation of the reinforcement, the type of polymer matrix, and loading conditions are the factors that affect the fatigue life (Yunlong Li, Wang, et al. 2018; Prasad, Venkatesha, et Jayaraju 2011; Brooker, Kinloch, et Taylor 2010). Unidirectional fiber-reinforced composites indicate superior fatigue resistance along the fiber direction but may fail prematurely under transverse or shear loading. Potential fracture modes in polymer composites are fiber breakage, matrix cracking, interfacial debonding, and fiber pull-out. As the fibers can bridge the crack faces and resist further growth in polymer composites, the crack propagation is often slowed by the reinforcement, which can be improved by optimizing the interface between the matrix and reinforcement (Brunner 2020; Sharafi et al. 2021; Kausch 2012; Lauke et Fu 2013).

Several factors influence the mechanical properties of polymer composites, including the polymer matrix material, type and amount of reinforcement, the processing conditions, and the quality of interfacial bonding (Al-Saleh et Sundararaj 2011; Bakshi et Agarwal 2011; R. Rahman et Putra 2019; A.K. Sinha, Narang, et Bhattacharya 2020). Thermosetting matrices provide high stiffness and strength but are brittle and have limited impact resistance, while thermoplastic polymers offer better toughness and ductility but may have lower stiffness and strength. Efficient stress transfer is a critical factor that is influenced by the compatibility and strong interfacial bonding between the polymer and reinforcing agent (Kausar 2017; N Saba et Jawaid 2018; Pascault et Williams 2013; Hemanth, Sekar, et Suresha 2014). Another important factor is the type and amount of reinforcement, such as fibers, platelets, and particles, that has a significant impact on mechanical properties. For instance, long and continuous fibers provide the best flexural and tensile properties; however, short fibers or particulate fillers improve compressive strength and impact resistance. On the other hand, a higher volume fraction of fillers generally leads to better mechanical properties but can reduce ductility (Gupta et Srivastava 2016a; Ashik et Sharma 2015; G. Shi et al. 2018; J. Ma et al. 2014).

The processing parameters and processing methods can have a significant impact on the final mechanical properties. Although high processing temperatures and pressures can improve the consolidation of fibers and matrix, leading to better mechanical performance, excessive heat or inadequate curing can lead to defects like poor adhesion, voids, and fiber misalignment, which weaken the composite (Mohan et al. 2017; Saroia et al. 2020; Mallick 2017; Tadmor et Gogos 2013). The final factor is the strength of interfacial bonding between the matrix and the reinforcement to resist the applied loads. Strong interfacial bonding improves compressive, flexural properties, and tensile as it ensures efficient stress transfer from the matrix to the reinforcement. For instance, surface treatment of fibers or fillers, such as chemical etching, can enhance the interfacial bonding (Liu et al. 2015; Ning et al. 2012; Arash, Wang, et Varadan 2014).

Table 1 presents a comprehensive comparison of the mechanical properties—Young's modulus, elongation at break, tensile strength, and toughness—of various polymer-based nanocomposites. The integration of nanomaterials into polymer matrices significantly affects these properties. For instance, an increase in Young's modulus is observed in composites reinforced with materials like carbon nanotubes and graphene, indicating improved stiffness and rigidity. At the same time, these nanofillers contribute to a higher tensile strength, which enhances the material's ability to withstand tensile loads. Elongation at break, which reflects a material's ductility, can vary widely depending on the type and concentration of nanofillers. For example, the addition of flexible fillers may maintain or even improve elongation, whereas more rigid fillers may reduce ductility. Toughness, a measure of the energy absorbed before failure, is also enhanced in certain composites due to the optimized interaction between the polymer matrix and the nanofiller. The data in the table provide a detailed overview of how different nanocomposites, such as graphene-polymer or glass-polymer systems, exhibit tailored mechanical properties for specific applications. These findings demonstrate the potential of polymer-based nanocomposites to be engineered for demanding uses in sectors such as aerospace, automotive, and biomedical industries.

5. Thermal and Environmental Properties

The performance of polymer composites is significantly influenced by their thermal and environmental properties, including their conductivity and thermal stability, degradation and aging behavior, and resistance to environmental factors such as moisture and UV radiation. Thermal stability depends on both the polymer and reinforcing phases, determining the ability of a material to retain its mechanical, chemical, and structural properties when exposed to elevated temperatures (Y. Guo et al. 2020; Arrakhiz et al. 2013; M.O. Prakash et al. 2018; Chen et al. 2016).

Thermosetting polymers like epoxy, polyester, and polyimides generally exhibit better thermal stability than thermoplastics due to their crosslinked structures. Crosslinked networks prevent the polymer chains from moving freely at higher temperatures, which provides better thermal resistance. Polymers with high glass transition temperatures (T_g) and melting points (T_m) typically exhibit greater thermal stability (Chen et al. 2016; Burger et al. 2016; K. Malik et al. 2022; Kausar 2017). Reinforcement materials such as fibers or nanoparticles can increase the thermal stability, heat dissipation ability, and thermal degradation resistance of polymer composites. Thermal stability is defined through the thermal decomposition temperature (T_d) of a material. At this temperature, the breakdown of the polymer chains takes part, resulting in the loss of mechanical integrity (Han et Fina 2011; Saleem et al. 2016; Krishnasamy et al. 2019).

There are various methods to measure the thermal stability of polymer composites, such as thermogravimetric analysis (TGA), differential scanning calorimetry (DSC), and dynamic mechanical analysis (DMA) (N Saba et Jawaid 2018; Naheed Saba et al. 2016; Muthukumar et al. 2022). The weight loss of a material as a function of temperature is measured by TGA, which provides the decomposition temperature, thermal stability, and the amount of non-volatile residue (Mohammad Asim et al. 2020; Nurazzi et al. 2021; Celina 2013). The melting and glass transition temperatures are determined by DSC, identifying the heat flow changes in the material as a function of temperature (Naheed Saba et al. 2016; Turi 2012). DMA measures changes in the material's modulus and damping characteristics under varying temperature conditions (Lorandi, Cioffi, et Ornaghi Jr 2016; Bashir 2021).

There are important factors that affect the thermal stability of polymer composites, such as the type and amount of fillers, filler dispersion, and filler-polymer interface (Chen et al. 2016; Han et Fina 2011). Adding fillers to polymer composites can effectively improve the thermal conductivity due to the high aspect ratio of fillers, which form conductive networks within the polymer structure. However, the concentration of fillers, filler dispersion, and alignment within the polymer matrix determine the degree of heat stability improvement (Chen et al. 2016; Huang, Jiang, et Tanaka 2011; A. Li, Zhang, et Zhang 2017). Homogenous dispersion of fillers enhances the thermal conductivity, while poor dispersion can lead to agglomeration and create thermal hotspots. To achieve better filler dispersion, techniques such as high-shear mixing, sonication, and using surfactants or compatibilizers can help (Chen et al. 2016; Azwa et al. 2013). Moreover, the polymer-filler weak interface significantly impacts the overall thermal conductivity, which can act as a thermal barrier and prevent efficient heat transfer. Therefore, surface treatment or filler functionalization can improve the interfacial interaction, leading to better heat conduction (T. Yu et al. 2010; Huang et al. 2012).

Polymer composites experience degradation due to several factors, such as environmental exposure, thermal cycling, chemical reactions, and mechanical loading (Azwa et al. 2013; Komal et al.

Table 1. Mechanical properties of different polymer-based nanocomposites.

Polymer	Reinforcing agent (s)	Young's modulus (GPa)	Tensile strength (MPa)	Elongation at break (%)	Toughness	Ref.
polymethyl methacrylate (PMMA)	Carbon naotube (CNT) Graphene sheet (GNS)	3.7 4.4	103 112	17 17	…	(Yunlong Li, Wang, et al. 2018)
polyethylene (PE)	thermally reduced graphene oxide (TrGO)	109.3 ± 12.7	3.2 ± 0.5 GPa	6	…	(Pang et al. 2019)
Epoxy	Graphene nano-platelets (GNPs)	3.36	35.5 ± 1.3	…	…	(King et al. 2013)
Polyester	Sisal/banana	…	65.20	…	…	(B. Singh, Gupta, et Verma 1995)
Epoxy	Glass/abaca	0.270	44.5	…	…	(Ramnath et al. 2013)
Polyester	Jute/palm leaf stalk	3.78	83.3	…	…	(Shanmugam et Thiruchitrambalam 2013)
Poly lactic acid (PLA)	Sisal/banana	1.7	57	…	…	(Asaithambi, Ganesan, et Ananda Kumar 2014)
Polypropylene (PP)	Cordenka/jute	3.2	72	…	79 kJ/m^3	(M.A. Khan, Ganster, et Fink 2009)
Acrylate	Hemp/Kenaf	1.2-3	11.3	…	6-40 kJ/m^3	(Graupner, Herrmann, et Müssig 2009)
Bisphenol-C-formaldehyde	Jute/jamun flower husk	…	12	…	…	(Arbelaiz et al. 2005)
Epoxy	Carbon/glass	23.966	210	…	…	(Guermazi et al. 2014)
High density polyethylene	Agave/pine	0.620	24	…	53 kJ/m^3	(Pérez-Fonseca et al. 2014)
Polypropylene (PP)	CNT/glass	6.1	38	…	7.75	(Boroujeni et al. 2014)
Epoxy	CNT/carbon	63.87	854.2	…	…	(Boroujeni et al. 2014)
Polycarbonate (PC)	MWCNT	1.5	72	…	…	(Castillo et al. 2011)
Polyethylene (PE)	SWCNT	0.72	33	…	…	(Mierczynska et al. 2007)
Polypropylene (PP)	MWCNT	2	25	…	…	(H.-Y. Wu et al. 2018)
Epoxy	Ag-MWCNT	3.17	118	…	…	(P.C. Ma, Tang, et Kim 2008)
polymethyl methacrylate (PMMA)	Carbon nano fiber	1.3	37	…	…	(Jimenez et Jana 2007)
Epoxy	Graphene	1.5	50	…	…	(Wajid et al. 2013)

2020). Over extended periods, thermal degradation occurs when the polymer composite is exposed to elevated temperatures, leading to chain scissions, loss of mechanical properties, and oxidation. At high temperatures, the oxidation of polymers may result in changes in molecular weight and structure and also catalyze the breakdown of the polymer chains (Pielichowski, Njuguna, et Majka 2022; Azwa et Yousif 2013; La Mantia et al. 2017). When the polymer composite experiences alternate heating and cooling or repeated thermal cycling, it can lead to the development of microcracks and delamination within the composite, reducing its structural integrity (Ghasemi et Moradi 2017; Barbosa et al. 2017). Humidity, UV radiation, and pollutants are the environmental aging factors that refer to the gradual deterioration of the polymer composite, resulting in a loss of mechanical strength, color changes, and surface cracking (S. Ray et Cooney 2018; Brebu 2020; Lu et al. 2018). Exposure to chemicals such as acids, bases, and solvents can cause chemical degradation of the polymer composite, leading to stress cracking and swelling (B.C. Ray et Rathore 2015; Azwa et al. 2013; Sethi et Ray 2015).

6. Application of Polymer Composites

Polymer composites have emerged as versatile materials in modern engineering for a wide range of applications due to their unique properties, including durability, flexibility, mechanical strength, and weight reduction (Figure 9) (Phiri, Gane, et Maloney 2017; Mohammed et al. 2015). In aerospace and automotive industries, where lightweight, durable, and strong materials are needed, polymer composites have become a material of choice due to their ability to significantly reduce the weight of vehicles and aircraft without compromising structural integrity or safety. In aerospace applications, weight reduction is vital, which leads to lower fuel consumption and improved performance (Muhammad et al. 2021; Brunner 2020; Irving et Soutis 2019). For instance, carbon fiber-reinforced polymer composites are commonly used in aircraft due to their high strength-to-weight ratios and superior fatigue resistance (Ozkan, Gok, et Karaoglanli 2020; Muhammad et al. 2021). The demand for fuel efficiency and emissions reduction in the automotive industry has driven the adoption of polymer composites in vehicle design and manufacturing. For example, glass fiber-reinforced polymer composites are frequently used because they have lower cost and satisfactory mechanical properties, which reduce fuel consumption and carbon dioxide emissions (Sathishkumar, Satheeshkumar, et Naveen 2014; Volpe et al. 2019; Panaitescu, Koch, et Archodoulaki 2019). Additionally, the integration of polymer composites into electric vehicles (EVs) is particularly significant because the weight reduction directly affects the range and efficiency of a battery of EVs (Lyu et Choi 2015; M. Malik, Dincer, et Rosen 2016).

Beyond transportation, polymer composites can be used in construction and infrastructures. Traditional construction materials such as steel, wood, and concrete are increasingly replaced by polymer composites due to their high strength, lightweight, and corrosion resistance (Fang et al. 2019; R. Jain et Lee 2012). Fiber-reinforced polymer composites are commonly used for repairing structures such as tunnels, buildings, and bridges in civil engineering (R. Jain et Lee 2012). Moreover, the polymer composites are resistant to harsh environmental conditions like moisture, UV radiation, and chemicals, enhancing the durability of infrastructure in regions prone to corrosion or weather (Dittenber et GangaRao 2012; Ticoalu, Aravinthan, et Cardona 2010).

In the biomedical field, the biocompatibility, lightweight, and good mechanical properties of polymer composites have made them ideal for creating revolutionary medical devices, implants, and prosthetics (Kaur et al. 2015). For example, in orthopedics, polymer composites are used to fabricate screws, joint replacements, and bone plates, in which their biocompatibility reduces the risk of adverse reactions in the body (Krishnakumar et Senthilvelan 2021; P. Kumar, Irudhayam, et Naviin 2012). On the other hand, the lightweight nature of polymer composites makes them ideal for developing comfortable and functional artificial limbs in the field of prosthetics, which causes greater mobility and comfort for patients (Scholz et al. 2011). In dental applications, polymer composites can employed as crowns, fillings, and bridges to bond well with natural teeth (Kundie et al. 2018; Moszner et Hirt 2012).

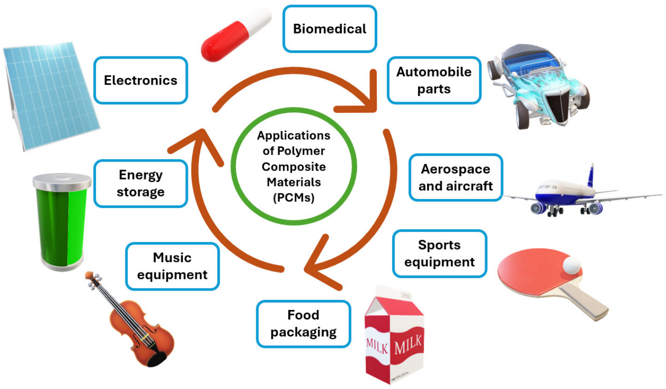


Fig. 9. Different applications of polymer composite materials (PCMs).

In recent years, polymer composites have had remarkable applications in electronic industries and energy storage devices (Q. Wang et Zhu 2011). In energy storage, polymer composites have developed advanced batteries, supercapacitors, and energy harvesting devices. Adding nanomaterials such as graphene and carbon nanotubes into polymer has led to improved electrochemical performance. In supercapacitors and batteries, the polymer composite-based electrodes and electrolytes offer higher electrical and ionic conductivities, increased energy density, and improved cycling stability (Y. Sun et Shi 2013; Srivastava et al. 2014; H. Wu et al. 2022; Hu et al. 2020; W. Luo et al. 2022; R. Zhang et Pang 2021; S. Li et al. 2020). In electronic sectors, polymer composites have been used for the fabrication of flexible printed circuit boards (PCBs), wearable devices, and sensors. The polymer composites enable the production of flexible electronics that can make complex shapes for wearable technologies (Bharath et al. 2020; W. Lee et al. 2022). In electromagnetic interference (EMI) shielding, polymer composites play a key role in protecting sensitive electronic components from interference that is caused by external electromagnetic waves. Researchers have developed effective and lightweight EMI shielding materials by incorporating conductive fillers into polymer matrices (Kruželák et al. 2021; Wanasinghe et al. 2020; Devi et al. 2022; Banerjee et al. 2023; Dassan et al. 2020). Furthermore, polymer composites are being explored for use in energy harvesting technologies, such as triboelectric nanogenerators (TENGs), which convert mechanical energy into electrical energy. Researchers have fabricated efficient and flexible energy harvesting devices that can be used in self-powered sensors and smart textiles, which hold great demand for sustainable and efficient energy solutions (Hatta, Mohammad Haniff, et Mohamed 2022; Choi et al. 2023; Tao, Chen, et Wang 2023; Shanbedi, Ardebili, et Karim 2023; L. Shi et al. 2021; Parandeh et al. 2020).

7. Future Perspectives and Challenges

Polymers have already made remarkable impacts in industries due to their unique properties when they combine with reinforcements like fibers, nanoparticles, and other fillers. As technological demands continue to evolve, understanding and overcoming the critical issues related to innovation, sustainability, and scaling up for the commercialization of polymer composite materials will be key to solving various applications.

The innovation in material design and processing techniques of polymer composites is one of the most exciting areas of future development. Traditional polymer composites are designed with a single-function component that improves mechanical strength or thermal stability. However, next-generation polymer composites can be multi-functional composites that offer multiple functionalities, such as thermal conductivity, electrical conductivity, and responsiveness to external stimuli like light, heat, and magnetic fields, which can be used in aerospace industries where low-weight and multi-use components could improve performance. Another challenge in polymer composites is the addition of nanomaterials with proper distribution and alignment. Particularly, graphene has garnered considerable attention due to its superior conductivity, flexibility, tensile strength, toughness, and thermal stability.

Additive manufacturing has also introduced transformative design in polymer composites for the precise control of material architecture and composition with complex geometries that would be difficult with traditional methods. Future perspectives in 3D printing technology will focus on enhancing interlayer bonding, improving the integration of composite materials, and expanding the range of polymers and nanomaterials that can be used.

The sustainability and recycling of polymer composites with synthetic fibers is another global issue that has an intense environmental impact as these materials contribute to environmental pollution. One approach is to use the bio-based polymers, reducing the carbon production. For example, polylactic acid (PLA) and polyvinyl alcohol (PVA) are biocompatible and biodegradable polymers that offer competitive mechanical properties while being environmentally friendly. However, bio-based polymer composites still have poor mechanical properties that need to be addressed before fully replaced with high-performance composites. Development of thermosetting resins instead of conventional thermoset polymers are easier to recycle due to non-crosslinked structures. Depolymerization, which breaks down the polymer chains to its monomers, can be re-polymerized composites into new materials, which is called the chemical recycling technique.

Despite the advances in the polymer composites field, significant challenges remain unsolved, such as the heterogeneous nature of polymer composites, making recyclability more difficult as they combine with different types of polymers and fillers, and each component may require different treatment methods. Furthermore, the recovery and reuse of polymer composite and precise control over the material composition and the dispersion and alignment of fillers on a large scale are difficult due to the lack of standardized recycling infrastructure and the complexity of manufacturing processes.

Another significant barrier to scaling up the polymer composites is cost. Most of the advanced materials, such as graphene, carbon fibers, and newly developed composite materials, are expensive to produce. To overcome this challenge, developing lower-cost carbon fibers and improving the production scalability of nanomaterials could help to reduce the overall cost of polymer composites.

Thus, polymer composites have exciting future but also significant challenges. Innovations in materials design, addressing sustainability and recyclability, scaling up, and commercialization issues in various industries will be critical to ensuring that polymer composites contribute to a better future of materials science and engineering.

Conclusions

Polymer Composite Materials (PCMs) are a diverse class of materials that offer significant advantages over traditional materials due to their combination of polymer matrices and reinforcing phases. The combination of polymers and fillers can increase the electrical, thermal, mechanical, and chemical properties across a wide range of industries. Selecting the type of reinforcement, polymer matrix, and processing conditions can tailor the structural properties for advanced applications. Polymer composites not only meet the needs of modern technologies but also address environmental sustainability through recyclability and the use of renewable resources. Each of the processing techniques of polymer composites has its advantages and challenges, which determine the final properties of the composite. Additive manufacturing as an advanced technique has opened up new possibilities for producing high-performance polymer composites that can meet the growing demand for lightweight, high-performance materials in different industries. The application of polymer composites spans a wide range of industries, such as construction and infrastructure, biomedical, electronics, and energy storage devices. Polymer composites are expected to play an incredible role in shaping the future of various industries and driving technological innovation.

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