



Applications and Disposal of Polymers and Polymer Composites: A Review

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ABSTRACT

Polymers are ubiquitous materials that have found usage in almost all facets of modern life, primarily due to their low cost, light weight, high specific strength, and modulus. Likewise, their flexibility and accurate control of structure and properties have made them versatile materials for several applications in aerospace, marine, medical, automobile, construction, packaging, and other industries. Current innovations in the polymer industries include the development of fiber-reinforced polymers (FRPs), glass fiber-reinforced polymers (GFRP), carbon fiber-reinforced polymers (CFRP), polymer-based nanocomposites, biomaterials, and other hybrid polymer-based composites with excellent characteristics to meet high-tech application performances. GFRP and CFRP are identified as substitutes for metals in transportation networks and other applications. With the growing population and industrialization, the global demand for polymer composites will continue to increase and has projected to reach approximately 600 million tons in the next two decades. Thus, this paper hereby reviews the various polymer fabrication techniques, advantages, and disadvantages of polymer composites, applications, and various recycling techniques of polymers after usage. The common challenges in the development of polymer-based composites are discussed alongside their future potentials.

Key words: polymer-based composites; applications; disposal; recycling

INTRODUCTION

The quest to develop durable materials with a combination of distinct properties such as high strength, lightweight, good fracture toughness, and at a competitive cost, has led to optimum global interest in polymer-based composites [1–3]. Polymer-based composites consist of a polymer matrix and reinforcement(s) and are easy to process at low temperature due to their flexibility [4–6]. They also possess high specific strength and modulus, fatigue resistance, and thermal stability [7–9]. However, the development of polymeric composites is based on the mixture of matrix and reinforcement to enhance the polymer's inherent properties such as strength and stiffness. By utilizing the traditional processing route, it is possible to develop polymeric materials with desired properties to meet specific application requirements by selecting a suitable matrix and reinforcement [10], where the matrix helps to firmly hold and protect the reinforcement from environmental and/or mechanical damage. It also distributes evenly or transfer the externally applied load through the fibers. Meanwhile, the reinforcements are the major load-bearing constituents because they induce strength and stiffness, thereby making the developed composites exhibit enhanced mechanical properties, which is usually higher than that of the polymer matrix [11]. Nowadays, polymer composites can be tailored towards any application requirement at a low cost. The global consumption rate of polymers and polymer composites have been increasing yearly with a prediction that the annual demand will reach an approximate value of 600 million tons in the next two decades [4]. Based on this, there is a growing interest to meet this demand while minimizing cost. Interestingly, the world has witnessed a lot of advancement in polymer composites, which include the use of glass fiber-reinforced polymers (GFRP) and carbon fiber-reinforced polymers (CFRP) to replace metallic materials in transportation networks and other applications [1,5]. Despite the numerous benefits that polymer-based composites are

offering, their drawbacks such as low thermal resistance and high heat expansion coefficient have hampered their usage in several potential applications [1]. Several attempts to resolve the aforementioned problems have led to intriguing discoveries in terms of functionalities and performances. The recent advancement in nanotechnology has helped formulate a design that has led to the right alignment of nanofillers or nanofibers of high modulus such as aramid, silicon carbide (SiC), boron, and carbon to replace glass fibers and other relatively low-modulus fibers into a polymer to develop very strong materials with enhanced properties and performances. These formulations have paved the way for the fabrication of materials with alterable structural and load-bearing properties. Composites that are fabricated with nanofibers offer good application performance due to their larger surface-to-mass ratio between the fiber and matrix when compared to traditional fibers, and their use in aerospace, defense, and military industries cannot be underestimated. Nevertheless, the polymers that are reinforced with nanofibers, nanoclays, carbon nanotubes (CNTs), and graphene are used in making ballistics, gloves, boots, armor, smart textiles, and wastewater treatment applications [12]. The alternative way of improving the mechanical properties of polymeric composites is to fabricate hybrid polymer composites [13]. For instance, Bhajantri *et al.* [14] reported that a hybrid polymer-based composite of the right composition, orientation, and distribution of fibers/fillers materials showed a significant improvement in mechanical properties when compared to that of steel and can be used in specific tribological applications. Gururaja *et al.* [15] tested and confirmed the application of hybrid polymer composites in various applications such as aircraft, defense, marine, turbines, construction, and smart communications [10,11,16]. On the other hand, another major drawback of polymer composites is the difficulty surrounding their disposal. The disposal of polymer composites after use is of great concern today as their landfill and incineration pose serious environmental threat and pollution. Therefore, the recycling of polymer composites is currently seen as the way forward to solve the disposal problem. Srebrenkoska *et al.* [16] and El Abbassi *et al.* [17] have concluded that it is not all existing but a few polymeric composites that can be recycled and be used for the production of a new class of composites with unprecedented properties. Notwithstanding, there are still some challenges unresolved that are related to polymer recyclability. Matabola *et al.* [3] and Asmatulu *et al.* [18] have reported that polymer composites recycling can be very challenging because they are made up of different materials consisting of contaminants that can pose a huge setback towards the recycling process. Moreover, the presence of a polymer crosslink is another major factor that hinders the recycling and processability of polymers. For instance, thermoset resin, which is an example of a polymer, cannot be remolded because of its high cross-linkage. Given this, our paper reviews some of the research conducted on polymer and polymer-based composites with a focus on their fabrication techniques, applications, advantages and disadvantages, disposal, and their future trend.

POLYMERS AND POLYMER-BASED COMPOSITES

Polymers

Polymers consist of repetitive units of monomers that are combined to form giant molecular units. The units can be a combination of carbon, hydrogen, oxygen, or nitrogen. Polymers possess distinct characteristics such as toughness, viscoelasticity, and show great potential to transform into glassy and semi-crystalline structures rather than a crystalline structure, which is attributed to macromolecules that have been found useful for mankind since time memorial. Polymers can be processed by heat and pressure and shaped into different engineering components such as bearing, bushes, gears, and many others. However, several studies have shown that the quantity of polymers used annually is more than that of steel. Although, they are mostly used in diverse applications due to their lightweight, ductility, and ease of processing. Unfortunately, polymers exhibit lower strength and modulus when compared to other material counterparts such as metals and ceramics. In a bid to overcome the challenges, polymers are reinforced with appropriate reinforcement to meet certain applications demand.

Classification of Polymers

Polymers can be classified into different groups based on the following: Firstly, by their origin such as natural, semi-synthetic, synthetic; linear, branched, net-work/cross-linked; and addition and condensation polymers. Secondly, their molecular force determines the functionality of the polymers. For example, elastomers, thermoplastic, and thermosetting. Thirdly, by the number of their repetitive units such as pectin; homopolymers; and copolymers. Lastly, by the type of polymerization growth such as chain growth and step-growth [19, 20]. The molecular structures of polymers are shown in Fig. 1, while Table -1 compares selected polymers, their properties, and applications, of which the majority of the polymers are used as matrixes to develop polymer-based composites.

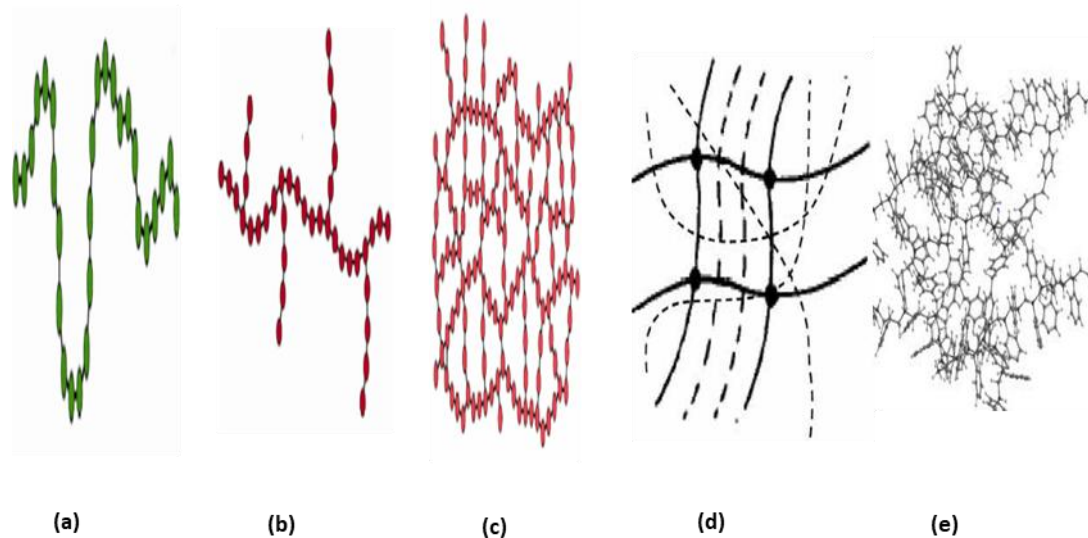


Fig. 1 Different structure of polymers molecules; (a) linear, (b) branched, (c) cross-linked, (d) interpenetrating, (e) hyper-cross-linked structure [21,22]

Table – 1 The properties and applications of selected polymers [23]

Selected Polymers	Tensile Strength [MPa]	% Elongation [%]	Elastic Modulus [MPa]	Density [g/cm ³]	Impact Strength	Applications
Thermoplastics						
Low-density Polyethylene	21	800	276	0.92	4.9	Packing films, wire insulation, squeeze bottles, tubing, household items
High-density Polyethylene	38	130	1241	0.96	2.2	
Ultrahigh Polyethylene	48	350	690	0.934	16.2	
Polyvinyl chloride (PVC)	62	100	4140	1.40	/	Pipes, valves, fittings, floor tile, wire, insulation, vinyl automobile roofs
Polypropylene (PP)	41	700	1517	0.90	0.50	Tanks, carpet fibers, rope, packaging
Polystyrene (PS)	55	60	3103	1.06	0.2	Packaging, insulation foams, lighting panels appliance component, egg cartons
Polyacrylonitrile (PAN)	62	4	4000	1.15	2.6	Textile fibers, precursors for carbon fibers, food container
Polymethyl methacrylate (PMMA)	83	5	3100	1.22	0.3	Windows, windshields, coatings, hard contact lenses, lighted signs
Polychlorotrifluoroethylene	41	250	2070	2.15	1.4	Valve components, gaskets, tubing, electrical insulation
Polytetrafluoroethylene (PTFE, Teflon)	48	400	550	2.17	1.6	Seals, valves, non-stick coating
Polyoxymethylene (POM) (acetal)	83	75	3590	1.42	1.2	Plumbing fixtures, pens, bearings, gears, fan blades
Polyester (PET)	72	300	4140	1.36	0.3	Fibers, photographic films, recording tape, boil-in-bag containers, beverage container
Polycarbonate (PC)	76	130	2760	1.20	8.6	Electrical appliance,

	Polyamide (PA) (nylon)	83	300	3450	1.14	1.1	automobile components, football helmets, returnable bottles
	Polymide (PI)	117	10	2070	1.39	0.80	Bearings, gears, fibers, rope automotive and electrical components
	Polyetheretherketone (PEEK)	70	150	3790	1.31	0.90	Adhesives, circuit boards, fibers for space shuttles
	Polyphenylene sulfide (PPS)	66	2	3310	1.30	0.3	High-temperature electrical insulation and coatings
	Polyether sulfone (PES)	84	80	2410	1.37	0.9	Coatings, fluid-handling components, hair dryer components
	Polyamide-imide (PAI)	186	15	5030	1.39	2.2	Electrical components, microwave oven component
Thermosets	Phenolics	62	2	9	1.27	/	Electronic components, aerospace and automotive applications
	Amines	69	1	11	1.50	/	Adhesives, coatings, Laminates
	Polyesters	90	3	5	1.28	/	Adhesives, cookware, electrical moldings
	Epoxies	103	6	4	1.25	/	Electrical moldings, decorative laminates, polymer matrix in fiberglass
	Urethanes	69	6	/	1.30	/	Adhesives, electrical molding, matrix for composites
	Silicone	28	0	8	1.55	/	Fibers, coatings, foams, insulations
Elastomers	Polyisoprene	21	800	/	0.93	/	Adhesives, gaskets, sealants
	Polybutadiene	24	/	/	0.94	/	Tires, golf balls, shoe soles
	Polyisobutylene	28	350	/	0.92	/	Industrial tires, toughening other elastomers, tire's inner tubes, steam hoses, weather stripping
	Polychloroprene (Neoprene)	24	800	/	1.24	/	Hoses
	Butadiene-strene (BS or SBR rubber)	21	2000	/	1.0	/	Hoses, cable sheathing
	Butadiene-acrylonitrile (Buna-N)	5	400	/	1.0	/	Tires
	Silicones	7	700	/	1.5	/	Fuels hoses and Gaskets
							Gaskets, seals

Polymer-Based Composites

Polymer-based composites otherwise known as polymer matrix composites (PMCs) consist of a polymer as a matrix together with fibers/fillers as reinforcement. PMCs has found a wide range of application in different sectors due to their combination of unique physical, chemical, and mechanical properties such as good damping capacity, corrosion

and fatigue resistance, low density, high strength, and stiffness. Their tendency to show a high level of resistance to environmental degradation like water absorption, chemical attack, temperature, and impact forces, depends strongly on the properties of the polymer matrix [1].

Classification of Polymer-Based Composites

Polymer-based composites can be classified based on the (i) polymer matrix and (ii) reinforcement source.

Classification Based on Polymer Matrix

The typical matrix used in the development of composite materials are polymers. About 75% of the total composites produced today have polymers as their matrix, because they can be easily processed at a low temperature without damaging the reinforcement [24]. The matrix can be classified into three, namely:

- Thermoset
- Thermoplastics
- Elastomeric/Rubber

Thermosetting is well known for its unique behavioral properties of making three-dimensional bonds after curing. For instance, polyester, vinyl-esters, epoxies, bismaleimides, polyamides, phenol-formaldehyde, and isocyanates possess a three-dimensional crosslinking structure that is caused by their curing process. Besides, thermosets are chemically and dimensionally stable and possess good thermal stability and high resistance to cracking. They are commonly used as a polymer matrix because of their lower cost and their ability to withstand elevated temperature. However, their major drawback is that they are difficult to be remolded after being formed into shape. Thus, this poses a serious threat to their recycling capability; however, they can be crushed and used as filler materials. Thermosets-based composites have a wide range of commercial purposes in various sectors such as aerospace, sports, construction, automobiles, bio-medical, and other real-life applications [11,25].

In contrast, thermoplastics can easily be softened and melted by heat and remolded into new shapes. Common examples of thermoplastics are liquid crystals polymers (LCPs), polyamide-imide, polyetherimide (PEI), polyethylene sulphide (PPS), polyesters, polypropylene (PP), and polyetheretherketone (PEEK). Nevertheless, in comparison to their counterpart, thermoplastics are not chemically stable, the viscosity range of thermoplastic is 500 times higher than that of uncured thermosets during melting and they soften quickly at high temperature, and they are a good matrix used in the fabrication of composites for aerospace applications due to their dimensional and density stability. Moreover, they show superior resistance to impact damage and cracking [1,19,25]. The merits and drawbacks of some selected thermoplastic and thermosetting matrices are explained in Table -2.

Table – 2 Merits and demerits of some selected polymer matrices [25]

Polymer Matrix	Merits	Drawbacks
Polystyrene (PS)	Resistance to moisture, chemical, and weather Good resistance to fatigue	Brittle, flammable, and reduced impact resistance
Polypropylene (PP)	Good thermal resistance, Excellent resistance to chemical, lightweight and	Very difficult to compress, High cost and not readily available
Polyvinyl chloride (PVC)	Inexpensive, good tensile strength, optimum dimensional stability, fire retardant, and versatility	Poor resistance to ultraviolet rays and heat
Natural rubber (NR)	Increased resilience, low cost, resistance to water	Dissolution and poor resistance to hydrocarbon
Polyethylene (PE)	Less cost, good ductility, high impact strength, and good resistance to fatigue	High thermal expansion, low resistance to weather, and flammable
Epoxy resin (EP)	Good water resistance, good thermal and mechanical properties, less curing time, and durability	Hard to process, corrosive amine hardener
Vinylester (VE)	High resistance to chemical and good mechanical properties	High curing shrinkage, requires post-curing, expensive, high styrene content
Polyester (PES)	Ease of use reduced cost	Moderate mechanical properties, high curing shrinkage
Phenolic (PHEN)	fire retardant	Hard to fabricate and high gas emission.
Polylactic acid (PLA)	Good strength and modulus, low cost, and nontoxic	Brittle, poor impact strength, low thermal degradation
Starch (ST)	Biodegradable, low cost	Sensitive to water.
Cellulose (CL)	Low cost, readily available, moderate impact and heat resistance, and eco-friendly	High moisture absorption and low decomposition

Elastomers are one of the early-discovered and largely used materials for different applications. Elastomers are a class of polymers that exhibit extraordinary reversible ex-tension with low hysteresis and minimal permanent set. An

elastomer is a material that can exhibit a rapid and large reversible strain in response to a stress. They are the type of polymers that are relieved of molecular interactions, chain rigidity, and crystallinity constraints. Common characteristics of elastomers are low modulus with poor abrasion and chemical resistance. Theoretical concepts have been established for their thermodynamics and kinetics. This knowledge has been adopted to improve their properties with the design of chemical and molecular structures, modification or control of crosslinking, blending, or additions of fillers [26]. During the vulcanization process of elastomeric compounds and in other processing stages, different chemicals called accelerators are used. These accelerators determine the type of network structure and, hence, the material properties. The formulations of elastomers are built up for each constituent to meet some specific requirements and contribute to the final properties [27]. However, despite the available choices of constituents, the desired properties may still not be achieved, and often times, a combination of two or more rubbers has to be used in the preparation of compounds for special properties. Thus, elastomeric materials are blended for properties improvement, better processing, and lower cost.

For instance, natural rubber (NR) is the suitable choice when good tensile and tear strengths are desired since these properties can be achieved due to the ability of NR to crystallize under stress [28]. On the other hand, polybutadiene rubber (BR) is characterized by its superior abrasion resistance, so the blends of NR and BR will form a synergy of excellent processing and physical properties of NR with the superior abrasion resistance of BR. This method is being used in the industry for the production of tire treads and conveyor belts [29]. Since rubber mixtures are usually multiphase systems, according to the adopted compounding mode, different distributions of the additives in each rubber phase can be achieved, depending on the degree of affinity that each additive has towards each rubber. Usually, competitive vulcanization occurs due to different rates of vulcanization and/or rates of diffusion of the additives in each of the elastomeric phases. Hence, when two or more rubbers are blended, one of the expected challenges is the difference in vulcanization rate for each rubber presents. NR is known to have a strong tendency to undergo reversion as a result of thermo-oxidative degradation brought about by long heating times. Upon thermo-oxidative degradation, which normally occurs via scission or depolymerization of the polymer molecules, NR gradually becomes softer and sticky, and as a consequence, the maximum torque, which is the parameter related to the number of crosslinks, decreases. One of the reasons for blending BR to other elastomers is the difficulty in processing while the lower price of NR is one of the positive factors in favor of these blends.

Classification Based on Reinforcement Source

Polymer composites can be classified based on the reinforcement source into:

- Natural fiber
- Synthetic fiber

Fibers can either be natural or synthetic (advanced). Natural fibers are derived from renewable and carbon dioxide neutral resources such as wood or plants, which are 100% biodegradable. Conventional natural fibers used in PMCs are sisal, hemp, silk, wheat, jute, bamboo, kenaf, and coir. Whilst that of synthetic (advanced fibers) are Kevlar, nylon, glass, latex, aramid, carbon, and alumina. The reinforcement in PMCs offers stiffness, toughness, hardness, and strength as they form the major load-bearing constituent of the composites [5]. They exist as particles, fabrics, nanoparticles, or fibers [1]. Fibers can either be natural or synthetic (advanced). Conventional natural fibers used in PMCs are sisal, hemp, silk, wheat, jute, bamboo, kenaf, and coir. Whilst that of advanced fibers are Kevlar, nylon, glass, latex, aramid, carbon, and alumina. Overall, natural fibers are advantageous over synthetic fiber. For instance, low cost, recyclability, durability, formability, biodegradability, lightweight, readily available, and excellent mechanical properties, are what identify natural fibers as eco-friendly replacement for synthetic fibers [10,13]. Generally, the fibers used to reinforce polymers can be classified based on shape or orientation as follows: Continuous, discontinuous, unidirectional, bidirectional, and random. Whichever shape/orientation is selected, the final mechanical properties of fiber-reinforced polymer composites (FRPs) still depend on several other factors like modulus and strength of both fiber and matrix, and the interfacial bonding between them. Likewise, the mechanical properties of FRPs can be tailored according to the preferred orientation and direction of fibers. However, the ability of natural fibers to form aggregates due to incompatibility issues with some hydrophilic polymers is another drawback to consider before using natural fibers. That is why fiber surfaces are chemically treated to improve their surface characteristics such as wetting, adhesion, porosity, and surface tension [25,30]. Kumar et al. [30] reported that surface modification treatment has positively influenced the mechanical properties of natural fibers as it improves the surface roughness of the fibers to aid strong adhesion between the matrix and the fiber phases. Notably, it is recommended that alkaline treatment is the most suitable treatment for natural fibers. The versatility in the use of FRPs is not limited to construction and military, but also automobiles, marine, biomedical, sport, and electronics applications [9,26,30]. Several automotive components are fabricated from polymeric composites of polypropylene and polyesters matrixes, reinforced with fibers such as sisal, hemp, and flax [2,31-32]. GFRPs are commonly used synthetic composites for engineering applications due to their strength, durability, and excellent resistance to chemicals, impact, and wear. However, its disposal and short lifetime are its major challenges. On the other hand, CFRPs, boron fiber-reinforced polymers (BFRPs) and aramid fiber-reinforced polymers (AFRPs) were later developed as a substitute for aluminum in aircraft and other applications requiring high

technological performances [1,33]. Some selected fibers used in reinforcing polymer matrix, the fabrication techniques, and their applications are shown in Table -3.

Table -3 Fibers used with selected polymer matrix, fabrication techniques, and their applications [34]

Polymer Matrix	Fibers Used as Reinforcement	Fabrication Techniques	Applications
PP, epoxy resin, Polyether ether ketone (PEEK)	Carbon	Injection molding, filament winding, resin transfer (RTM), Pultrusion	Fuel cells, armor, sports, lightweight automotive product
Polystyrene, (PS), epoxy, Polyaniline (PANI)	Graphene	CVD, Pultrusion, hand/spray up method	Wind turbines, Gas tank, aircraft/automobile parts
PP, PS, epoxy resin	Sisal	Hand lay-up, compression molding	Automobile body, roofing sheets
PE, PP, PU	Hemp	RTM, compression molding,	Furniture, automotive
PLA, PP, Epoxy resin	Kenaf	Tooling, bearings, automotive parts	Compression molding, Pultrusion
PP, Polyester, epoxy	Flax	Compressing molding	Textile
PP, Polyolefin, PLA	Ramie	Extrusion with injection molding	Bullet proof vests, sockets prosthesis, civil
PU, PE	Rice husk	Compression/injection molding	Window/door frames, automotive structure
Polyester, PP	Jute	Hand lay-up, Compression/injection molding	Ropes, roofing, door panels
PP, epoxy, resin, PE	Coir	Extrusion, injection molding	Automobile structural components, roofing sheets, and insulation boards

Development of Bio-Composites

In recent times, more academic research and industrial development have begun to explore new ways of creating eco-friendly materials for a variety of applications. Natural fibers offer the potential to deliver renewability, sustainability, and better quality at a competitive cost in various industries. The ever-increasing volumes of scientific works in the literature refer with interest to the potential of natural fibers in technological, economic, and ecological terms. This enthusiasm tends to encourage more research on the use of natural fibers, and by extension, to the areas of human life and socio-economic development for the fiber crop growers and their communities [35]. Thus, the use of agricultural wastes has brought a paradigm shift in the way in which natural fibers are being addressed. What was usually referred to as waste is now being called agricultural by-products due to the value that is being attached to these products. Though there is little information on the growth of these natural fibers for commercial purposes, but it is envisaged that with the trends of technological advancement, a new boom in the demand for natural fibers will translate to real improvement in the quality of life of crop fiber growers and their communities in the future.

Bio-composites are made of biological materials as either polymer matrix and/or fibers/fillers as reinforcement. They often mimic the structure of living materials and offer biocompatibility properties. Polyolefin thermoplastics such as polypropylene and polyethylene are considered for fabricating bio-composites due to the difficulty in developing biodegradable polymers. The biological reinforcements are fibers derived from plant sources such as hemp, sisal, kenaf, jute, cotton, flax, or fibers that are processed as waste papers, recycled wood, farm by-products, and nanofibrils of cellulose and chitin [10,11]. Bio-composites are biocompatible, sustainable, and environmentally friendly materials for several applications ranging from biomedical, automobile, packaging, insulation, and construction industries. However, their moisture sensitivity has limited their usage in high-humidity environments. Likewise, their mechanical properties are still unsatisfactory and need to be improved for applications requiring high strength and toughness. Phuong et al. [36] fabricated a sustainable, biodegradable, non-woven composite membrane from poly(lactic acid) PLA, bamboo fiber dimethyl carbonate, and the developed membrane had porous structure (porosity of 0.719 ± 0.132) with tensile strengths (32.7–73.3 MPa), which is comparable to traditional materials like polypropylene. Further analysis revealed that an increase in the bamboo content causes improved mechanical stability, reduced swelling, and enhanced permeance up to $1068 \pm 32 \text{ L/m}^2\text{/h/bar}$ in water. The result from the experiment affirmed that the bamboo/PLA membrane could be a sustainable substitute to conventional membrane materials, thus reducing the demand for petroleum-based, non-degradable polymers and toxic solvents being used in desalination, food processing, petrochemical, and pharmaceutical industries.

Development of Hybrid Nano-Composites

Hybrid composites are some of the recorded successes in the fabrication of polymer composites. The quest for a safer environment and ecosystems and the industrial compliance with environmental policies have reduced the overdependence on petroleum products, thereby encouraging emergent research towards the development of biodegradable materials. Hybrid composites are produced by combining at least two different reinforcement phases (fibers, fillers, and/or particulates) with a matrix. The reinforcements can both be natural or synthetic. Hybrid composites are advantageous because of their flexibility in designs and can easily be tailored to desired mechanical properties [13,34, 37]. Of recent, additive manufacturing industries have made use of polymeric composites to achieve little or no waste production processes by making it possible to fabricate complicated parts that are in excessive demand in high-tech applications like automotive, aerospace, biomedical, electronics, and robotics. Hence, FRPs are promising materials to meet the future needs of next-generation materials and technologies [38,39]. Several studies and reviews have been carried out on hybrid composites. Bhajantri *et al.* [14] studied the mechanical properties of polymer-based hybrid composites based on glass fibers and other fillers as reinforcement in polyester resin. Their results showed that the hybrid reinforcement significantly enhanced the tensile, impact, and flexural properties of the polyester resin. It was therefore concluded that hybrid composites demonstrated better mechanical performance than conventional composites at low cost. Nair *et al.* [39] studied the synthesis and characterization of hybrid polymer composites. From their study, coir and human fibers were used to reinforce epoxy resin via hand layup technique. The mechanical characterization of the developed composites showed that the tensile strength of hybrid composite increases from 16 MPa to 19 MPa while the optimum flexural and impact strengths were 56 MPa and 6.8 MPa, respectively. From their analysis, synthetic fibers can be used to replace eco-friendly fibers to develop hybrid composites of superior mechanical performance. Therefore, it is an alternative way of improving the mechanical properties while minimizing the cost. In another work, Salih *et al.* [40] investigated the influence of locally sourced rice husks and date palm fibers on the mechanical properties of hybrid composites for construction purposes. Their results revealed that the fracture, compressive, tensile, and impact strengths of the composites were improved as the fiber fractions of palm fibers increases at the expense of rice husks. A further investigation showed that the reduction of palm fibers' length to micrometer range increases the fracture toughness of the polymer composite by 98%. The results from the analysis confirm that palm fiber better enhanced the mechanical properties of polymer-based composites. Kaushic and Suresh [41] studied the mechanical behavior of hybrid composite using E-glass and Kevlar as reinforcements. The sample formulation consists of 60%wt of epoxy and varying volume fraction of E-glass and Kevlar fibers. Afterwards, the samples were fabricated by using a compression molding technique. From their findings, the mechanical properties (tensile, impact, and flexural strengths) of the hybrid composites were significantly improved by the addition of hybrid fibers. To conclude, the hybrid composite is suitable for applications requiring high strength and toughness. Akash *et al.* [42] evaluated the mechanical properties of hybrid composites reinforced with sisal and coir fibers, which were fabricated by the cold-pressing technique. By varying the weight fraction of the individual fibers within an epoxy matrix, the hybrid composites were made to possess better mechanical performance than pristine epoxy and other composite systems. However, the major issue related to hybrid composites is their irregular water absorption behavior. For instance, the water absorption properties of hybrid composites usually increase with an increase in the volume fraction of fibers. Recently, sisal and coir fibers were used to fabricate a low-cost bio-composite, suitable for high-strength applications. The bio-composite consisting of a polyethylene matrix was developed by Bazan and co-workers [43]. They combined varieties of natural fibers such as coconut, basalt, and sawdust of varying proportions into a polyethylene matrix to fabricate polymer-based hybrid composites. Upon further investigation, both the theoretical and experimental results showed that the mechanical properties of polymer composites can be improved by combining different fibers together. Therefore, their work has justified the effectiveness of using natural fibers as reinforcement towards the development of polymer-based composites for intending applications. However, a study conducted to evaluate the superiority between basalt-wood and basalt-coconut as reinforcing fibers/fillers showed that basalt-wood-reinforced composites possess higher strength (50%) and stiffness (65%) over basalt-coconut-reinforced composites. From the SEM images in Fig. 2a,b, there is a clear difference in the interfacial bonding between the fibers and matrixes for each composite. In Fig. 2a, the wood flour consists of well-embedded hollow cylindrical cells and strung that are parallel to one another within a polyethylene matrix. From the image, it can be seen that a good surface bonding existed between the fibers and matrix. Whilst in Fig. 2b, it was observed that the surface adhesion or roughness between the coconut-basalt fibers and matrix is weak. Thus, it justifies the reason that the hybridization of wood flour and basalt fibers within a polymer matrix possesses better mechanical properties than that of coconut- and basalt-based composites. To conclude, the strength and stiffness of hybrid composites made from wood flour and basalt fibers increases by 50% and 65%, respectively, compared to composites reinforced with basalt and coconut hybrid fibers. Jose *et al.* [44] investigated the mechanical properties of a hybrid composite reinforced with coir and wood dust particulates. Scanning electron microscopy as shown in Fig. 3a and b show an even distribution and good interfacial bonding of the coir and wood in the particulates to the polymer matrix, and this causes increases in tensile strength and flexural strength with an increase in concentration of the fibers and coir particulates

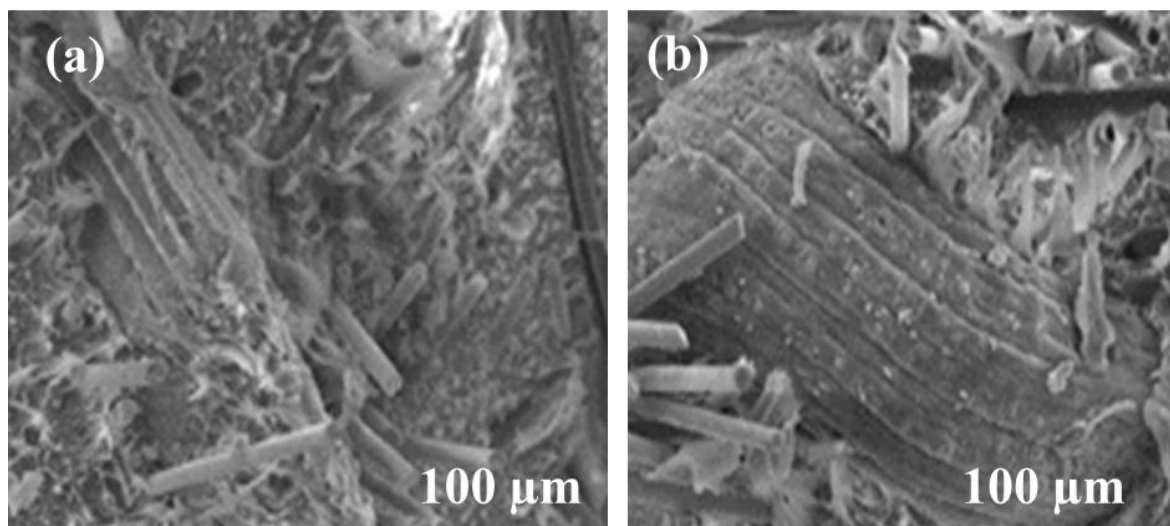


Fig. 2 SEM images of polyethylene-based hybrid composites consisting of (a) wood flour and basalt fibers and (b) coconut and basalt fibers [43]

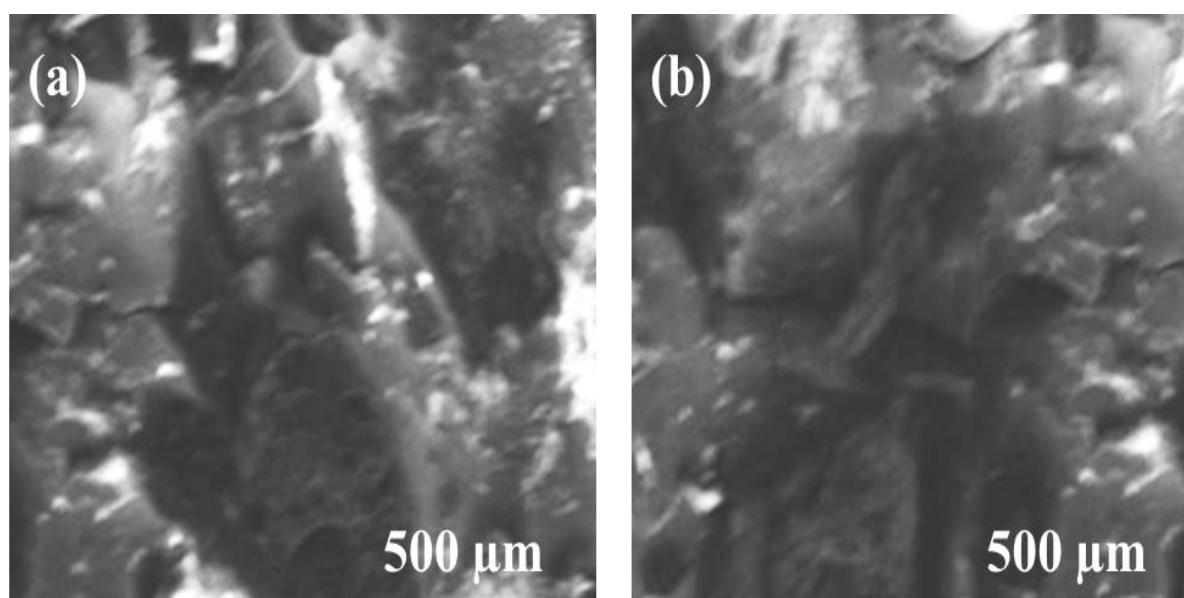


Fig. 3 SEM images of (a) coir and (b) wood dust particulate reinforced hybrid polymer composites [44]

According to the review paper published by EL-Wazery [13], it was concluded that polymer-based hybrid composites can be used for diverse applications requiring low density, excellent rigidity, and strength in relation to nanotechnology, orthopedics, wind power generation, transportation, construction, chemistry industries, and smart technology. Most especially, the application of hybrid composites in nanotechnology has paved the way for the use of particulates in their nano-scale range as reinforcement to develop these composites of targeted mechanical properties. As a result, it has given them room to exhibit a good surface–volume ratio to afford better interfacial bonding between the reinforcement and polymer matrix [1,4]. For instance, if a polymer composite consists of well-dispersed nanoparticles, it will produce a polymer nanocomposite of excellent compressive strength, fatigue, and fracture resistance. The reason is that an improved infiltration and impregnation of resin will be made possible when the reinforcing particles do not agglomerate as a result of the sizing effect, and thus justify the importance of polymer nanocomposites in high-tech applications [8]. Nevertheless, the processing techniques for developing nanocomposites are in-situ and ex-situ polymerization, melt intercalation, template synthesis, and sol-gel processing [35]. Several research works have reported the use of certain polymers such as polyamides, polypropylene, polyethylene, epoxy, acrylics, and polyurethanes, as a matrix towards the development of nanocomposites for different engineering purposes. Recently, the research focus has been on the development of biodegradable polymeric materials. Some polymers are being reinforced with suitable reinforcing fillers/fibers to improve their biodegradability to ensure a sustainable environment [44–47]. Rajak *et al.* [35] showed in their studies that carbon nanotubes (CNTs) polymer composites are of good mechanical, thermal, electrical, and

magnetic properties. Satis and co-workers [45] investigated the morphology and thermal stability of epoxy reinforced multi-walled CNTs. From their findings, it was observed that the thermal stability of the epoxy was improved due to CNTs addition. The SEM morphology of the epoxy composite as shown in Fig. 4 has revealed that good interfacial bonding existed between the epoxy matrix and CNTs, as well as structural homogeneity. Thus, it was the reason that the strength and toughness of the epoxy composites were improved. In summary, multi-walled CNTs are a suitable reinforcement for enhancing the mechanical properties and thermal stability of epoxy-based composites. Furthermore, it is noteworthy to mention that polymer-based nanocomposites possess better mechanical, thermal, and flame-retardation properties than conventional composites due to the higher surface area that exists between the nanofiller and matrix [46].

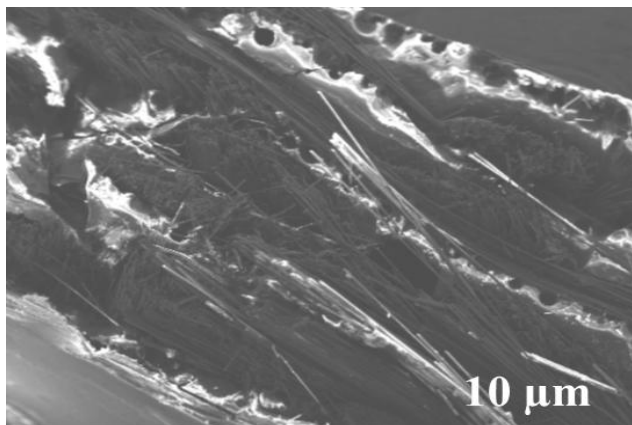


Fig. 4 SEM morphology of the fractured surface of Epoxy-reinforced multi-walled carbon nanotubes (MWCNTs) [45]

Advantages and Disadvantages of Polymer-Based Composites

Polymer-based composites offer numerous advantages ranging from a reduction in fuel consumption as a result of less weight associated with excellent specific strength and stiffness, as well as being less energy-intensive for their production. Other advantages include good fracture toughness, top-notch resistance to corrosion and fatigue, good damping capacity and high tolerance to damage, high resistance to impact and abrasion, flexibility in design, and low processing and maintenance cost. All these and many others are the important advantages of polymer composites. However, the challenges limiting the use of polymeric composites are due to their low strength, low thermal resistance, low glass transition temperature (T_g), and a high coefficient of thermal expansion between the polymer matrix and reinforcement.

FABRICATION TECHNIQUES OF POLYMER-BASED COMPOSITES

The underlying principle behind the development of composites is based on the application of heat and pressure to cure a mixture of polymer and reinforcement into the desired shape and geometry. The process involves the following: Material sourcing, sorting and pre-treatment, fiber impregnation, forming into shapes, curing, and finishing [48]. Nevertheless, the commonest fabrication techniques of polymer-based composites are discussed below.

Wet/Hand Lay-Up

This is the most commonly used technique in the development of small and large components. The process is usually carried out in an open mold by placing preform fibers either in woven, knitted, or stitched fabrics, followed by resin impregnation, which is carried out by using brush, nip, roller, or impregnator. The process of resin impregnation is to force a resin into fabrics to form laminates followed by curing under atmospheric conditions. However, some of the advantages of the process are low tooling cost, ease of processing, and flexibility. In contrast, the major challenges to be faced during the process are the quantity of viscous resin used and the non-uniformity in its distribution [35,49].

Spray up

The similarity between hand lay-up and spray-up technique is that they make use of the open mold and roller for exerting pressure when needed. In the case of the spray-up processing technique, chopped fibers are held in a gun and fed into a spray of resin. Afterwards, it is deposited inside the mold and allowed to cure. Although the spray-up process is faster than the hand lay-up process, it is not suitable for manufacturing parts requiring high structural and dimensional tolerance [49].

Vacuum Bagging

Vacuum bagging involves the use of flexible diaphragm like polyvinyl alcohol or nylon polythene that requires the use of a hand lay-up process to first make the laminates before spreading a plastic film over them. Thereafter, pressure is applied to improve its consolidation while the trapped air is extracted using a vacuum pump. To compare and contrast vacuum bagging and hand lay-up, the former can be used to develop composites consisting of high fiber loading with lesser void and volatile constituents. However, vacuum bagging is a capital-intensive technique that requires highly skilled operators. Hence, it is the reason that the cost of production under vacuum bagging is much higher than that of the hand lay-up process [35].

Pultrusion

Pultrusion is an automated technique used for processing composite materials into continuous and constant cross-sections in the form of rods, tubes, and dies. During the process, strands of continuous fibers are pulled through a resin bath, which is later allowed to pass through a heated die. Hence, the final product has the same shape as the die, which helps to complete the impregnation process. The pultrusion technique is a rapid process that gives room for mass production of desired products with good fiber control. However, the process is limited only to near-shaped or net cross-section components [35].

Filament Winding

Filament winding is a technique used for fabricating hollow, circular, and oval shape components such as pipes, tubes, cylinders, large tanks, and many others. During the process, flexible fibers are made to pass through a resin bath and wound into different orientations through a feeding mechanism via rotating mandrel to form a desired component, which is then allowed to cure in an oven or autoclave. The major advantage of the filament winding process is that it is very fast and economically viable. Additionally, it can be used to create complex patterns with fibers for load-bearing applications. However, its processing requires resin with low viscosity, and it is limited to convex-shaped components only [35].

Resin Transfer Molding

Resin transfer molding (RTM) is a processing technique that involves the arrangement of fibers into desired preform or orientation. During the process, the fibers were first held together by using a binder and pre-pressed into a mold shape. Afterwards, another similar mold was clamped over the first mold while a resin is forced into the cavity by pressure. The variance of this process is called vacuum-assisted resin transfer molding (VARTM), whereby a vacuum is applied to the cavity to aid the impregnation of resin into the fibers. The process can also be carried out at atmospheric or elevated temperatures under closed conditions to ensure good environmental control [35]. Finally, the process is cost-effective and suitable for the development of complex shapes and geometry.

Extrusion

This technique is a continuous process employed by industries to incorporate fibers/particles into a polymer matrix to produce polymer composites. In extrusion, a mixture of molten polymer and fiber/particles are continuously passed through a die with a predetermined shape in a flow state. It is one of the fastest developing techniques for the fabrication of polymer composites due to the wide range of advantages it offers such as continuity, short time of processing, good mixing efficiency, high capacity, good quality of products, diversity, and versatility. Extruders are classified into single screw and twin-screw extruders, single screw extruders are being used when a low mixing effect is required, but the configuration of single-screw extruders offers better alignment of fibers in the polymer matrix at higher temperature. However, an excellent mixing effect and homogenous distribution of fibers or nanoparticles in polymer melt can be achieved by using twin-screw extruders. The process parameters for the extrusion process are screw profile, speed, residence time, and temperature, and optimization of these process parameters plays a vital role in the final properties of the composites produced. Therefore, the thermal stability of the fiber should be considered while adjusting the process temperature, and process parameters should be correctly defined to enhance the aspect ratio of the fibers as well as reducing possible damages to the fibers [50].

Melt Blending

This is the most preferred technique of preparing polymer nanocomposites of either thermoplastics or elastomeric polymer matrix and it is becoming more popular owing to its significance in industrial applications. In melt blending, the polymer is melted at a temperature above its softening point and mixed with the desired quantity of intercalated nanoparticles using an extruder. This process is carried out in the presence of an inert gas such as neon, argon, or nitrogen. Moreover, the polymer may be dried and mixed with intercalant before heating in a mixer and subjected to shear force sufficient to form the desired polymer nanocomposites. The merits of melt blending over in situ intercalative polymerization of polymer solution intercalation are that the process is environmentally friendly due to absence of

organic solvents, it provides better mixing of polymers and clay-nanofillers compared to solution-blending techniques, and its compatibility with current industrial processes such as extrusion and injection molding. Important operation parameters for this process are melting conditions such as feed rate, temperature, screw speed, mixing time, oxidative environment, die pressure, materials grades, and the chemical nature of the nanoclays [51,52].

Solution-Blending

This is a solvent-based method in which solubilized polymers or pre-polymers are mixed with fillers under continuous agitation by mechanical stirring, and the polymers are firstly dissolved using appropriate solvent such as water, chloroform, alcohol, or toluene. The polymer chains are intercalated, and the solvent is displaced within the interlayer when the polymer and fillers are mixed in the solution. The solvents are removed by either vaporization or precipitation, and the intercalated sheets are reassembled yielding polymer/nanocomposites. Entropy gained from desorption of the solvent molecules acts as the driving force for the intercalation in the process. The whole process involves three stages, namely the dispersion of nanoparticles in a polymer solution, controlled removal of solvent, and casting of the composite film. Most times, the polymers are heated, or the pH is adjusted to enhance the formation of film and improve film properties. Lately, solution blending is often used in preparing thermoplastic and epoxy composites at the laboratory scale due to its ease of operation, optimum particle dispersion, coupling chemical reactions, and no special equipment is required. A composite with excellent properties can be obtained with careful selection of appropriate solvent and controlled fabrication techniques. The drawbacks of solution blending include the fact that intercalation can only take place for certain combinations of polymer, clay, and solvents, a large quantity of organic solvents is required, and this may not be environmentally friendly and economically viable [52,53].

In Situ Polymerization

This was the first method used to synthesis polymer clay nanocomposites based on the use of nylon 6. The layered silicate is swollen within a solution of liquid monomer so that the formation of polymer can take place between the intercalated sheets. The polymerization can be initiated either by heat or radiation by diffusing a suitable initiator or used of organic initiator or catalyst that has been fixed inside the interlayer before the swelling stage. This method gives room for versatility in molecular designs of polymer matrix and provides an efficient approach to the synthesis of varieties of polymer/nanocomposites with a range of properties, and flexible tuning of matrix composition and structure can be achieved through this method [52].

Sol-Gel

In the sol-gel method, organic molecules and monomers are embedded on the sol-gel matrix and organic groups are introduced to form chemical bonds. This leads to in situ formation of a sol-gel matrix within the polymer and the generation of organic or inorganic networks. The nanoparticles are synthesized within the polymer matrix by using an aqueous solution containing polymer and silicate building blocks. Nucleation and growth of the inorganic host crystal are aided by the polymers, and the polymers get trapped within layers as they continue to grow [51]. The process is limited to polymers with hydrogen bond acceptor groups with the ability to form hydrogen bonds with hydroxyl groups on the inorganic filler surface [54]. Table- 4 present the advantages and the disadvantages of each polymer fabrication method. More research still needs to be carried out to investigate comparatively the influence of these production methods on the properties of the developed products. This is necessary since each of these techniques will bring about different structures and, thus, varying properties. Moreover, the influence of these manufacturing processes on new advanced materials needs to be ascertained.

Table -4 Merits and demerits of selected polymer-based composites fabrication techniques

Fabrication Technique	Merits	Demerits
Wet/Hand layup	Low tooling cost, ease of processing and flexibility, any combination of fiber and polymer matrix can be used	Non-uniformity in resin distribution
Spray up	Faster than hand lay-up process, economical for producing small to large parts	Difficult to control fiber volume, styrene emission, not suitable for manufacturing parts requiring high structural and dimensional tolerance, does not provide good surface finishing on both sides of the product, can only use short fibers
Vacuum bagging	Composite of high fiber loading with lesser void and volatile constituents can be produced	Capital intensive, highly skilled operators required,
Pultrusion	Fast and give room for mass production	Limited to only near shaped or net-cross-section components

Filament winding	Fast and economically viable, resin content can be controlled.	Requires resin with low viscosity, limited to convex shaped components, rough external surface of component, cost of mandrel for large components can be high
Resin Transfer Molding	Cost-effective and suitable for fabrication of complex shapes and geometry, lower emission, high-quality finishing,	Sizes of part are limited to the type of mold, tool offset is required for high production rates
Extrusion	Low cost, flexibility	Size variances, product
Melt Blending	Fast, simple, and environmentally benign	Poor dispersion of particles in matrix
Solution Blending	High particle dispersion,	High cost of solvent, not environmentally friendly
In situ Polymerization	Faster polymerization, easy to AUTOMATE	Uses expensive equipment,
Sol-gel	Low equipment cost, reduce fiber damages due to low processing temperature	Limited to polymers having hydrogen-bond acceptors,

APPLICATIONS OF POLYMER-BASED COMPOSITES

The applications of polymer-based composites are prominent in areas like aerospace, automobiles, construction, marine, and biomedical, due to the promising advantages of being lightweight in combination with their satisfactory mechanical properties such as specific stiffness and strength, good corrosion, and fatigue resistance.

Marine

One of the basic objectives of manufacturing marine structures is to produce components of low density and high specific strength. Properties like lightweight and good corrosion resistance have made it possible for polymer composites to be useful for boat making, marine construction, and the fabrication of components such as the bulkhead, deck, mast, and craft [9]. Other important engineering properties, for example, fatigue resistance and temperature stability together with low maintenance cost, have made CFRP (an example of a polymer-based composite) a suitable material in various marine sectors, and they are used for fittings and internal equipment such as valves, ducts, pumps, heat exchangers, pipes, naval vessels, small ships, superstructures, heat exchangers, bulkheads, machinery, propellers, propulsion shafts for warship equipment, etc. [49].

Automobiles

Automobile industries use a lightweight material to maximize fuel efficiency and reduce environmental pollutions generated through emissions. These have made polymer composites an important material in the automobile industry. Examples of automobile parts produced using polymer-based composites are engine frames, dashboards, door panels, interior structures, and storage tanks. They are made possible by reinforcing polymers with natural or synthetic fibers. Examples of commonly used fibers are sisal, jute, bamboo, cotton, glass, flax, carbon, and hemp [34–35,46]. Rajak et al. [35] reported the use of glass/carbon matrix thermoplastic to manufacture an automobile bumper beam due to its exceptional impact strength and lightweight compared to conventional glass thermoplastic bumper beam. Kim and co-workers investigated the application of polymer composites made of polyamide matrix and alumina fibers (60 wt.%) for automotive lamp reflector purposes and reported that the composite exhibited a remarkable thermal conductivity when compared with fog lamp reflectors that are made from conventional polybutylene terephthalate [54].

Aerospace

The aerospace industry is the largest consumer of polymer composites, as weight reduction and safety are the major considerations in designing aircraft structures. Several studies have shown that there is about 50% and 20% weight reduction and cost cut, respectively, when polymer composites are used for fabricating aircraft structural parts compared with metals. Examples of such parts are wings, stabilizers, fuselages, floor beams, rotor blades, and rudders, among others. Since the 1950s, the aerospace industry has been adopting glass-fiber-reinforced polymers (GFRPs). Their relatively low cost and high specific strength make them attractive in the aerospace industry to date. Another polymer-based composite that is commonly used for fabricating aircraft components is carbon-fiber reinforcement polymers (CFRPs). Other potential replacements for aluminum (Al) in aircraft structures are BFRPs and AFRPs [1,6,55]. Research has shown that several natural fibers-reinforced thermosets and thermoplastics meet performance requirements of aircraft interior panels such as specific weight, good resistance to heat and flame, ease of maintenance, and recoverability. The biodegradability and cost-effectiveness of the composites are added advantages for the industry [34]. Kesarwani [33]

reported the use of CFRPs in the wing box, upper deck floor, and rear pressure bulkhead of A380 aircraft as shown in Fig. 5, causing a weight reduction compared to when an aluminum alloy was used. The work further emphasizes the importance of polymer composites to solve problems related to an increase in fuel cost, environmental instability, and maintenance in the aviation industries.

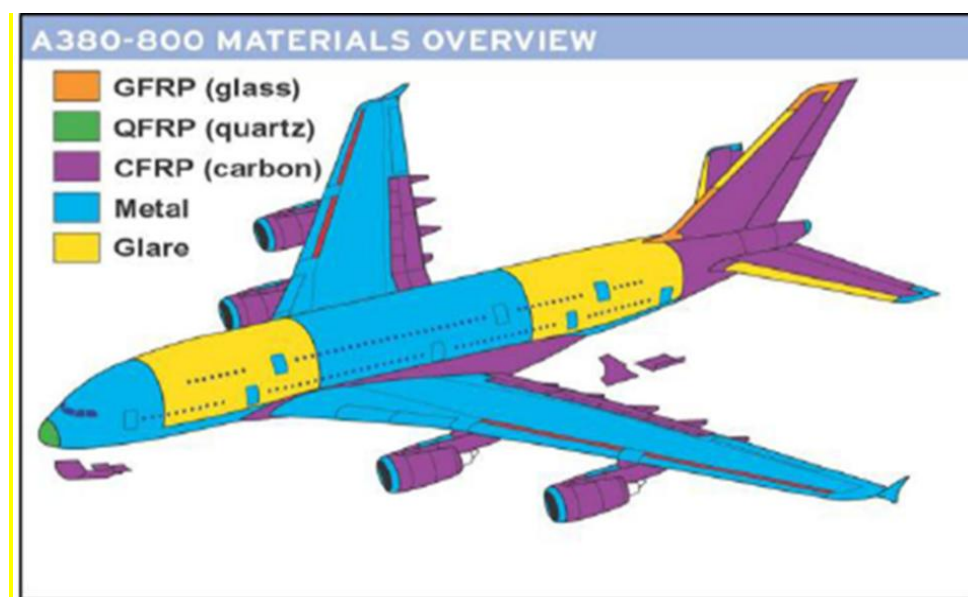


Fig. 5 Schematic showing the composite structure of A380 aircraft [56]

Medical

Strength and biocompatibility are important properties requirements for polymer-based composite materials in the dentistry and orthopedics field. This will enable them to act as a good replacement for metals in the fabrication of medical implants and devices. Problems associated with the use of metallic implants are metal allergy, which is caused by ionic reactions, and the inability of the metallic implant to match the elastic stiffness of the body part being attached to it. Fatigue is also a big issue while using metal as an implant. However, the aforementioned problems can be subdued if the polymer composite is used because its stiffness can be adjusted to the intending body part, thereby annulling any negative reaction caused by stiffness imbalance [49, 56]. The wide range of fiber-reinforced polymer composites used for prostheses, correction of bone defects, and producing dentures and sutures. Gunatillake and Adhikari [57] reviewed the application of synthetic biodegradable polymers in tissue engineering. They reported a vast number of biodegradable polymers with structures tailorable to desired mechanical properties for medical applications. Finally, they discussed the use of polymer composites as precursors like polyols, injectable polymer systems, and scaffolds, for tissue engineering applications. Polymers reinforced with clay-nanofillers have successfully been used to fabricate scaffolds in cell-transplantation and neural tissue engineering. The scaffolds are made to exhibit a high degree of porosity, biodegradability, and biocompatibility. The quantity of nanoclays used in making the scaffolds has a significant effect on their elastic modulus and storage capacity. However, studies have shown that scaffolds made from polymer-nanoclays exhibit high antibacterial properties, which in turn contributes to their rapid degradation rate [52].

Construction

Polymer composites have found application in the construction of bridges, fire-resistance concrete, concrete beams, deck panels, pile materials, earthquake-resistance columns, and sensors used for structural health monitoring technology. Benefitting from the lightweight, corrosion resistance, durability, and earthquake failure resistance, polymer composites are now being harnessed in construction sectors. In contrast to most common construction materials, fiber-reinforced polymer composites offer increased strength-weight-ratation and increased stiffness-to-weight ratio [49].

Military

Over the decades, there has been an increase in the use of nanomaterials in the defense and military sectors with efforts to improve the performance of military devices and ensuring the comfort and safety of military personnel. Polymer nanocomposites are used in various defense and military sectors, and they are being used in the production of military devices, materials, and structures that are lighter, smaller, and of good strength. They are suitable materials used in the production of body armor, smart textiles, gloves, and boots [49].

Food Packaging

The unique combination of properties of polymer nanocomposites such as being a good barrier to many gases and good mechanical, optical, and thermal properties have made these composites good materials for food packaging. Over the decades, many polymer nanoclay composites have been developed with less permeability to gases and enhanced thermal and mechanical properties. Okpala [46] has reported the use of nanofiller-reinforced polymer composites for strong containers and packaging of both consumable and non-consumable substances owing to their lightweight and good abrasion resistance.

Wastewater Treatment

The adsorption technique is used for the removal of pollutants from water. With water pollution and treatment of wastewater from various industry becoming a crucial problem due to the presence of toxic substances and the complex mixture of water and organic substance that can be difficult to treat, quite a number of adsorbents have been produced using advanced polymer/nanocomposites in recent years in treating these wastewaters. Polymer nanoclay composites show high adsorption capacity and a good life cycle for water treatment due to their ease of processing, effective cation exchange, low cost, and toxicity. They are capable of removing various pollutants from aqueous solutions and effective in the treatment of water [52]. Alamaar et al. [58] developed polybenzimidazole (PBI), graphene oxide (GO), and reduced graphene oxide (rGO) nanocomposite membranes through blade coating and phase inversion techniques, for the treatment of wastewater produced from the oil and gas industry. The experiment shows that the addition of a small weight percent of GO into the PBI matrix gives effective oil-removal efficiency up to 99.9%; moreover, the presence of GO also improved the mechanical stability of the membrane. It was concluded from the work that the nanocomposites' membrane shows promising performance for wastewater treatment under harsh industrial conditions, and the membranes can de-oil high-salinity emulsions for reuse.

Miscellaneous

Polymer composites have found several applications in many sectors ranging from the household as shown in Fig. 6 to advanced materials such as panels, insulators, hydrogels, bio-boards, connectors in electrical industries, fabrication of golf clubs, fishing rods, tennis rackets in sports, windmills, etc. Phuong et al. [36] reported the use of bio-polymer composites in the developments of biodegradable membranes used in different industrial sectors with a wide range of applications in food processing, petrochemical, desalination, and pharmaceutical industries. These composites are promising substitutes for non-renewable, petroleum-based polymer materials and toxic solvents currently used.



Fig. 6 Selected polymer-based household products in Akure, Nigeria

DISPOSAL OF POLYMER AND POLYMER-BASED COMPOSITES

Due to the versatility of the use of polymeric composites, they are readily available in large amounts globally. In developing countries, where there is no stringent measure to curtail the indiscriminate disposal of wastes from initial products, they are usually a menace to the global community as shown in Fig. 7. Most times, they are burnt, and after burning, the scar left behind will still not be conducive to an ideal environment since the entire polymeric product will not be burnt, as shown in Fig. 8. Activities from these parts of the world contribute to the global challenges in the oceans and atmosphere as these pollutants will end up in such places. Hence, there is a need to proffer global solutions that will discourage the illicit act.



Fig. 7 Refuse dumping site in Akure, Nigeria, with a lot of polymer and polymer-based composite products



Fig. 8 Refuse dumping site in Akure, Nigeria, after burning the polymeric waste products

Over the years, a linear increment in the production and consumption of polymers and polymeric composites has been recorded due to their numerous applications in different fields. However, our manufacturing industries need to consider the end-of-life disposal of their products following the existing environmental policies and waste management regulations, to achieve a sustainable and eco-friendly environment. It is tenable because an increase in the production and usage of these materials will create wastes that must be handled in the future [3]. Landfill, incineration, and recycling are the common methods of disposing of polymers and polymer-based composite wastes [16,17]. Incineration is associated with global warming problems, while landfills contributed to waste in every environment as there are land shortages. Some of the polymer wastes are also transported to oceans, which adversely affect the marine life and humans who later consume them via the food chain. The prohibition of waste storage by Germany and the introduction of additional taxes by Sweden, which is projected to extend to other countries soon, and the existence of other regulations that are aimed at forming effective material recycling and energy recovery processes in line with environmental and economic consideration are against the use of landfill and incineration as disposal methods. The proposition of the European Commission (EU) tagged ‘Plastic Strategy’ projected that, by 2030, recyclable and reusable plastic will be used for all forms of packaging, to ensure the recovery of waste polymers and their reclaim towards the development of new materials [4]. Researchers have reported that recycling is the best material disposal method by putting environmental effects into consideration. The underlying principle of recycling is carried out at different stages such as separation, shredding, and chemical or mechanical treatment, followed by drying, reforming, and development into a final product. Compared to other materials like steel and aluminum that have effective recycling processability, this is not so for polymer composites whose recycling processing is more complex because they are made from heterogeneous materials like fibers, organic matrixes, and additives [59].

Asmatulu and co-workers [18] reported that the presence of heterogeneity in the materials used for polymer composites results in contamination, which is one of the major challenges encountered during the recycling process. In addition, the cost of collecting, classifying, and separating the material scraps needs to be considered due to economic reasons. The encouragement of developing eco-friendly materials like polymer composites has helped to improve the efficiency of the existing recycling process and maximizing their energy requirements [3]. Several recycling technologies have been developed to handle the several tons of composite wastes produced annually. The technologies can be grouped into mechanical, thermal, and chemical methods, of which nearly all of these methods involve the reduction of the waste materials into smaller sizes [35].

The mechanical recycling method, which is among the most investigated technologies, is known as the economically viable method for recycling polymers and polymer-based composites. The method involves stepwise material reduction via mechanical processes such as cutting, crushing, shredding, grinding, and milling. All the unwanted components such as metals and impurities are separated before grinding and milling. After which, the material is classified into different sizes, ranging from powder to various fiber lengths, which are subsequently used as reinforcement, which is then mixed with virgin materials to develop new composite components for other applications. The mechanical method of recycling has been used for CFRPs, GFRPs, and many other reinforced composites [18,59]. Srebrenkoska et al. [16] reported the use of recycled rice-hull-filled poly(lactic acid) (PLA) bio-composites for the development of new environmentally friendly materials with suitable thermal and mechanical properties. The flexural strength and modulus of the recycled bio-composites can be compared to that of traditional formaldehyde wood fiberboards used for indoor constructions. As shown in Fig. 9, the scanning electron microscope (SEM) micrographs of cryogenically fractured samples of recycled biodegradable PLA-based composites revealed the surface bonding between the reinforcing fillers and matrix before and after it was subjected to external loading. The SEM images show the similarity between the surface morphology of the virgin and that of the recycled composites. From the analysis, it indicates that the recycling process does not affect the surface adhesion between the filler and matrix, and that explains why the recycled composites showed a comparable mechanical and thermal property with the virgin composites.

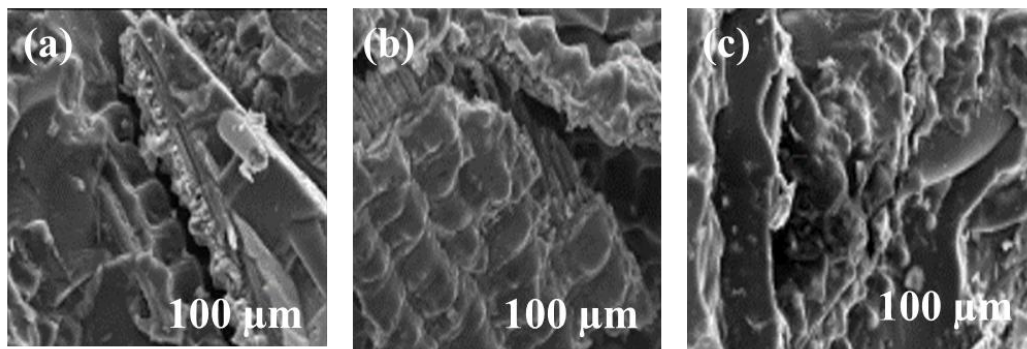


Fig. 9 SEM images of cryogenic-fractured surfaces of: (a) Virgin poly(lactic acid) (PLA)-based composite (b) 1x1 recycled PLA-based composite, and (c) 2x2 recycled PLA-based composite [16]

Das et al. [60] reinforced mechanically recycled polypropylene (RPP) derived from post-consumer plastic products with jute caddies. The composite was developed using the solution impregnation method, in which silane coupling agents of two different respective weights of 2 wt.% and 6 wt.% were used and treated with 6 vol.% Vinyltrimethoxysilane (VTMO) to improve the interfacial interaction between the RPP matrix and jute caddies. It was reported that the flexural strength and modulus were improved by 7.4% and 22.7%, respectively. The surface treatment method reduced the water absorption behavior of the composites while the thermal stability of the composites was enhanced. Adhikary [61] investigated the mechanical properties, dimensional, and thermal stability of wood flour recycled polymer composites (WPCs) panels as building materials. The WPCs were made from recycled high-density polyethylene (rHDPE) and polypropylene (rPP), while sawdust (*Pinusradiata*) was used as filler. From the result, both matrices showed superior dimensional stability and mechanical performance when compared with the virgin materials. Meanwhile, the addition of 3wt.% maleated polypropylene (MAPP) as a coupling agent and 50% wood flour as a filler increased the tensile strength of WPCs made from rHDPE and rPP by 60% and 35%, respectively. Hugo et al. [62] studied the mechanical and thermal properties of recycled polymer composites for structural application. The blend of pulverized recycled amorphous and semi-crystalline polymers of 10 mm size was reinforced with different fillers. In their work, the developed hybrid composites possess excellent strength and modulus after incorporating a small quantity of mica blended with polymer reinforced with glass fiber. Their studies have shown that the hybrid composites exhibited appreciable properties at a reduced cost. In another work, Keskisaari et al. [63] investigated the mechanical properties of thermoplastic composites developed from recycled high-density polyethylene (HDPE) and varieties of fillers. Composites developed with primary sludge as filler showed excellent mechanical properties. Benoit [64] in his investigation mechanically reinforced rHDPE

with 15wt.% flax fibers. The mechanical analysis shows that flax fiber is a good reinforcement alongside recycled matrix and concluded that a higher percentage of the mechanical properties was retained in the composite after recycling when compared with the virgin matrix used in the fabrication of the composites. Martikka and Kärki [65] reported that the addition of suitable compatibilizers to mechanically recycled plastic provides an economically viable means of recycling mixed waste plastics to be used for manufacturing wood mixed polymer composites. About 50% improvement in the mechanical properties and moisture resistance of the composite was reported, which was attributed to the presence of compatibilizers in the wood-mixed waste plastic composites. Hirayama et al. [66] uses chopped carbon fibers of 4.5 mm and 3.0 mm length recovered from aerospace waste materials to fabricate polypropylene-based composites. The recycled carbon fibers can reinforce the composite despite the complex phase structure and low reduced adhesion relationship that exist between the carbon fibers and polypropylene matrix. The European Research Centers on Mathematics (ERCOM) located in Germany and Phoenix Fiberglass in Canada are examples of industrial-scale development of mechanical recycling. Their technology helps to recycle automobile waste by shredding, milling, and classification, even down to powdery products used in the production of new sheet materials. However, the two companies have stopped operating due to economic reasons. Alternatively, the European Composites Recycling Services (ECRC) was founded in 2003 to follow the European Union policies on end-of-life vehicles. The ECRC adopts a cost-effective closed-circuit technology to achieve shredding and grinding [67]. Tuner et al. [68] use a novel recycling method developed by the University of Sheffield and Qatar University called polymer reformative engineering in recycling plastic waste. The process can handle a large quantity of industrial and domestic waste, and reform them into structural components for various engineering applications such as railway sleepers, noise barriers, flood defense, communication, and utility poles. The recycled composite is passed through a novel high-speed filtering operation, which makes it a faster and more efficient process than conventional methods. Furthermore, the composites developed via this route are reported to have good mechanical and thermal properties. The composites can be potentially used as a replacement for concrete, tropical hardwood, or treated softwood in some applications. However, a very promising recycling process for thermoset composites was designed by Pickering in his studies in which a combination of mechanical and thermal techniques were used, whereby the reduction of scrap size used to produce recyclate was achieved by mechanical means. Meanwhile, the thermal processing route was used to achieved disintegration of scraps into fibers and recovers the energy. The thermal recycling technique involves the application of heat to decompose composite wastes into different products such as solid, liquid, and gas. The various techniques of thermal recycling are combustion, fluidized bed combustion, and pyrolysis. These methods recover fibers, fillers, and inserts but no recovery of monomers that can be re-used as a matrix because thermal recycling is carried out at a temperature around 450 °C–750 °C depending on the types of material and resin at these temperatures, which volatilize into lower molecules of gases such as carbon dioxide (CO₂), hydrogen (H₂), and methane (CH₄) [63,67]. A good merit of the thermal recycling technique is the ability to generate energy from the liquid and gas product during the process [69]. Combustion and incineration do not bring about recovery of materials. That is why it is not referred to as a recycling technique. It involves the burning of scraps to produce an energy source that can be converted into other forms of energy such as mechanical and electrical energy. Polymer composites reinforced with glass fibers can be used as recovery materials and be converted into energy in cement kilns, especially those inorganic short fibers whose recovery from the resin composites seems difficult. About 10% of the fuel used in a cement kiln can be replaced with GCFR, which has immensely reduced the production cost of cement. However, the quality of the cement produced is affected by the presence of boron E-glass fibers. Notwithstanding, based on reports from the European Recycling Service Company (ERSC) and the European Composites Industry Association (ECIA), the composites industries in Europe still recommend the cement kiln route to be the eco-friendliest means of managing glass fibers reinforced thermoset wastes even though the process is less economically viable in comparison to landfill processes [18,67]. Pyrolysis is carried out either in the presence or absence of air, and the latest trend involves the presence of steam. The products of the decomposition of the matrix are oil, gases, and solids, which are used as filler, fibers, and char. It entails degradation and conversion into oils, gases, and a solid portion, which can be used as reinforcement to fabricate composites. Post-treatment is required to purify the fibers contaminated with char. For glass fiber-reinforced polymers, special attention must be given to control temperature and residence duration in pyrolysis to ensure full decomposition and pollutant-free recovered fibers. The technique can be used for the recycling of both GFRPs and CFRPs because it is used for the development of recycled GFRPs on an industrial scale. However, studies have confirmed that deterioration up to about 50% of the mechanical properties of glass fibers happen while recycling at higher temperatures. Thus, it is suggested that the minimum temperature for processing GFRPs during recycling should be set at 450 °C. Despite carbon fibers' minimal sensitivity to temperature, they are contaminated with the remains of the decomposed resin, which looks like char and inhibits the required interfacial bonding between the recycled fibers and resins. To enhance the properties, there is a need for further treatment [67,69–70]. The pyrolysis carried out between the temperatures 450 °C and 550 °C shows reasonable retained strength for carbon fibers while the glass retains no more than 50% of its mechanical properties at a reduced temperature of 400 °C. The blend and mixture of different recycled fibers from different stocks of varying properties can help to achieve good mechanical properties comparable to that of virgin fibers. This strategy is usually carried out in the industries to reduce the rate at which the properties of the recycled fiber are varied, suggesting that the properties of the pyrolysis recycled fiber is up to 90% of the virgin fibers [69]. Szpieg [71] used fluffy, short carbon fibers recycled through a pyrolysis technique from aircraft parts, and transformed

them into preforms, which are used to reinforce the recycled polypropylene matrix to produce recycled CF/PP composites. The interfacial bonding, stiffness, and strength of the composites were enhanced due to the addition of maleic anhydride polypropylene grafted to the recycled polypropylene. Shuaib *et al.* [72] reported that the microwave-assisted pyrolysis (MAP) technique offers better retention strength for carbon fibers than the fluidized bed technique. Moraes *et al.* [73] uses the MAP technique to recover laminated glass fibers and their results showed about 3 wt.% humidity, 68 wt.% weight loss, and about 76% reduction in the tensile strength of the composites developed by recycling fiberglass compared with virgin fiberglass. Witik and co-workers [74] evaluated the life cycle assessment (LCA) of both pyrolysis and incineration for end-of-life treatment of CFRPs and their results showed that pyrolysis is a very efficient recycling method for carbon fibers when environmental impact is more important than energy recovery. Abdou *et al.* [75] recycled polymer composites obtained from industrial waste for carbon fiber recovery by pyrolysis, and a thorough evaluation of the effect of temperature, time, and atmosphere condition on the recovered carbon fibers was carried out. From the result, they inferred that at a temperature of 550 °C for a duration of 1 h, it was possible to obtain free carbon fibers from the polymer matrix, and the fibers recovered are free of pores, material fracture, and carbonization. The results showed that pyrolysis with sample communication can be applied in the disposal of polymer composite. Nevertheless, pyrolysis is an established process for the recovery of useful products from GFRPs scraps. It is also known as the basic optimized process that uses a hydraulic guard to ensure safety processes and energy-saving via the recovery of useful products like clean and reusable fibers, oil fractions with minimal sulphur, halogen, and heavy metals. The oil fraction can be directly used as fuel without further purification or inclusion of other raw materials [76]. Wu *et al.* [70] demonstrated catalytic pyrolysis in molten Zinc chloride ($ZnCl_2$) via the recovery of carbon fibers from epoxy composite wastes. The enhanced recovery process with full de-polymerization of the epoxy matrix at a temperature of 360°C in 1 h 20 min under standard temperature was reported due to the complete solubility effect of the molten $ZnCl_2$ on the epoxy matrix. The catalytic fracture of the C-N bonds is by the Zn^{2+} ion. Reclaimed carbon fibers from the catalytic process with destroyable graphitization structure have surfaces almost the same as virgin fibers with a tensile strength greater than that of the processed fiber in atmospheric conditions. Property retention of about 95% in comparison with new fibers occurs, as well as a reasonable reinforcing effect on the flexural property and inter-laminar strength of epoxy composites reinforced with carbon fibers, whose performance can be likened to that of the composites reinforced with T700 carbon fibers. Studies have shown that microwave thermolysis is a fast and efficient process for the recovery of clean carbon fibers and also saves energy better than conventional thermal recycling processes [77]. Adherent Technologies, Inc.'s (USA) optimization of the pyrolysis process has led to the development of a catalytic pyrolysis process operated at a reduced temperature of 200 °C to recover clean fibers with tensile strength ranging from 83% to 99% of that of virgin fibers [78]. The fluidized bed recycling (FBR) process has been studied and used for recovering high-grade glass and carbon fibers from wastes glass and carbon-reinforced composites. Compared to other common techniques, the FBR process shows a moderately high rate of recovery of filler and resin materials. It involves the use of a bed made of silica sand, operated at a temperature of 450°C–500°C. The bed is fluidized with oxidants made of hot air to ensure fast heating of the materials and the recovery of the fibers from the resin. Due to the volatility of the organic part of the scrap composite by the action of the hot air, they are transferred with silica particles in the air streams, followed by separation using appropriate classifying and recovery media. However, the recovery of energy from the organic portion of the resin can be achieved by further combustion at a temperature of 1000 °C to produce a pure flue gas [18,59]. Several methods of the fluidized bed combustion process have been developed. The University of Nottingham developed the fluidized bed combustion technique to remove resin from the waste composite to be used as a source of energy to recover glass and carbon fibers to be used as reinforcement in the fabrication of new composites. Meanwhile, the University of Hamburg has utilized the process to recycle fibers to be used as reinforcement for the manufacture of composite and recovery of secondary fuel [58]. The FBR process is of great interest today because of its capability to process and recycle mixture and contaminants. It is also recommended as the best processing method for end-of-life waste polymer composites. Nevertheless, some of the shortcomings of this method are that the process causes more degradation to carbon fibers and has gases as the only by-product from the resin part, whereas pyrolysis offers less degradation, and still gives room for the recovery of other valuable products containing oil [67,69]. Pender and Yang [79] experimented on the influence of metal catalysts (CuO) nano-powders on fluidized bed recycling of epoxy composite reinforced with glass fiber. The integration of CuO nano-powders as a catalyst for the process helps to reduce the recycling temperature of the composites and increases the rate of de-polymerization of the epoxy. About 59% of glass fibers were recovered at a reduced temperature of 400 °C. The mechanical analysis showed no adverse effect on the CuO nano-powders. The chemical recycling technique involves selective chemical dissolution of composite waste in chemical solutions of solvents such as acid, bases, alcohol, and washing liquids. The chemical solvents depolymerize the matrix to recover clean fibers and fillers, which are further used as material for various purposes. Mechanical treatment such as grinding/disintegration of composite waste is first carried out to increase the surface area between the solid waste and chemical solution, as this helps to increase the rate of diffusion and dissolution. The dissolution process is classified as solvolysis and hydrolysis based on the solvent used. For instance, water is used in hydrolysis while the organic solvent is used in solvolysis [18,67]. On the other hand, hydrolysis is a chemical recycling process in which chemical depolymerization of the composite is achieved by dissolving the solid composite in water. Whereas solvolysis involves the degradation of organic components of the composite via a chemical reaction between the ester linkages and solvent at the

prevailing concentration and time, taking into consideration the process parameters that influence the rate of the process such as temperature, rate of agitation, pressure, and catalyst [18]. Chemical recycling techniques produce uniform, long fibers, with surfaces free of resin and good mechanical proportion retention compared to other techniques because the process is not rapid and has been used in the recycling of carbon fibers. However, recovery of fibers with high mechanical properties and low environmental impact can be achieved by optimizing the use of supercritical fluids [18,61]. For instance, solvolysis and glycolysis can depolymerize epoxy resins into their monomers for use as chemical feedstock [67]. Water seems to be the most commonly used solvent because it is neat and environmentally friendly, and can be used with other solvents like alcoholic, amine, phenolic, and less-acidic catalysts [68,80]. Knight [80] uses sub-critical and supercritical water to recycle woven CFRP on a scale that is 30% higher than the already reported scale. The experiment shows that up to 99% of highly cross-linked resins are separated from an aerospace-grade composite system with the recovery of single-filament woven fibers with 100% retention of tensile strength and modulus, which are later used in the manufacture of reclaimed fiber composites with up to 95% and 98% retention of flexural strength and flexural modulus, respectively. Shibata and Nakagawa [81] use a benzyl alcohol solvent with tri-potassium phosphate as a catalyst to dissolve epoxy resin from a used tennis racket in the recovery of carbon fiber. The composite waste was held in the solution for 10 min at a temperature of 200 °C. The recycled carbon fiber-reinforced polymer developed from recovered carbon fiber has mechanical attributes that relate to that made with virgin carbon-fiber non-woven fabric. In addition, the developed composite shows that the degraded epoxy, when solidified, can be used as recycled epoxy. Jiang et al. [82] studied the use of supercritical propanol in the recycling of a carbon fiber/epoxy resin composite. The process was carried out in a reactor for 10 min, at 300° and 50 bars, and the recycled carbon fiber shows comparable mechanical properties with fresh carbon fibers, despite a noticeable reduction in the interfacial bonding with epoxy resin due to the reduction in surface oxygen. Liu et al. [83] developed a mild chemical process of recycling aerospace fiber/epoxy composite waste. Despite the difficulty in the use of a chemical method to recycle the CFRP with a high glass transition temperature of above 200°C, the research group use ZnCl₂/ethanol catalyst in the process. The efficient degradation of the chemical bonds of the polymer was reported to be the result of the good coordinating effect of ZnCl₂, which has C-N bonds and the swelling capability of ethanol to yield clean fibers and depolymerized polymers.

Table – 5 Control measure for polymer-based materials disposal

Expectation from RESEARCHERS:	(i) To carry out recycling of waste products (ii) To develop alternative sources of plastic materials
Expectation from CONSUMERS	(i) Stop indiscriminate dumping of polymer waste products (ii) Do not leave everything for the Government or others.
Expectation from the GOVERNMENT:	Government should be committed to good environment and take action on policies that can ensure clean environments.
Expectation from INDIVIDUAL:	We should show commitment to whichever of the abovementioned classes/categories as it relate to us.

Future Benefits of controlled Disposal Systems

- The waste serves as raw materials for new ones.
- Job and wealth creation opportunity.
- Socio-economic activities will increase, and many people will want to stay in a well-organized environment/place.

PAST, CURRENT, AND FUTURE POTENTIALS OF POLYMER AND POLYMER-BASED COMPOSITES

Modernization has led to the discovery of new materials that are useful for mankind. History has told us about the different ages (stone, bronze, iron, etc.), with each of these ages depicting the kind of materials use by human at that time. Although, biological polymers such as Deoxyribonucleic Acid (DNA) and proteins have been in existence from inception. The absence of detailed knowledge about how synthetic polymers are developed and the existence of long-chain molecules limit their adoption. The birth of the polymer occurred over 100 years ago. The generic idea about polymers or macromolecules started replacing pre-existing theories that infer that macromolecules were formed from aggregates of small molecules. Along this line, it recorded an increase in the development of numerous synthetic fibers, plastics, and elastomers, as did, the formulation of techniques for manufacturing high molecular weight polymers from

monomers [84]. Ever since then, polymers have remained the material of much interest to date. Their unique properties contributed to this as they have found numerous applications ranging from domestic use such as piping, food packaging, and waste bags, to high-tech application like aerospace parts, military, computers, medicals, and information technology [3]. The USA's exordium of sweeping reforms of composite development technologies in the 1950s formally marks the start of the development of polymer-based composite, of which 1955 – 1963 and 1964 – 1973 were tagged as the foundation and sustaining periods, respectively. During this time, there was an increase in the cost of oil from 1974 to 1983. This transition period was a decade in which a reduction in the growth of PMCs was experienced due to expensive raw material, reduction in the cost of fuel, and competitions from other materials companies. These are the reasons that the PMCs industries delved into new application of products and versatility of the applications of PMCs to enhance the industrial economic viability. Between 1984 and 1993, various studies ascertained the usability of PMCs in global industries on the basis of safety, durability, and service integrity in combination with improvement in the manufacturing technologies [85]. In present day, the world has witnessed a lot of research on polymers and polymer-based composites. Some of the recent advancements in the PMCs field include but are not limited to the design of cost-efficient fabrication techniques, development of ecological and bio-composites from a blend of natural and synthetic polymers, and hybridization of two or more reinforcements in one matrix to manufacture hybrid composites with improved functional and structural performances in various high tech applications [86]. Advancement in nanocomposites to improve mechanical, optical, nonlinear optical, photochemical, and electrical properties of polymer-based composites, development of multifunctional, smart, and intelligent materials, use of polymer-based composites in powder-based additive manufacturing processes, and products of all these advances have found application in different fields such as medical, petroleum, automotive, aerospace, military, sports, energy generation and storage, construction, etc. [6,7,13,87–92]. With the emergence of various developments in diverse fields, the future trends of polymers and polymer composite industries revolve around the development of multiphase polymer blends, organic and inorganic hybrid composites, and the design of more novel production techniques and models to study the effect of residual stresses on resins. Advanced research will continue on the development of intelligent materials, how the present challenges of polymeric materials overcome the fabrication of polymers of high molecular weight without chain entanglement, excellent ductility, appreciable glass transition temperature, good impact strength, reasonable modulus, excellent optical clarity, and electrical conductivity. It is projected that an upgrade in the existing polymeric composite will lead to the fabrication of composites with effective damping capacities and lightweight properties [93]. With the increasing interest in the development of secondary materials rather than creating new ones, recycling of polymer/polymer-based composites has become pertinent. Availability of these wastes as raw materials globally will aid the widespread development of its secondary materials [94]. Hence, it is expected that from macro- to nano-levels, more research efforts should be tailored towards improving the properties of both virgin and recycled polymers and polymer-based composites.

CONCLUSIONS

This review paper discussed the properties, fabrication methods, modernized applications, and disposal of polymers and polymer composites. Polymers have a combination of unique properties such as lightweight, low cost, recyclability, and ease of fabrication that have boosted their relevance in all aspects of modern life. These inherent properties have made polymers the most preferred in all areas of applications. Hence, there is a global rise in demand for polymer products because they can act as substitutes for metallic materials in numerous applications. Interestingly, the global demand for polymers and their composites is expected to reach approximately 600 million tons in the next two decades. Further advancement in polymeric materials such as fiber-reinforced composites, nanocomposites, and bio-composites is inevitable. Polymer-based composites are promising to meet the current and future demands of the industries where performance, sustainability, and eco-friendliness are key requirements. However, the challenges faced by the industries are the difficulties associated with their disposal. Most especially, the serious threat they pose to lives and the environment. Studies have shown that polymer recycling is an effective means of solving any environmental problem associated with polymer disposals after use. In essence, polymer and polymer-based composites will continue to be relevant, considering the continuous worldwide thirst for economically viable, sustainable, and eco-friendly materials with unprecedented properties for high-tech applications. Given the foregoing, the current developments in the areas where polymers are being used, the future trend of polymeric composites will involve the fabrication of multiphase polymer blends, organic and inorganic hybrid composites, the design of novel and rational production techniques like additive manufacturing, and the development of models to evaluate the influence of residual stresses on resins, and much more research is expected on their usage as intelligent materials as well.

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