Review Article

Modern Applications of Polymer Composites in Structural Industries: A Review of Philosophies, Product Development, and Graphical Applications

Isiaka Oluwole Oladele* and Linus Nnabuike Onuh
Department of Metallurgical and Materials Engineering, Federal University of Technology, Akure, Nigeria

Suchart Siengchin and Mavinkere Rangappa Sanjay
Department of Materials and Production Engineering, Sirindhorn International Thai-German Graduate School of Engineering, King Mongkut's University of Technology North Bangkok, Bangkok, Thailand

Samson Oluwagbenga Adelani*
Materials Science and Engineering Program, University of Colorado Boulder, Colorado, USA

* Corresponding author. E-mail: iooladele@futa.edu.ng, samson.adelani@colorado.edu
DOI: 10.14416/j.asep.2023.07.003
Received: 10 March 2023; Revised: 15 April 2023; Accepted: 16 May 2023; Published online: 19 July 2023

Abstract
Polymer-based materials have been discovered as the most outstanding class of material that is fast displacing other materials in all areas of human needs. The dire need for durable, aesthetic, and lightweight materials has favored the increasing demand for polymer-based materials in structural industries. The application of polymeric-based materials in all aspects of human endeavor is based on their ease of formation, lightweight, and acceptable properties. The philosophy of composite development has also contributed immensely to the production of components from polymer-based materials suitable for several structural applications. More recently, interest in green materials also encourages the use of polymer-based materials in structural applications. The suitability of a material for any selected application is justified by structural and environmental compatibility. Thus, researchers have focused on these two major areas in their investigations for product development. Despite continuous efforts in these two directions, they are still issues of great concern to researchers in satisfying the desires of users presently. Hence, this review presents the philosophies of researchers, the product developed, and areas of application for polymer-based materials in structural industries such as biomedical, building and construction, energy, and sports. The paper advanced graphical presentation of the application of developed products and strongly supports the recommendation of polymer-based composite materials as a viable alternative to other materials due to their remarkable capabilities in many application domains.

Keywords: Application, Assessment, Impact, Industries, Materials, Polymer, Structural

1 Introduction

The world is filled with various materials as provided by nature and human beings have had the opportunity of having various materials in different decades. Researchers have had different materials to deal with right from the stone to aluminum ages, and currently, the polymer age [1]. All these changes are necessitated by the influence of man on the environment thereby creating the need for improved materials to suit the present needs and applications. Polymer, which perhaps is one of the best materials ever due to its unique properties, has gained predominance in vast areas of application and is the current material of the century. For the material to adequately possess the required properties needed for top performance in diverse fields, polymers are usually reinforced with other materials to form composites. Hence, the formation of polymer matrix-based composites (PMCs) has remained one of the most efficient methods to influence the properties of polymers [2]. Polymer materials have been discovered as being beneficial for various applications for several decades but due to a lack of proper understanding of these materials and technology, their applications have been greatly hindered. However, with a change in this trend, polymer materials have gradually and continually been made suitable for most applications now.

In recent times, due to improved research and knowledge, polymer-based materials are the first choice materials for several applications and are now replacing other materials continuously. Advanced materials from polymers are evolving on a daily basis as a substitute for other materials even in areas where polymers are considered not to be suitable formerly. More recently, polymers have replaced metals and ceramics in applications like construction, aerospace, automobiles, medicine, and many more. This advancement will no doubt continue due to its inherent properties and sustainability potential. Today, most of the limitations of polymers are being taken care of in the formulation of composites in conjunction with their adaptation to positive environmental influence by scientists and researchers globally [1]. The application of polymer matrix composites is now dominant across various industries and sectors as they significantly help to improve the performance and efficiency of materials across these diverse fields due to their outstanding properties. Presently, polymer-based composites are been used in every area of human activities without exception, some of which are in transportation [3]–[5], civil construction [6], biomedical [7], military [8], sport and leisure [9], food and packaging [10], [11], and electrical and electronics [12], [13]. All these have culminated in the advancement of these materials presently.

Nanotechnology has led to the development of advanced and dynamic materials through the combination of the benefits of nanotechnology with the advantages of polymer-based materials. Going by the present events, it was assumed that future trends in the use of PCMs will depend ultimately on the use of nanomaterials as reinforcements to meet the ever-evolving and dynamic requirements of different fields. This assumption was based on the premise that nanofillers greatly aid good interaction between the polymer matrix and the reinforcement that usually resulted in outstanding material properties. The sole incorporation of nanotechnology for the production of these advanced composites usually provides the materials with further improved properties required for ever-increasing properties needed for satisfactory performance. Also, additive manufacturing techniques have aided the development of many products from polymer-based materials. Polymer-based composites contain a wide range of unique characteristics that have helped the special material find use in all sectors of human lives as noticed in our environment in the modern days.

Much research has been carried out to investigate the structural compatibility of polymer-based composites in many areas of applications. The outputs from these researches are the eventual products that are found in several obvious applications in our environments today. Also, the numerous areas of applications in our environments and the enormous wastes emanating from polymer-based materials attest to their wide acceptability. Therefore, there is a need to identify the areas of strength and weakness of these materials from their uses. Interest in these materials from the several areas of applications can help focus more on various factors that usually caused materials to fail in service due to structural defects; thereby, looking for methods to overcome them. Thus, this review presents the ideology behind the development of suitable structural materials for industrial applications in this modern day. This is to aid the advancement of future development and as well impact our environment positively in a sustainable approach. The paper promotes graphical illustration in addition to the mode of production from research outputs. This was done to begin to advanced pictorial presentation in the future.

2 Polymer and Polymer Matrix Composites

Polymer composites, also known as polymer matrix composites (PMCs), are remarkable multi-material polymer systems made up of numerous materials of various kinds embedded in a polymer system (which acts as a parent or base matrix) with exceptional physical, mechanical, and chemical capabilities [14]–[16]. Polymer matrix composites have exceptional mechanical and physio-chemical capabilities as well as extremely low weight when compared to simple polymer materials [17]–[19]. Table 1 shows the mechanical properties of selected natural fibers while Table 2 lists a few common natural fiber-reinforced PMCs and applications.

Table 1: Properties of selected natural fibers [4]–[37]

Fiber	Density (g/cm^3)	Tensile Strength (MPa)	Elongation (%)	Young Modulus (GPa)
Ramie	1.5	220–938	2–3.8	44–128
Hemp	1.48	550–900	1.6	70
Oil Palm	0.7–1.6	50–400	4–8	0.6–9
Sugarcane Bagasse	1.1–1.6	170–350	6.3–7.9	5.1–6.2
Jute	1.3–1.46	393–800	1.5–1.8	10–30
Cotton	1.5–1.6	287–597	3–10	5.5–12.6
Sisal	1.33–1.5	400–700	2–14	9–38
Betel Nut	0.2–0.4	120–166	22–24	1.3–2.6
Flax	1.4–1.5	345–1500	1.2–3.2	27.6–80
Coir	1.2	175–220	15–30	4–6
Bamboo	1.2–1.5	500–575	1.9–3.2	27–40
Kenaf	0.6–1.5	223–1191	1.6–4.3	11–60

In the fabrication of PMCs, there are three main types of reinforcements: fiber reinforcements, particle reinforcements, and structural reinforcements, which together comprise fiber-reinforced polymer composites (FRPC). There are times when it can also be a composite of hybrid reinforcements or reinforcements of the same kind [2]–[20]. Composite materials that are fiber-reinforced use a polymer matrix with fibers including glass, carbon, and basalt fiber [2]–[22]. Silica and red mud are used as reinforcement particles and materials with diverse physical and chemical properties combined to create structures [23]–[26].

2.1 *Fiber-reinforced polymer composite*

Since they meet the requirements and transfer strength to the matrix constituent, modifying and enhancing their properties as needed, fibers are an essential type of reinforcement [27]. Fibers are inserted in a matrix material to create FRPCs [4]. If the qualities of such a composite vary depending on the length of the fibers, it is known as a discontinuous fiber or short fiber composite [28]. The composite is continuous fiber reinforced, on the other hand, when the length of the

Table 2: Common PMCs and their basic applications [14]–[16]

Polymer Matrix	Reinforcements		Properties	Area of Applications
	Natural	Synthetic		
High-Density Polyethylene (HDPE)	Wood fibers, Kenaf fibers		High bonding strength	Furniture, Storage containers
Polyester	Banana fibers, Sisal fibers, cow tail hair fibers, chicken feather fibers		Excellent tensile strength, high tensile modulus, high flexural strength	Used as a construction material
Polyamide		Copper	High thermal conductivity	Production of smart materials
Epoxy resin	Jute, kenaf fibers, sisal fibers, bunches, and banana fibers	Single-walled carbon nanotube, glass fiber, alumina fibers, silicon carbide, and aramid fibers	High tensile strength, high impact, high flexural, good thermal conductivity, and shear resistance	Automobile industry, bulletproof vests, building construction, aerospace industry, marine industry, and orthopedic industry.
Nylon		Aluminum and its alloy		Used as 3D printing material
Polystyrene	Wood fibers		Excellent bonding strength	Used in fabricating furniture materials, in modular building constructions.
Denture cure resin	HAp	Glass and carbon fiber	High impact and flexural strength	Applied as a matrix material for HAp reinforcements, used as dental implant replacement.
Polymethyl methacrylate		Carbon nanotube	High shear strength	Applied in electrical, and thermal optics

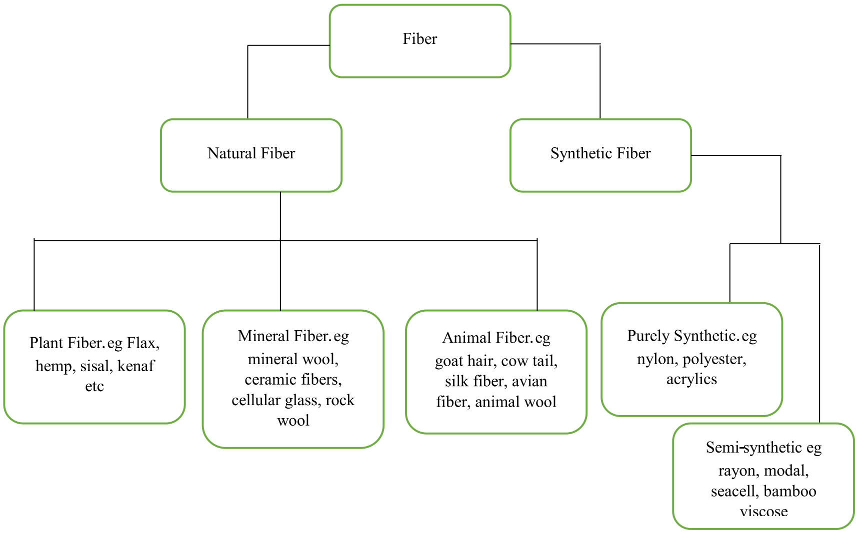

Figure 1(a): Classification of fibers [38].

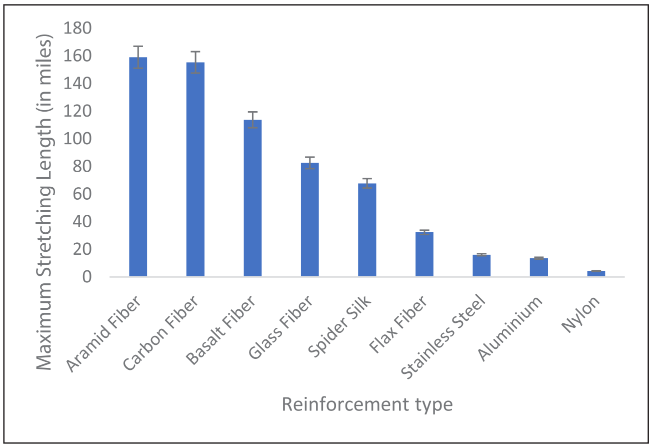

Figure 1(b): Breaking length of materials [14]–[16].

fiber is such that any additional increase in length does not further raise the elastic modulus of the composite. Despite having excellent tensile qualities, fibers have a small diameter and bend quickly when pulled axially [29], [30]. To prevent individual strands from bending and buckling, these fibers must be supported [31]. Figure 1(a) depicts the general classification of fibers, although additional typical fiber-reinforcing materials include asbestos, carbon/graphite fibers, beryllium, beryllium carbide, beryllium oxide, molybdenum, aluminum oxide, glass fibers, polyamide, natural fibers are available [16]–[32], [33]–[35]. Figure 1(b) also indicates the maximum breaking length of some commonly used fiber materials. Epoxy, phenolic, polyester, and vinyl ester are examples of common matrix materials [36], [37].

2.2 *Particle-Reinforced polymer composites*

Particle-reinforced polymer composites (PRPC) are metal and ceramic composites with microstructures that exhibit one phase's particles dispersed throughout the other. There are known reinforcement shapes that are square, triangular, and round, but all of their sides are found to be roughly similar in size. The hydrostatic compulsion of fillers in polymer base matrices and the particle reinforcements' relative hardness to the matrix strengthen the system in PRPCs [39]. Small mineral particles, metal particles like aluminum, animal wastes like animal shells and bones, amorphous materials like carbon black, and other nanoparticles are only a few examples of the particles utilized for reinforcement applications in ceramics and glasses. Using particles, the matrix's ductility is reduced while its modules are increased [39]–[41]. Particles are also employed to make composite materials less expensive. However, FRPCs are preferred over PRPCs for several structural applications.

2.3 *Hybrid reinforced polymer composites*

It has been established by many researchers that the hybridization technique can be used to improve the properties of polymer-based composites [1]–[3]. Hybridization is the use of two or more reinforcement materials in a single matrix phase to form a synergy with respect to the essential or needed properties of these reinforcements while retaining their individual properties in the resultant composites [18], [19]. Thus, the hybridization of natural fibers with synthetic fibers improves the mechanical properties of the reinforced composites [34], [35]. There are three major modes of blending synthetic and natural fibers in a hybrid composite which are: inter-layer, intralayer, and intra-yarn. In the inter-layer configuration, layers made of different fibers are placed on top of each other while in the intra-layer, both fibers are entangled within a single layer using techniques such as weaving. However, for intra-yarn configuration, both fibers are intertwisting within a single yarn. In a hybrid reinforced composite system, the advantages of one fiber complement the disadvantages of the other fiber while advancing the advantages of both reinforcements. Natural/ synthetic fiber hybrid reinforced composites offer multi-functionalities such as weight reduction that cannot be achieved with a single fiber and synergic effect between the reinforcements [31]. Hybridization is considered a valid strategy and effective technique that can be used to tailor the mechanical behavior of reinforced polymer composites to desired strengths for specific applications [2]-[31], [34], [35]. Hence, to achieve the desired properties, the reinforcements histories need to be known and the selection criterion needed to be well ascertained. Hybridization is a giant stride in the advancement of composite development in meeting the dire needs of the human race. Formulation of a hybrid is an open-end materials design method that will continue to attract and encourage the development of more novel advanced materials in the present and future.

The matrix enclosing the hybrid fibers in composites retains them in the proper location and orientation and acts as a higher load transfer medium between them, allowing the composite to withstand greater loads than would be possible with single-fiber reinforcements of the same type [29], [30]. For structural applications, cheap hybrid biofiber-based composites for cellular plates were created [31], [32]. When compared to conventional pipe construction, hemp mat has been shown to save costs by 20% and reduce weight by 23% in glass/ jute fiber-reinforced pipe bend [31]–[33]. Panels for partition and false ceiling, partition boards, wall, floor, window and door frames, roof tiles, storage devices (post-boxes, grain storage silos, biogas containers), furniture, electric devices, mechanical, aerospace, automobile, biomedical, marine, and many other manufacturing industries are just some of the many important applications of hybrid composites [36]–[41].

2.4 *Polymer composites reinforced with structural reinforcement materials*

A new classification of polymer reinforcements is making a wave in the construction industry. This class of reinforcement is the structural reinforcement materials [42]. They are predominantly applied in the construction industry. Common examples were found in the production of building materials like rebars and cement, the construction of elevators in skyscrapers as well as in the construction of bridges and tunnels [43], [44]. These materials have high resistance to harsh environmental conditions that can cause corrosion and also possess high tensile and flexural strengths [45]. These materials can be in the form of fibers or particulates that are used for reinforcement in metal or ceramic matrixes. Examples of these reinforcement materials include carbon fibers, graphene nanoplatelets, and nanotubes from carbon and other hydrocarbons [46].

3 Structural Applications of Polymer Composites

3.1 *Orthopedics*

PMCs are special materials with a wide range of potential applications [47]. However, these applications heavily rely on the reinforcements' characteristics. Each reinforcement completes the matrix phase and adds extra stiffness, strength, and other distinctive qualities. The matrix and reinforcement phases can replicate natural bone in orthopedic applications and can be placed inside the bone to support it from the inside [48], [49]. PMCs have numerous uses in both orthopedics and general medicine. Orthopedic composites are a type of substance known as a biomaterial, which may replace and operate like natural tissues in the body [50]. At some time, certain implantable biomaterials were constructed of organic materials like wood, some organ tissue, zinc, gold, and iron. The qualities and architectures of biomedical composites should be as similar to living tissues as possible given that they perform their role in the body and interact with tissues [51]. For instance, in orthopedic composites, the stress placed on bones is almost 4 MPa, while for other tissues, such as tendons, this stress can reach up to 40–80 MPa with routine use. The typical load on the hip joint is close to 3000 N, but it can rise to 10000 N during a jump. Furthermore, this level of stress is variable and subject to fluctuate depending on the type of activity [51].

Polymeric composites are a better alternative material to ceramic composites since they are shown to have less failure than other groups of materials [52]. They come in a variety of shapes and forms and are changeable, differing in their composition, performances, and properties (such as films or fibers). They can also be used as fillers and to absorb liquids. It is common to use polymeric materials with a lower modulus. Reinforced polymeric materials, which have a low modulus and great strength, are the ideal option. Thermoplastic polymers (PEEK-PAEK) form strong connections, are biocompatible, and exhibit resistance to wetting and moisture [7]. Epoxy resins are an example of a thermosetting polymer that differs and has varying levels of biocompatibility and durability. When used in orthopedic applications, they perform poorly. However, they have been discovered to be appealing for fracture fixation, and they have significantly, better processing characteristics than thermoplastics [53], [54].

Figure 2: Previously used steel-Ti alloys and Co-Cr alloys for bone plates and screws [58].

3.2 *In bone fractures*

There are several approaches to treating bone fractures, including external fixation and internal fixation [55]. The tissue does not need to be opened for external fixation. Devices and materials like casts and splints are used to keep the bone fracture in place. The casting material is composed of a composite material with a calcium-sulfate matrix and reinforcement materials like glass fibers and polyester [56]. In internal fixation, a bone fracture is treated utilizing surgical methods and implants. Depending on the type of bone fracture, various implants, such as wires, pins, screws, bone plates, or intramedullary nails, may be employed [57]. The most popular internal fixing components are plates and screws, which can be formed of Steel-Ti alloys or Co-Cr alloys as shown in Figure 2 [58]. The bone screws and plates are removed from the body almost a year or two after the surgery. After the plate is removed, the bone can support less force and becomes fragile and susceptible to breaking. Due to Ti's lower modulus, utilizing Ti alloys reduces bone thinning; also, using plates made of materials with moduli that are closer to those of the bone is preferable. Alternative materials include PA-PTFE and polyester (HAp reinforced), which are frequently used to heal bone fractures as shown in Figure 3. Their characteristics demonstrate that it has inadequate strength and low

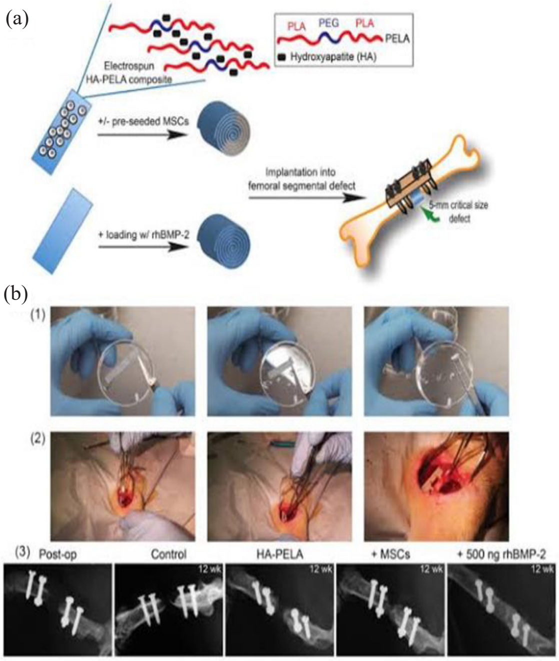

Figure 3: Hydroxyapatite and PA-PTFE as an alternative materials for bone fracture and repair [60].

modulus. Therefore, the polymeric composite is the ideal option as a material with high strength and appropriate stiffness [59].

3.3 *For bone plates*

The strength and stiffness of the material used in non-resorbable composite plates remain constant while it is inside the body and in [59]. Epoxy composites reinforced with carbon or glass fibers are examples of thermoset or thermoplastic composite materials that can be used to make it (thermoset non-resorbable material). There have been reports of some hazardous monomers in partially cured epoxy material. Thermoplastic: CF/PMMACF/PP-CF/PS-CF/PE-CF/Nylon CF/PBT-CF/PEEK (this material is difficult to hydrolyze and biocompatible; it is also stiff and fatigue resistant, and there has not been much evidence of carbon fibers being rejected by tissue) [61]. Polylactic acid (PLA) can be destroyed in the body, and after a while, this substance weakens [59]. Fully resorbable bone plates are composites made from resorbable materials and reinforcing fibers. Examples include glass fibers made of calcium phosphate and poly-L-lactic acid (PLLA) fibers. In partially resorbable materials, non-resorbable materials like carbon fibers and polymeric fibers are used to strengthen the resorbable polymers' mechanical capabilities. Like CF/PLA composites, they are referred to as partially resorbable materials [62], [63].

The two other criteria for joint replacement materials—load distribution and articulating surfaces—can also be met by polymers. Because of their lesser rigidity than bone, they are typically utilized in conjunction with metals for load-bearing applications such as THR femoral stems [64]. However, a material that can be shaped to the shape of bone and solidify in place, like PMMA, will offer a good, even load distribution. Polymers bearing counter faces have low friction and use a hard material for the convex component bearing upon a concave component of a less hard material, as is the traditional engineering design. In 1939, ICI created low-density polyethylene for the first time, and in the 1950s, high-density polyethylene (HDPE) was developed [65]. Simple $(C_2H_2)_n$ structural polyethylene has no side groups. A high degree of crystallinity—the ratio of crystalline to amorphous regions in the material—is made possible by this structure and the mobility of the chain. Compared to Low-Density PE (LDPE), HDPE has less branching, which results in more effective packing and, consequently, higher crystallinity and density. Despite having a lower density and crystallinity than HDPE, Ultra High Molecular Weight PE (UHMWPE) has a substantially higher mean relative molecular weight, ranging from 1 to 4106 $gmol^{-1}$ [66]. While increasing molecular weight enhances tensile and impact strengths, increasing the degree of crystallinity decreases toughness while boosting stiffness and yield strength. The chemical formula for polyacetal sometimes referred to as polyoxymethylene (POM), is $(OCH_2)_n$. The brand name for the polyacetal homopolymer sold by Du Pont is Delrin. The linear structure of its backbone is comparable to that of polyethylene. However, the shorter backbone (C-O) link permits the molecules to be packed in tighter, producing a tougher polymer with a higher melting point [59]. Figure 4 shows other uses for polymer composites in the medical sector. It entails soft tissue applications, instrumentation of the spine, repair, and instrumentation of dental structures, and replacement of intramedullary nails. Figure 5 also shows the broad category of polymer composite biomaterials.

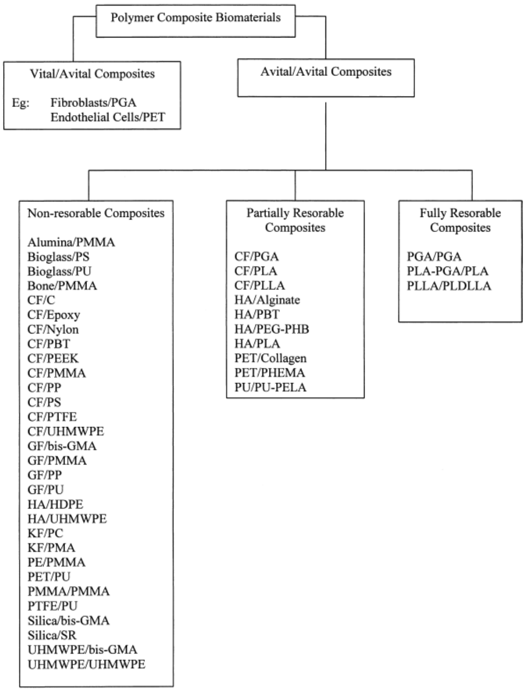

Figure 4: Broad application n of PMCs in medicine [52].

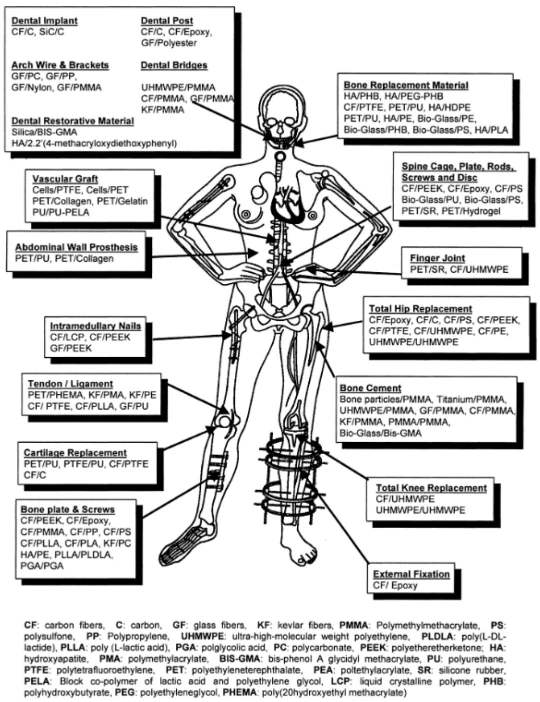

Figure 5: A broad class of biomaterials developed from PMCs [52].

Figure 6: In constructing elevator cables of skyscrapers [71].

3.5 *Building construction*

Due to their advantageous engineering characteristics, such as high specific strength and stiffness, lower density, high fatigue endurance, high damping, and low thermal coefficient, advanced polymer composite materials have seen increased use in the automotive, aerospace, and marine industries over the past few decades (1960 and on). Civil engineers and the building sector have just started to recognize composites' potential as a strengthening material for a variety of issues related to the deterioration of infrastructures [67]–[69]. Due to its excellent engineering characteristics, FRPC application in the construction industry has increased over the past ten years. Additionally, because of the ongoing decrease in the price of FRPC materials, these are being thought of as a replacement for traditional steel in reinforced concrete structures. Figures 6 and 7 illustrate some uses in the construction of skyscrapers and external walls [69]–[71].

Figure 8 illustrates uses in the construction of floor beams, slabs, masonry walls, shear walls, and foundations. It also demonstrates the first applications of composites as rebars and structural forms. As shown in Figures 9–12, which illustrate the applications of FRPC in the rehabilitation and renovation of bridges, the repair of bridges that have collapsed, the reinforcement of cement and the production of construction materials, the seismic repair of beam-column joints, and the production of composite concrete, various aspects of

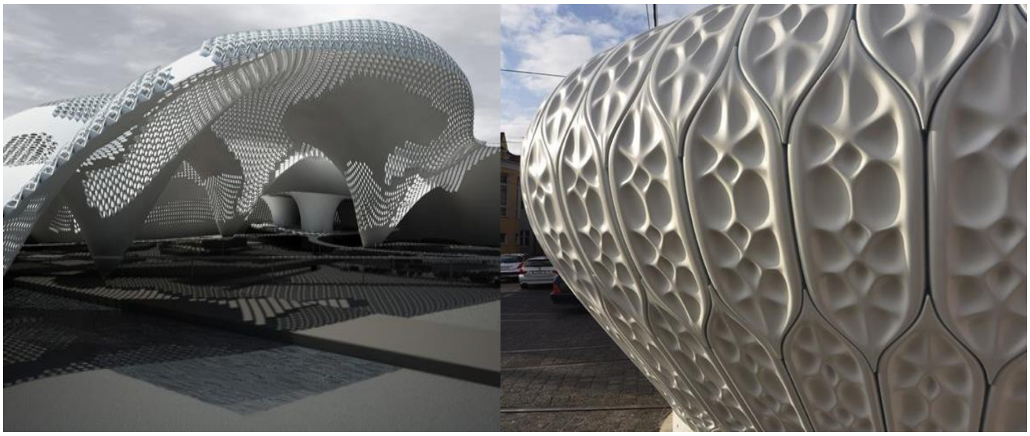

Figure 7: In building exterior walls [70].

Figure 8: In constructing floor beams, slabs, masonry walls, shear walls, and foundation [42].

Figure 9: In rehabilitation and renovation of bridges [42].

Figure 10: In the repair of the collapsed bridge [42].

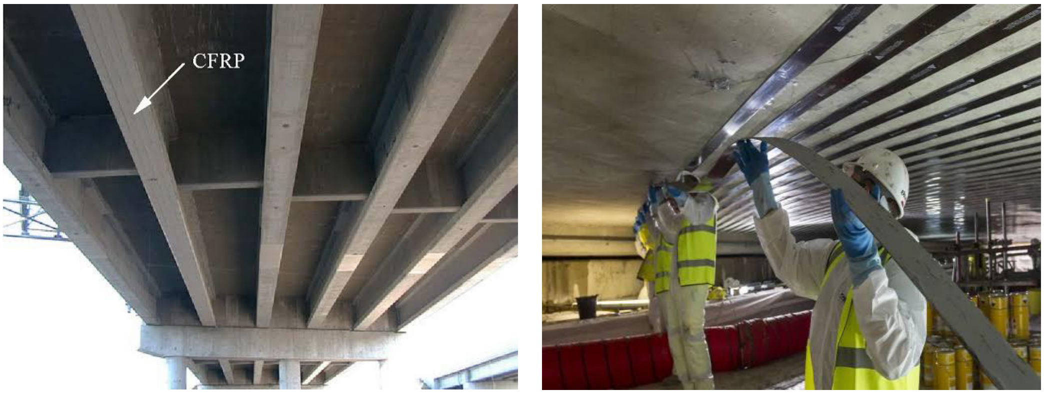

Figure 11: In the reinforcement of cement and production of construction materials [42].

(a) (b)

Figure 12: In the seismic repair of beam-column joints and production of composite concrete [42].

FRPC materials, including guidelines for the selection of polymer adhesives for strengthening and rehabilitation of concrete structures, have attracted considerable interest [42]–[72].

Later, FRPC laminates were utilized to retrofit the concrete columns shown in Figures 13–16 and to strengthen the concrete bridge and tunnel girders by connecting them to the tension face of the girder. FRPC is readily available as rods, grids, sheets, and winding strands.

Figure 13: In the fabrication of materials for tunnel construction [73].

Figure 14: In repair and renovation of tunnels [73].

Figure 15: Maintaining room temperature in tunnels [73].

Bakis *et al.*, [74] offered another basic overview of the class of materials, which includes FRPCs utilized in civil construction. The entire review was broken down into structural shapes, bridges, standards, and codes, as well as internal and externally bonded reinforcement. Deniaud and Cheng [75], Bousselham and Chaallal [76], and others conducted a review on the shear strengthening of RC beams with FRPCs.

The use of external epoxy-bonded steel plates

Figure 16: In the construction of complex structures [70].

Figure 17: To protect intricate building structures from corrosion [70].

has become one of the most common methods for reinforcing RC beams [77], [78]. Experimental evidence suggests that using this method can boost a structural member's flexural strength by roughly 15%. The steel bonding method is easy, affordable, and effective. However, it was discovered that it has a severe issue with the bond weakening at the steel and concrete interface owing to steel corrosion. Corrosion-resistant and lightweight FRPC plates have taken the role of steel plates in building construction as shown in Figure 17.

Figures 18 reveal how FRPCs contribute to increased strength and ductility without unduly increasing stiffness [79]. When fibers are positioned perpendicular to cracks, strength, and stiffness are significantly increased compared to when they are positioned obliquely to the cracks [28], [80]. The serviceability, strength increase, cracking patterns, and failure modes of RC beams strengthened with glass,

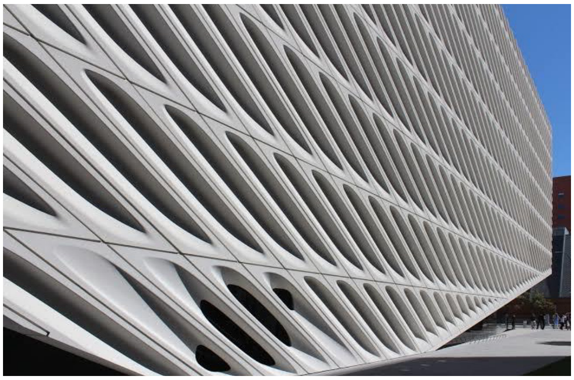

Figure 18: For upgrading of building walls [80].

Figure 19: Application in bicycle production [83].

Figure 20: CFRPC bicycle part [83].

Figure 21: Bicycle rims [83].

carbon, or aramid FRPCs have all been the subject of much experimental research. According to a review of the literature, carbon fiber-reinforced polymer composites (CFRPC) may increase strength by around 200% whereas glass fiber-reinforced polymer composites (GFRPC) can increase strength by almost 40% for RC beams [6]. The use of FRPC enhances the slabs reinforced with FRPC's ability to absorb energy and carry loads. Because strengthening enhances overall cohesiveness and the ability to transfer stress across cracks, fracture formation is delayed and FRPC reinforcement can therefore fully realize its promise for reinforcing slabs [81], [82].

3.6 *Sports*

This section was created to examine current and emerging trends in the use of polymer composite materials in the realm of recreation and sport. Figures 19–27 show different polymer composite applications in sports and recreation. The structures of bicycles are currently being developed and produced by AX-Lightness GmbH (Germany), the primary supplier of polymer-based composite materials in the Formula One industry [83] (Figures 19 and 20).

Figure 21 illustrates their actual proposal for high-tech mountain bikes with wheels built from epoxy prepregs reinforced with woven carbon fiber from Umeco [84]. Combining unidirectional and fabric-reinforced prepregs for bicycle components for Australian triathletes is another accomplishment they are happy to point to.

Samsara Surfboards, an Australian manufacturer of eco-friendly surfboards, is currently making ultra-high-performance eco-surfboards (Figures 22 and 23).

Figure 22: Polymer-based surfboards [86].

Figure 23: In the fabrication of a sports boat [86].

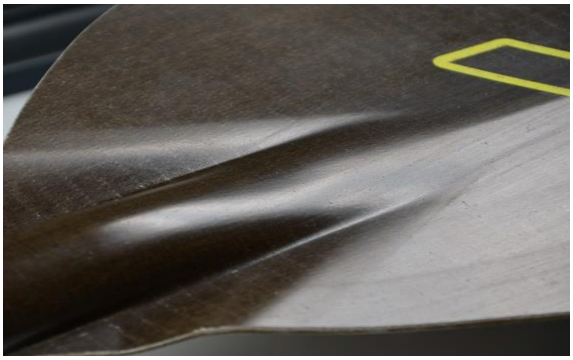

Figure 24: Polymer-based paddles for sports [87].

Figure 25: Production of sports helmet [88].

Figure 26: In the production of protective equipment for sport [88].

Figure 27: In the production of other protective equipment for sports [88].

These surfboats are manufactured exclusively of substances that have little negative environmental impact. A typical Samsara surfboard is made of flax fibers that have been mixed with PLA and PP [85], [86].

Figure 24 shows that Werner Paddles Inc. (Sultan, USA) is the industry leader in the production of kayak paddles [86]. They discovered a solution to enhance the looks, prices, and performance in collaboration with RTP Company (Winona, USA) by utilizing a carbon fiber-reinforced recycled material from Boeing's 787 Dreamliner scrap. Other products made from CFRP include sports protective gear like the helmet, wrist guard, knee guard, and chest shield (Figures 25–27). These are primarily utilized in sports like rugby, kickboxing, golf, tennis, and other strenuous recreational activities [88], [89].

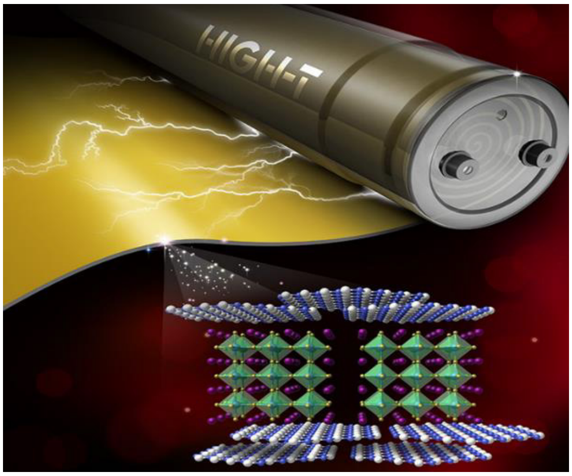

Figure 28: Material for solid electrolyte [95].

Figure 29: Production of thermal containers [96].

Figure 30: Polymer-based plates for battery production [97].

3.7 *Energy generation and conservation*

Due to its environmental friendliness and lack of regional limits, solar energy stands out [90], [91]. One of the most efficient methods for energy conservation is the solar cell. The majority of current solar cell research and development is concentrated on advanced silicon-based solar cells, gallium arsenide (GaAs), copper indium gallium selenide (CIGS), cadmium telluride (CdTe), photovoltaics (OPV), dye-sensitized solar cells (DSSC), and perovskite solar cells (PSC).

However, because of their adaptable and flexible chemical and physical properties, polymers have received a lot of attention in recent years. Figures 28 and 29 illustrate how the three-dimensional network structures of polymers determine whether they can be used as a template to create mesoporous materials or as a polymeric matrix in the solid electrolyte. Additionally, because of their high catalytic activity for I3-reduction, they are also suitable as counter-electrode materials [92], [93]. The functional groups in polymers determine that they can be used as the interface layers to passivate defects, adjust the work function of the metal electrode, and improve device performance. The polymers' functional groups also enable them to act as electron and hole transfer materials due to their high carrier mobility, diverse structural makeup, and functional modifications [94].

The fabrication of polymer-based micro/nanostructure devices for battery generation is also made possible by the processability of polymers, as shown in Figure 30. Conductive polymers, which are partial polymers with strong conductivity, are widely employed in a variety of industries [96]–[98]. The conductive substrate is in charge of supporting cells, transmitting light, and collecting and sending electrons according to the DSSC principles. Indium-doped tin oxide (ITO) glass, fluorine-doped tin oxide (FTO) glass, ITO/polyethylene terephthalate [PET, shown in Figure 31(a)], and ITO/polyethylene naphthalate are some of the common conductive substrates [PEN, in Figure 31(b)]. The most popular conductive polymer substrates in DSSCs are ITO/PEN and ITO/PET because of their inexpensive price, high transparency, light weight, flexibility, and low sheet resistance of

(a) (b)

Figure 31: PET and PEN glass production, and polymer-based plates for battery production [103], [104].

Figure 32: Chemical tanks [4].

10–15 W sq-1 [99]–[101]. Roll-to-roll solar cells and other flexible and wearable electronics can be created due to the advantages of ITO/PEN and ITO/PET [102]. Chemical storage tanks shown in Figure 32 and battery plates [Figures 30 and 31(b)] are two products made from polymer composites.

3.8 *Petroleum and petrochemical industry*

The base polymer material and filler material, which primarily consists of fibers, are what make up the polymer composites that are most commonly employed in the petroleum and petrochemical industries. Due to their excellent mechanical and insulating qualities, as well as their resistance to deterioration, glass fibers are affordable and often used as reinforcements [27],

Figure 33: Industrial coating of pipe with polymer composites to prevent corrosion [107].

Figure 34: Production of pipe walls [107], Creative.

[105]. It is clear from the literature that thermoset resins containing glass fiber predominate. The use of thermoplastic polymers in pipeline applications is rather uncommon. Thermoset resins are a popular option in the field because they are simple to mold on pipe walls, solidify quickly, and resist degradation. Epoxy, polyester, vinyl ester, phenolic, polyurethane, and polyamide are some of the most popular thermoset resins. Epoxy is the resin type with glass fiber that is most frequently used in pipeline applications because of its excellent mechanical, adhesion, shrinkage, cure, corrosion, and heat resistance capabilities [106]. The use of glass-reinforced polymers (GRP) pipes in various applications has been experimentally investigated by several studies for the industrial coating of pipe with polymer composites to prevent corrosion and produce pipe walls (Figures 33 and 34).

When used in fastening applications, carbon fibers increase the susceptibility to galvanic corrosion because they are electrically conductive [105]. The failure probability of carbon fiber reinforced polymer

Figure 35: Strengthening and reinforcement of pipes [110].

(CFRP) composites must be at least 40% higher than that of a newly installed steel pipe [108]. The majority of pipeline applications for epoxy resin containing carbon fibers have been reviewed in the literature. Pipelines using CFRP have better strength-to-weight and burst-resistance ratios. A defective steel pipe was patched up using epoxy glue and carbon fiber [109]. The burst pressure tests show that, for confinement upon shattering of the brittle putty, the load transfer from the pipe material to the wrapped CFRP depends on the length of the defect in the hoop direction up to 20% less than the pipe diameter. As shown in Figure 35, CFRP was utilized in reinforcing and strengthening pipes due to their high thermal strength stability which can withstand elevated creep stress. Aramid fibers are strong, flexible, and lightweight, with higher strength and temperature tolerance (up to 500 C) compared to glass fibers. Synthetic fiber-reinforced polymer composites have been used for numerous pipeline applications by blending aramid fibers in thermoset and thermoplastic resins [105]–[110]. Many researchers, including [111], have focused on the mechanical characteristics of aramid fiber when used with thermoplastic resins. The two-layer, non-impregnated, new type of polyethylene liner pipes that are overwrapped with twisted Aramid cords was created. The Aramid yarns were encased in a viscoelastic, high-density polyethylene (PE) matrix. When under pressure, the pipes displayed a complex torsional response in a model that also had to account for the viscoelastic characteristics of the matrix. One or more reinforcement materials are used in a hybrid composite, typically with one fiber type having a greater failure strain than the other. High elongation and low elongation fibers, respectively, are the names given to them [112]. One benefit of hybridization is that it improves energy absorption and increases thermal strength [113], [114].

Figure 36: Increasing wall thickness of pipes [110].

Additionally, the combination of high tensile strength and high failure strain parts allowed for the precise tailoring of the mechanical properties of hybrid FRP composites, as shown in Figure 36 [105].

3.9 *Energy storage*

The term "energy storage" is used to describe the act of putting energy away for use at a later time. Several electrochemical devices have been recognized as promising tools that make use of polymers that are derived from bioresources. This is partly because biopolymers can be used to boost the efficiency of other biologically active compounds within a device while yet being biodegradable and biocompatible. Polymers have been used to create a variety of energy storage devices, of which the most notable ones are batteries and supercapacitors. Lithium-ion batteries and nickel-cadmium batteries are two examples of today's widely available battery technologies. However, there are concerns about the safety of these devices such as the possibility of poisonous leakage. Several methods have been tried in the past to develop eco-friendly products but the most recent effort to create eco-friendly batteries is the use of biomaterials from biopolymers.

Cellulose is a popular biopolymer that has been used for batteries. Bananas, corncobs, cotton, maize, and wheat are only a few of the plant-based bioresources from which natural cellulose fibers can be extracted. Bacterial fermentation cellulose has gained attention as a potential source of carbonaceous fiber material for use in high-rate lithium-ion batteries, which can be produced by pyrolyzing cellulose at high temperatures. There are many benefits to using bacterial cellulose precursors rather than more conventional ones, including the fact that they are more porous, have a higher surface area, are excellently biodegradable, can manufacture cellulose on a wide scale, and contain many hydroxyl groups [115], [116]. Due to its very strong interaction with various added chemicals and also the finely thinner morphology of bacterial cellulose compared to plant cellulose [117], [118], bacterial cellulose is transformed into a tunable flexible scaffold appealing biomaterial that attracts widespread interest in forming highly versatile three-dimensional carbon nanomaterials. Three-dimensional (3D) carbonaceous aerogel produced from bacterial cellulose was created by Huang *et al.*, [119] for use as a deformable electrode in lithium-sulfur batteries. The high sulfur loading made possible by the material's intrinsic microporous structure aids in both mechanical stability and electrical conductivity. Chitosan is another biopolymer that finds widespread use in battery applications. Shellfish bioresources like prawns, crabs, lobsters, and even some types of mushrooms are common sources of waste chitin. Using chitosan oligosaccharides, Tang *et al.*, [120] created a $Li_2ZnTi_3O_8$ electrode binder for lithium-ion batteries. Strong hydrogen bonds were formed between the hydroxyl groups of the active materials and the current collector, and inflammation of the electrode within the electrolyte solution was reduced, both of which contributed to the energy cell's improved electrochemical performance in their study. Pectin is a biopolymer that is utilized in the creation of batteries as an alternative. Most citrus fruit peels, especially those of apples and oranges, are excellent sources of natural pectin.

Supercapacitors are a type of chemical energy storage device that works by storing and discharging energy via the reversible adsorption and desorption of ions at the interface between the electrolyte and the electrodes [121]. Electrochemical pseudocapacitors and electrical double-layer capacitors are the two most common kinds of supercapacitors. (EDLCs). Electrochemical double-layer capacitors (EDLCs) absorb charged ions at the interface between the electrolyte and the electrodes to store electrical energy. Pseudocapacitors are electrochemical storage devices that use reversible redox processes to conduct charge between an electrode and electrolyte. The charging and discharging processes of hybrid supercapacitors combine features of pseudocapacitive and double-layer capacitive designs [122].

Due to their high energy conversion rate, fast charge speed, and great recyclability, supercapacitors have the potential to serve as excellent energy storage equipment. Conventional supercapacitor binder materials are poisonous and exhibit subpar mechanical characteristics. Hence, the biodegradability and high electrical conductivity of biopolymers make them an attractive replacement material. Cellulose is a popular biopolymer utilized in many types of supercapacitors. Carbon nanofiber and polypyrrole-covered cellulose (PPy-cellulose) composite electrodes were produced by Tammela *et al.*, [123]. An asymmetric supercapacitor was constructed with PPy-cellulose serving as the positive electrode and carbon fiber serving as the negative electrode. The use of chitosan, another biopolymer, in supercapacitors has been the subject of extensive study. Using chitosan, MWCNTs, graphene oxide, and polyaniline, Hosseini and Shahryari [124] created a ternary nanocomposite for use in supercapacitors. Supercapacitors could also make use of biopolymer lignin. Supercapacitors are also made from hierarchical porous carbon and lignin [125]. As an electrode material for supercapacitors, lignin's distinctive porous hierarchical structure allowed for favorable ion transfer and a high surface area, enhancing its electrochemical properties.

3.10 *Biosensors and bioelectronics*

DNA, hydrogen peroxide, glucose, and many other biologically important chemicals have all been detected with the use of polymer and its composite films [126], [127]. As an example, AuNP can form covalent bonds with a wide variety of biomaterials, including numerous thiolated probe single-stranded DNA (ssDNA) molecules, antibodies, and more [128]. Also, some biomolecules can be hybridized with GCFs for use as biosensors due to the presence of functional groups of polymers [129].

Polymers can also be used to create biosensors like the Field-effect transistor (FET) biosensor. This type of sensor makes use of the conductance shift of FET semiconducting channels upon the adsorption of target molecules to enable electronic detection. The GCFs use an aqueous environment, for instance, to detect cholesterol content in the body for disease prevention purposes. To contain the solution, a flow cell or sensing chamber is typically placed above the GCFs channel. Since ionic conduction can cause current leakage, the drain and source electrodes are isolated [130]. Additionally, GCF-based FET sensors find application in DNA analysis. The loading efficiency and capacity are often improved by the ability of AuNP to covalently connect with multiple ssDNA molecules.

Photoelectrochemical (PEC) biosensors have also made significant advances in the medical field. Enhanced electron transport between an analytic and semiconductor electrode is achieved via photocatalytic oxidation or reduction of molecules upon illumination, making PEC sensing possible. Quantum dots (QDs) and other photoactive materials have been widely adopted as popular visible-light active materials for use in the fabrication of PEC sensors. Likewise, based on its high conductivity, GFC can greatly enhance the composite film's photocurrent response capability. In light of these findings, the suggested PEC sensor offers a highly sensitive method for detecting genotoxic contaminants due to its high sensitivity, superior repeatability, and high stability.

As a result of their ease of use, fast binding kinetics, and high robustness, fluorescent probes such as dyes, QDs [131], and metal nanoclusters have attracted a lot of attention for their application in homogenous detection of target molecules via a fluorescence change. Through fluorescence resonance energy transfer, the GCFs film efficiently quenches the fluorescence of various dye-labeled aptamers bound to a target, and simultaneous multiplex target detection is achieved by recovering the quenched fluorescence caused by the aptamer's specific binding to a protein. High selectivity, sensitivity, and a short detection time are just a few of the reasons why this fluorescence sensor offers a promising alternative to more laborious techniques of detecting pathogens.

Since H_2O_2 is produced by most oxidase enzyme activities, a sensitive H_2O_2 sensor is also suitable for enzyme-based biosensing. An innovative method for producing an AuNP-embedded porous RGO thin film for use in the electrochemical sensing of H_2O_2 was described by Xi *et al.*, [132]. As a result of the AuNPRGO film's modification of the fluorine-doped SnO_2 electrode, the latter exhibits remarkable electrochemical characteristics and significant electrocatalytic activity towards H_2O_2 oxidation due to the RGO's high surface area and high density of edge-plane-like defects (as a model analyte). Additionally, the high conductivity of AuNP mediates an increase in the electron transfer rate, which expedites the oxidation of H_2O_2 on the RGO sheet surfaces. Non-enzymatic sensors are not as constrained by factors like temperature and pH as enzyme-based sensors, and they can be reused multiple times. This unique non-enzymatic glucose sensor, on the other hand, shows great promise as a practical glucose sensor due to its low cost, ease of manufacture, high stability, rapid response, broad detection range, high sensitivity, and high selectivity. Non-enzymatic H_2O_2 sensors have received just as much attention as glucose sensors. RGO-AuNP hybrid membranes, which are highly solvent-resistant, can also be used to create innovative non-enzymatic amperometric biosensors for H_2O_2 [133]. In-depth research has shown that modifications or reactions to molecular structures are increasingly being used as the connecting mechanisms in biosensors. Using the huge surface-to-volume ratio of polymer materials and the unique recognition ability of biological molecules, the biosensor's selectivity and sensitivity can be increased [134].

4 Modern-Day Technological Drive

4.1 *Nanotechnology*

To achieve adequate reinforcement of the polymer matrix, nanoparticle-containing polymer composites (including nanofibers with fiber diameters in the nano-dimension range) are frequently researched [4]. While the literature-reported nanocomposite investigations heavily emphasize the reinforcement elements, numerous additional variants and property advancements are now being researched, and in some cases, they are already being commercialized. Whereas the equivalent larger-scale particle inclusion would not produce the necessary property profile for use, the benefits of nanoscale particle incorporation can lead to a variety of application possibilities [135]. These fields include impact modification as shown in Figure 37, barrier characteristics, membrane separation, UV screens, flammability resistance, polymer mix compatibilization, electrical and thermal conductivity, and biological applications as shown in Figures 38–40.

Table 3 provides examples of the inclusion of nanoparticles, nanoplatelets, and nanofibers into polymer matrices as well as their prospective applications when characteristics other than mechanical property reinforcement are important [137].

Figure 37: In impact modification [4].

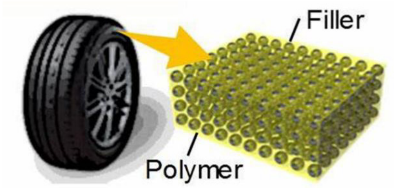

Figure 39: In polymer blend compatibilization [116].

Figure 38: In fireproof coating [136].

Figure 40: In biomedical application [116].

Table 3: Examples of nanoparticles used in the production of polymer composites [137]

Nanoparticle	Preferred Matrix	Nanoproperties	Major Application
Carbon nanotube	Epoxy	High stiffness, optimum strength	Fabricating hockey sticks and tennis rackets
Exfoliated clay and silica	Polyamides nylon, nylon MXD6 and SBR rubber, polyamide, thermoplastic polyolefin (TPO)	High stiffness, maximum barrier properties.	Auto fuel systems, films, beverage containers, timing belt covers, automotive exterior step assist
Carbon black	SBR, natural rubber, polybuadiene	High abrasion and wear strength	Production of tires, tribological applications
Silver	Natural rubber	Antimicrobial properties	In the production of latex gloves
MWCNT		Electrical conductivity	Electrostatic dissipation

4.2 *Additive manufacturing (3D printing)*

A method of additive manufacturing (AM) known as 3D printing allows for the layer-by-layer construction of components with intricate geometry. After Hull released the first machine onto the market in 1986, 3D printing gained popularity [138]. When selecting a material to print a particular portion, caution must be taken.

There are numerous commercially available polymers, however, no single polymer has all the qualities required for every application. Since they are used to make bottles, toys, tools, purses, phones, computers, tools, pillows, electronics, and transportation components, polymers have evolved into consumer items [139]. Therefore, it seems natural that efforts have concentrated on creating materials that can be 3D printed, as demonstrated in Figures 41 and 42 [140], [141].

The commercially available polymers utilized in several of the AM techniques are listed in Table 4. Thermoplastics, or plastics treated by heating to a semi-liquid condition and close to the melting point, are commonly employed in processes requiring polymers like polycarbonate (PC), acrylonitrile butadiene styrene (ABS), poly ether ester ketone (PEEK), polyetherimide (ULTEM), and nylon. The printed layers combine and solidify during extrusion. Fused Deposition Modeling (FDM), jetting (InkJet), and selective laser sintering are AM processes that utilize thermoplastics (SLS). Thermosetting polymers, or those that solidify after curing, are used in SLA and Direct Ink Writing (DIW) [143].

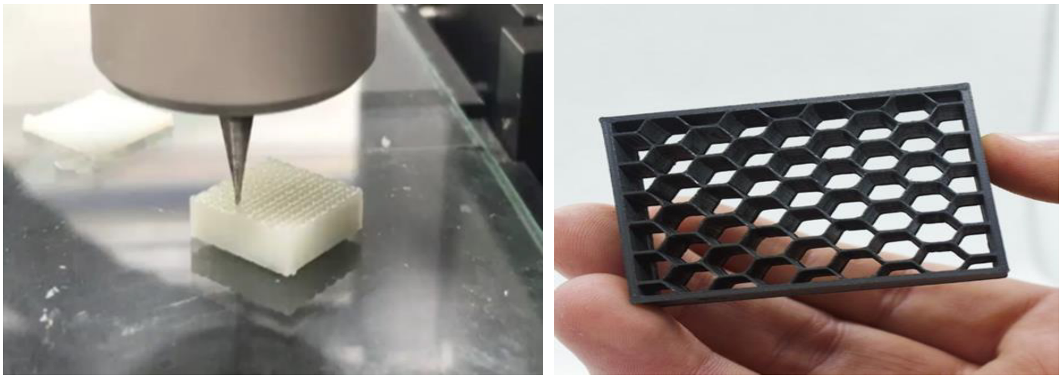

Figure 41: Epoxy and thermosetting-acrylates in additive manufacturing [142].

Figure 42: PCL and PLA materials for additive manufacturing [142].

Table 4: Commercially available polymers used in some of the AM processes (143)

AM Technology	Technique	Physical State	Starting Polymer Material
FDM	Melting and Solidifying	Solid State	PC, ABS, PLA, ULTEM, Nylon, ASA
SLA	Photocuring	Liquid State	Epoxy, Thermosetting-acrylates
SLS	Melting and Solidifying	Solid State	PCL, PLA
Jetting	Photocuring	Solid State	ABS, ASA, PCL, PLA, Vero
Direct Writing	Extrusion-heat or UV Curing	Liquid State	Thermosetting polymer

Biomedical engineers have primarily focused on reducing implant rejection and toxicity by creating biopolymeric materials with enhanced flexibility, strength, and patient compatibility for use in tissue and scaffold creation [139]. There are polymer mixes that contain cultured patient-isolated cells. Inkjet 3D printing technologies can make use of these polymers because they are hydrogels [139].

Since 3D printing makes it easier to design complex structures and create prototypes quickly, it is gaining traction as a manufacturing process across a variety of industries. AM makes use of a CAD program that allows architects to create microscopic structures and porosity specifications. To further enhance the design of the final product and probably reduce failure risks, modeling based on a specific application can be conducted due to the simple creation of 3D printed prototypes [143]. Over the past 4 decades, there has been substantial development in the 3D printing of polymers and polymer composites, and this trend is only likely to grow. Commercial thermoplastic materials suitable for FDM, SLS, and inkjet printing are easily accessible. PC, ABS, PLA, ULTEM, and PCLA are frequently used in the production of aerospace industry tools, prototypes, and other components [143]. However, these polymers are not a good fit for every need and cannot be considered a universal solution. For this reason, scientists are working to perfect materials for very specific uses. Scaffolds and implants are just two applications for polymers mixed with grown cells. Patients' cells can be cultured in the lab to create a product that is less likely to be rejected by the patient's immune system. Multipurpose materials with enhanced mechanical qualities can be created with the help of fillers and additives. The polymer can be made electrically conductive by adding fillers such as carbon nanotubes (CNTs), graphene, glass fibers, clay particles, and tungsten, or natural materials such as wood flour, rice husk, cocoa shell waste, animal shells, feathers, and bones [143]. There are still obstacles to overcome, even though new polymeric materials have been designed and developed for AM applications. There is a severe lack of polymeric inks that can withstand harsh conditions like extreme temperatures, high loads, and radiation. Polymer 3D printing technologies can be made more useful with the introduction of new materials. To lessen the environmental damage caused by plastics, some of these composites should be recyclable and/or made to be biodegradable [143].

Environmental, economic, and social factors all affect how polymeric materials are used in additive manufacturing. The environmental effects include resource consumption, material needs, waste management, product life cycles, recyclables vs. non-recyclables, and biodegradability. Supply chain management, novel applications, market evolution, manufacturing costs, machinery costs, and productivity are some of the economic effects. According to Mehrpouya and Al's paper [144], the consequences on society include social gains, labor development, product quality, public acceptability, ethics, and healthcare improvements as depicted in Figure 43(a) and (b). The limited supply of feedstock for sale in the polymer 3D printing sector is one of the major issues. Not all of the uses for the polymers listed in Table 1 can be employed. Pure polymers, in particular, lack the mechanical strength needed for load-bearing applications. Materials with great mechanical strength are frequently produced by adding fillers like silica and carbon fibers [143]. Additionally, the use of additives improves the functionality of the materials by giving

(a) (b)

Figure 43: Biomimetic material from polymer composite [144].

the components better UV and radiation resistance as well as anti-fouling qualities [145], [146].

5 Environment and Polymer in The Future

The availability of research knowledge from literature is one of the tools that have been changing the course of mankind in the areas of science and technology [2]. The current level of advancement in polymer-based materials and the environment has revealed that more can still be achieved. The fact that polymer-based materials are easy to process to achieve any desirable shape, properties, and applications has aided these accessibilities [1]. This review has provided more information regarding the various areas of applications of polymer-based composites. The work revealed the prospect of polymer matrix composites as indispensable materials for the future whereby only modifications and adaptations will be the trends in the use of polymer-based composite materials [2]. With the current and continuous rate of research and development globally on polymer-based materials, polymer-based components will continue to provide an excellent and aesthetic environment based on these several areas of applications as presented graphically in this review. Through the increasing modification and adaptation of both virgin and recycled polymers' properties, such as strength, melting temperature, degradation behavior, response to environmental influence, and many more, the material will continue to find more application in all areas of need based on its inherent benefits. Communication, transportation, building and construction, electronics, energy, household, packaging, sports, and leisure industries are not left out in the application of polymer-based materials. Presently, the development of polymer-based nanocomposites is already fully involved in the use of advanced composites for various applications.

5.1 *Present and future trends*

Two major challenges of polymer-based materials components presently are structural and environmental compatibilities. Environmental concerns have brought about various regulations in the present days thereby, leading to great modifications in materials design and developments. The effects of materials on environments during processing, application, and disposal are of interest to researchers recently. This has led to the use of more biodegradable materials in all areas of applications. Modern-day demand for green materials can easily be achieved with polymer being the most naturally abundant material from plants and animals. Their continuous synthesis will bring a turning point to the over-dependence on synthetic ones which are costly and has an adverse environmental impact. Naturally derived polymer-based materials are biocompatible with the environment and are safe for human consumption.

More efforts are to be given to the current level of recycling processes to overcome waste polymer-based materials pollution challenges. Primary recycling is generally known as a closed-loop, secondary recycling as downgrading, tertiary recycling as chemical or feedstock recycling which applies when the polymer is de-polymerized to its chemical constituents; quaternary recycling is energy recovery from waste or valorization [147]. Possible uses for recycled polymer-based materials were to be considered towards having zero tolerance for polymer wastes in our environments. In the future, the perceived environmental threat from waste polymers should be given attention by researchers on how to convert them to raw materials for research and development as well as major materials for new products like wearable textiles [148]. Also, more efforts should be given to polymers from the natural origin by working on how to improve some of the weak properties that are required in any targeted areas of applications. Nanotechnology should be highly deployed to polymer processing from both natural and recycled polymer-derived polymer-based materials in the future for sustainable and eco-friendly materials with acceptable structural properties. Hence, more research to overcome the present structural challenges in the areas of applications and environmental impact needs to be intensified. It is expected that polymer-based materials will continue to receive the attention of researchers and users in advanced materials components market demands due to the trends of human needs and desires. Polymer-based materials will remain in this movement based on their flexibility and availability, hence, they will sustain their status as the materials for present and future applications.

5.2 *New trends in the use of natural fibers*

Composites are the most promising and selective material of the 21st century. Demand for lightweight, high-strength materials for specialized applications is on the increase and this has led to a rise in the popularity of composites reinforced with fibers of synthetic or natural materials. In addition to a high strength-to-weight ratio, fiber-reinforced polymer composites show off impressive characteristics like high durability, stiffness, damping property, flexural strength, and resistance to corrosion, wear, impact, fire, and more. Composites are used in numerous production sectors because of their versatility [29]–[35]. Since the functional properties of many different fibers are available around the world, their classifications and the manufacturing techniques used to fabricate composite materials are the primary determinants of the materials' performance. It is necessary to study these factors to determine the optimal characteristic of the material for the intended application [4]. The optimal fiber-reinforced composite material for important applications can be found by reviewing a wide range of fibers, their qualities, their functioning, their classification, and the various fiber composite production. Fiber-reinforced composite materials are a viable alternative to single metals or alloys [4], [35] due to their remarkable performance in a wide variety of applications.

Fibers derived from plants are abundant and simple to harvest. Some of the material characteristics they show are biodegradability, low cost per unit volume, high strength, and particular stiffness [4], [30]. Compared to synthetic fibers, composites manufactured with natural fiber reinforcements appear to have a variety of advantages, including lower weight, cost, toxicity, environmental pollution, and recyclability. Natural fiber composites are preferred over synthetic fiber-reinforced composites in today's applications due to their lower cost and lower negative impact on the environment [149]. Different types of natural fibers have similar shapes but unique chemical makeups. High-performance uses have emerged due to the incorporation of both long and short natural fibers into polymeric matrices [150], [151].

Since sisal fiber (SF)-based composites have excellent tribological qualities [152], they are increasingly being used for automotive interiors and furniture upholstery. You can get furniture, motor parts, hand tools, and bearings [153] made from hemp fibers. Flax is utilized in building materials and textiles [154], [155]. Ramie is utilized to make bulletproof vests, prosthetic sockets, and structural components [156], [157]. Window and door frames can be made from rice husk, while jute can be used for roofing and door panels [153]–[158].

Load-bearing elements in composite structures are often made of natural fibers embedded in a matrix. The matrix material not only maintains the fibers' position and orientation but also helps transfer stress and shields the structure from the elements. When a higher strength-to-weight ratio is required, NFRP materials have been proven to be superior to metals [159]–[161]. Polymer composites have recently demonstrated considerable potential and superiority over the common but crucial problem of friction and wear experienced by traditional metals and alloys [162]–[164]. In addition to their exceptional tribological features, NFRP composites also enable multifunctionality via composition adjustment, making the development of new tribological materials a cost-effective endeavor [165]. NFRP composites are gradually replacing traditional unreinforced metals and alloys in automotive and aerospace applications due to their superior mechanical, thermal, electrical, and wear and corrosion resistance [166]. CFRP, GFRP, and aramid fiber-reinforced polymer (AFRP) are the most prevalent forms of FRP utilized as reinforcement in concrete structures. The FRPs have high shear and flexural stress resistance [167]–[170]. Reinforcing materials used in concrete must be resistant to corrosion and magnetism to survive in hostile environments. These features are present in FRP bars, making them a viable alternative to traditional steel reinforcement in RC constructions [171]–[173]. Due to their superior vibration-dampening qualities, hybridized flax and carbon fiber composites are gradually replacing aluminum 6061 in structural applications. The composite possesses a 252% increase in tensile strength and a 141% increase in damping ratio. Weight was reduced by 49% as a result of the decreased density of the material [174]. In comparison to carbon fiber-reinforced plastic (CFRP), hybrid composite structures made from jute and carbon fiber reinforcements are more cost-effective and environmentally friendly [175]. Aluminum sheet metal was swapped out for a black epoxy composite consisting of aluminum tri-hydroxide and glass fibers for the excavator engine cover [176].

5.3 *New trends in construction*

Fiber-reinforced polymer (FRP) composites have been used extensively to reinforce concrete structures for a long time, and recent studies have included inorganic/cementitious materials to generate fiber-reinforced inorganic polymer (FRIP) composites. When FRiP, made from phosphoric cement, is used in place of epoxy in an FRP composite, the structure's fire resistance is increased [177]–[181]. Portland cement, phosphate-based cement, alkali-activated cement, and magnesium oxy-chloride cement (MOC) are examples of these inorganic cementitious materials. About 47% of FRiP's strengthening effectiveness is maintained even after being exposed to fire [182]–[184]. As a type of laminated composite material, FRP sandwich material has advantages such as a high strength-to-weight ratio, thermal insulation, and durability. Hence, it has become widely accepted as a viable replacement for metallic skins in sandwich composites used for structural engineering. Bridge beams, footbridges, bridge decks, multipurpose roofs, cladding and roofing systems for buildings, railway sleepers, and floating and protective structures all benefit from the increased durability and lower cost than FRP sandwich systems offer [185].

FRP sheets glued to the tension face of concrete beams significantly increase flexural strength and load-carrying capability, even when exposed to the severe environment of wet and dry cycling [186]. To prevent reinforced concrete (RC) constructions from failing too soon due to debonding, larger strain levels are achieved by the anchorage of externally bonded FRP materials. Compared to other anchorage options, FRP anchors were found to be astonishingly efficient, with a 46% improvement over vertically oriented U-jacket anchors. Other benefits of FRP over concrete are its simplicity, non-destructiveness, and ease of installation [187]. Adding the newly produced basalt microfibers longitudinally as reinforcement to the concrete constructions allows for the evaluation of its feasibility and flexural behavior, resulting in an increase in the maximum moment capacity of the beams and an improvement in curvature ductility. The flexural capacity of beams is improved with an increase in BFRP reinforcement ratio, independent of concrete type [188]–[190]. The strain capacity of externally bonded FRP composites can be improved by using FRP anchors with a range of fiber contents and embedment angles in RC members. When the angle of the anchor dowel is increased in relation to the direction of the load, the joint's strength increases while its ductility decreases [191].

Sprayable ultra-high toughness cementitious composite (UHTCC) is used in the construction of long-lasting concrete structures and the restoration of older structures like bridges and tunnels as part of the bridge system. With greater compressive, tensile, and flexural strengths than cast UHTCC, the UHTCC increased the longevity of concrete structures. An increase in UHTCC layer thickness led to increased stiffness for RC-UHTCC beams, allowing for better management of fractures in the concrete layer of beam specimens [192].

Bridges built with FRP composites are strong and safe. In the building of bridges, FRP or hybrid FRP-concrete is typically used for girders, bridge decks, and slab-on-girder bridge systems. There is less stiffness degradation under design truckloads on hybrid FRP concrete decks compared to RC decks [193]. Public civil infrastructure, such as bridges, is at risk from new and unprecedented threats posed by terrorist operations or natural catastrophes, necessitating the impact and blast resistance design of such facilities. Concrete beams, concrete slabs, concrete columns, and concrete walls have all been reinforced and improved with FRP material to better withstand impacts. A higher strain rate also improves the materials' load-carrying capacity, ductility, energy absorption, and tensile strength [194].

When comparing FRP composites to RC for use as bridge deck panels, all FRP composites exhibited greater flexure and shear strength [195]. Hybrid fiber-reinforced composite decks were determined to be an excellent option that met all of the specifications. A hybrid composite was made using the hand lay-up method, using glass and jute fibers reinforced with vinyl ester as a matrix [196]. The construction of concrete-filled FRP tubes as earthquake-resistant columns and the seismic retrofitting of existing RC columns are two examples of structural locations where FRP composites are used as confining materials for concrete [197].

When compared to concrete, steel, or timber piles, the advantages of polymer composite piles are clear: they last longer, cost less to maintain, and have a smaller environmental impact. Hollow FRP piles give substantial advantages in terms of cost-effectiveness and structural capabilities [198], [199], and they show great promise in load-bearing applications. Carbon epoxy and E-glass epoxy composite systems not only increased the strength of damaged unreinforced RC slabs by more than 540% but also returned them to their previous capacity. Additionally, FRP systems exhibited a 500% improvement in unreinforced specimens and a 200% improvement in steel-reinforced specimens in terms of structural capability for retrofitting applications [200].

6 Conclusions

Polymer-based composite materials in this current era are one of the leading man-made materials that are available in large quantities or volumes in every segment of human lives compared to metallic and ceramic-based materials. Depending on the improvement in the needed property, certain single materials may be substituted by composite materials for specific applications in several sectors. Polymer-based composites are the leading in this regard and the reason for their widespread structural applications. Although the weight reduction is laudable, the structure and other properties of polymer-based composite materials such as strength, stiffness, biodegradability, machinability, and durability need continuous improvement. However, these characteristics depend on the composition of the polymer material, the type of reinforcement, and the type of manufacturing technique used to create it. Polymer composites have also demonstrated some remarkable features, such as resistance to impact, wear, thermal changes, corrosion, and chemicals which have made polymer composite materials useful in many desired structural industries depending on the needed qualities. However, more studies must be conducted to examine the possibilities of polymer composites in various ways that will advance the use of this special material for more structural applications in the future. It was discovered from the review that, one of the main areas of future advancement is in the hybrid reinforced polymer composites development owing to the continuous possibility of material selection, modification, and processing. Hybridization of different blends of materials will continue to aid the development of the needed advanced materials for various applications in the future.

Author Contributions

I.O.O.: conceptualization, reviewing, and editing; L.N.O.: writing the original draft; S.S.: writing administration; M.R.S.: writing administration; S.O.A.: writing, reviewing, and editing. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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