Review Article

A Review on the Philosophies for the Advancement of Polymer-based Composites: Past, Present and Future Perspective

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Abstract

Research has been consider as a tool for recycling existing scientific ideas to promote improved concepts for the development of new materials. All technological innovations have links with the ancient philosophies that are being adapted progressively. Given this, composite material development remains one of the most excellent methods to influence the environment to meet human needs. Various studies have shown that polymer-based composites have emerged as the leading group of composites that are fast displacing all other materials in several applications due to their inherent properties. Polymer-based composites can be entirely synthetic, completely natural, or a mixture of synthetic and natural-based. However, a recent desire for eco-friendly materials has shifted attention from complete synthetic-based materials to natural fibers, whether in a partial or a total replacement. Thus, this review provides an overview of research trends from synthetic to natural based polymer composites. The article also highlights the different intrinsic classifications of composites, their developments, areas of applications, and their projections into the future in line with considerations for environment and applications.

Keywords: Artificial composites, Technological advancement, Fundamental materials, Processing technology, Natural composites

1 Introduction

Composite materials belong to one of the classes of primary materials in both natural and synthetic/artificial forms. It is a class of materials with unique properties compared to other fundamental materials. Most naturally occurring engineering materials from plants and animals are composites with distinct properties. This class of materials has been researched with several products emanating across the globe as artificial composite materials to meet human needs. Among the matrix materials being used, polymer-based composites have been preferred above others like metals and ceramics. Its acceptance has been based on its numerous advantages such as lightweight, ease of processing, and high corrosion resistance, among others [1]. Therefore, the trends in its development need to be considered. Characteristics of polymer-based composites include high strength, less difficult manufacturing processes, and low cost. Their reinforcing materials can be in the form of fibers, particles, or specialized shapes existing as natural or synthetic materials. Kevlar, glass, and aramid are the commonly used synthetic fibers as reinforcements while particulate fillers commonly used include

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calcium carbonate, talc, and silica [2], [3]. Also, some common unique shapes include flakes, honeycomb, and nanoparticles.

Several polymer-based composites with synthetic reinforcements have been developed and used in different industries where advanced materials are needed for applications in industries like aerospace, electronics, construction and automobile. However, in more recent decades, the growing environmental concerns and the declining availability of petroleum-derived reinforcements have necessitated a shift from synthetic to natural reinforcements (fibers/particulates). Natural fibers have high specific modulus, they are lightweight with low-cost and, are biodegradable [4], [5]. In this way, these preferences make them profoundly acceptable strengthening materials in polymer composites. And, as materials from natural resources, they are green materials. The inclusion of these fibers in polymer-based composites makes them suitable bio-composite materials. Natural/bio-fibers like sisal, jute, kenaf, sugarcane bagasse, bamboo, wool, bone, feather, among others [5]–[7], are bio-fibers being used for the development of artificial bio-composites. These reinforcements are natural composites with two or more constituents forming them. Hence, they can be termed bio-composites, and besides, they are biodegradable. Thus, they are suitable materials for the development of green composites where biodegradation and impact on environment is crucial. The philosophies beyond artificial bio-composites development was that, they are formulated to have a superior combination of properties like high fracture toughness, specific strength, and modulus than natural bio-composites from plants and animals. In recent decades, the use of synthetic reinforcements in polymer-based composites has enabled the development of many advanced materials needed for different applications. Although these materials have led to significant scientific and technological advancements, including industrial growth, however, it has also contributed immensely to environmental degradation [8]. Some of these environmental degradations are witnessed in the deterioration of soil fertility caused by non-biodegradable plastics disposed off on land, open burning of plastics, and contamination of water bodies and aquatic life. Therefore, in addressing these environmental challenges as a matter of urgency, researchers worldwide are now focusing their research on eco-friendly materials. This new focus has led to the promotion of Green-Science and Green-Technology covering every areas of human activities including materials development. Recently, numerous efforts have been channeled towards substituting synthetic fibers with natural fibers in composite development due to increasing environmental regulations and the depletion of oil-based resources [9]. Green composite materials are developed from bio-based materials that are completely biodegradable and renewable. These composites promote the development of a sustainable and green environment as the matrices and reinforcements are made from biodegradable and renewable sources which do not cause damage to the environment. These materials can also be recycled at the end of their service life. Examples of biodegradable polymers include chitosan, pullulan, gelatin, cellulose, natural rubber, chitin, starch, levan and bioepoxies [10]–[12]. Unlike other composites, green composites attract enormous commercial benefits as their production processes require little energy consumption in terms of heat and pressure consumption and at the same time can reduce CO_2 emissions [13]. This makes it possible for them to be manufactured with little cost of production [14].

Several bio-fiber/particle reinforced composites exist in different areas of applications. The sources of these reinforcements are mostly obtained from plants, animals and microbes. Currently, cellulose fibers are majorly used as substitutes for synthetic fibers due to their ‘green’ image. Cellulose fibers are renewable and can be incinerated after use without causing air pollution. Interestingly too, the amount of CO_2 released during the incineration process is very minute when compared to the amount that the plant takes up throughout its lifetime [10], [11]. Polysaccharides can be utilized in many applications such as packaging, automobile, textiles, aerospace, electronics, biomedical, and many others. Most of these bio-fibers are readily available, biodegradable with low density, and have encouraged many researchers to adopt their potentials for many industrial applications. In the development of biocomposites, cellulose fibers have proven to be one of the most promising materials to be used as reinforcement. Nevertheless, improvements need to be done to the interfacial bonding between the matrices and cellulose fibers. Since the matrix-reinforcement interfacial interaction is the most important factor in achieving mechanically viable composites, quality interface interaction must be ensured. The extent of adhesion between the participating materials largely depends on their chemical structure and polarity. The presence of hydroxyl group in cellulose fibers makes them have high moisture absorption property leading to poor organic wettability with the matrix. This property then becomes responsible for the weak interfacial bond that exists between the reinforcement and the matrix. To prevent this defect in composite materials, it is important to increase the hydrophobicity of the reinforcing agent and improve the compatibility between the cellulose fibers and the matrices. Several pre-treatments are carried out on cellulose fibers to modify the interphase and the morphological changes in fibers. Researchers are employing various green techniques such as plasma treatment and treatments using bacteria, fungi, and enzymes to improve the compatibility between hydrophobic polymer matrices and hydrophilic natural fibers. Cellulose fibers are being used as an eco-friendly alternative reinforcement to glass fibers for thermoplastic and thermosetting-based composites. The research into bioplastics allows the development of plastic materials that can easily be degraded or bio-assimilated at the end of their life cycle which are crucial for promoting a cleaner and safer environment [8]. The degradation of biocomposites could occur by either microbial degradation or photodegradation. Microbial degradation is essential in the depolymerization of biopolymers, giving off water and carbon dioxide as the final products. In photodegradation, the degradation processes of biofilms are beneficial to plants since the biofilms serve as their mulching sheets and organic fertilizer in the soil.

Environmental awareness has contributed immensely to the shift from artificial reinforcements to natural ones in composite development. The demand for biodegradable materials from automobile, building, and electronics industries with proper environmental impact assessment from sustainable materials are responsible for this trend [12], [13].

Composite materials remain the most prominent and sensitive materials in this era. At present, more composites from bio-fiber materials are in high demand due to the desire for lightweight and eco-friendly materials [15]. Several researches have proven that composite materials are essential for human advancement as it cuts across every human endeavor: health, biomedical, transportation, automobile, marine, aerospace, construction, building, road, and bridges; electronics, boards, chips, and packaging [10], [16]. Therefore, there is the need for researchers to focus more attention on improving existing technologies for the development of polymer composites with enhanced properties that will meet the dynamic demands. One of the fastest-growing research areas is in the development of polymer nanocomposites with much focus on controlling the nanoscale structures via innovative synthetic approaches. The properties of polymer nanocomposites depend on their constituents' properties, their morphologies as well as their interfacial characteristics. The unique properties of polymer nanocomposites are now making the development of new materials with novel properties possible. Unlike macro composite materials, nanocomposite materials lead to new and improved properties in the materials, hence, they are now the first choice materials for applications in various industries such as for components with a high strength-to-weight ratio in aerospace and automobile industries and corrosion-resistant materials in the marine industry. By increasing the global contributions of research findings on the production of polymer nanocomposites, a new world of intriguing properties in polymer composites can be unlocked for numerous advanced applications in several industries. Thus, this review article highlights the need for green composites, the influence of classifications, constituents, modifications and method of production on the properties and performance of polymer composites. The article stimulate researchers interest for future material demand and possible ways to meet them.

2 Synthetic Fibers Reinforced Polymer

Synthetic fibers are also regarded as man-made or artificial fibers because they are produced by chemical synthesis. They can be classified as either organic or inorganic-based synthetic fibers depending on their composition [17]. Fibers generally serve as the load-bearing components in composite materials because of their higher strength and stiffness properties when compared to the matrix material [18]–[20]. For glass fiber which is the most widely used synthetic fiber, they possess excellent strength, high durability, high thermal stability, high impact, wear, friction and chemical resistance.

Irrespective of these advantages, there are still challenges that arise from using glass fiber-reinforced polymer composites (GFRPs). The machining of GFRPs is slow and causes reduced tool life when using conventional machining systems. There is also the problem of disposal at the end of the service life [21]. These limitations give room for researchers to explore the potentials of other synthetic fibers like carbon, basalt, aramid, polypropylene (PP-F), polyacrylonitrile (PAN-F), and polyethylene terephthalate (PET-F) to be used for specific applications where their desired properties are needed [22]. Carbon fiber-reinforced polymer composites (CFRP) are used to replace GFRP in applications where very high stiffness is required and serve different application requirements in various industries such as automobile, sports, aerospace, and civil industries [17], [23], [24]. When the weight percentage of carbon fibers increased from 10% to 30%, there was a significant increase in the Young modulus of solids and foams by 78% and 113%, respectively, and when carbon fiber/polypropylene (CF/PP) reinforcement was used to make composite foams prepared by microcellular injection molding, the improvement in the cellular structure led to increase in the foams Young modulus by 35% [25]. Graphene fiber is a new class of high-performance carbonaceous fiber that possesses high tensile strength and improved electrical conductivity when compared to carbon fibers. Graphene fibers possess enormous potential in knittable supercapacitors, actuators, lightweight conductive cables and wires, solar cell textiles, and micromotors applications [21], [22]. The molecular dynamics simulation of polymer composites with graphene reinforcements showed increases in Young's modulus, shear modulus, and hardness by 150%, 27.6%, and 35%, respectively with a 35% and 48% reduction in the friction and abrasion rate coefficient [26].

Basalt fibers on the other hand are both cheaper than carbon fibers and have improved mechanical and physical properties to that of glass fibers. Pascal *et al.*, [27] studied the effect of temperature on basalt fiber-reinforced polymer composites (BFRP). They discovered that a decrease in temperature of BFRPs increased their static strength and their fatigue life at specific maximum stress [27]. Kevlar fiber-reinforced composites (KFRCs) undergo enhanced thermal properties on hybridization with either carbon or glass fibers. However, there is less research on the hybridization of Kevlar fibers (KFs) with natural fibers. KFRCs are anisotropic which makes them have low compression strength but they are considered to possess high impact strength with a high degree of tensile properties [28]. Typical synthetic fibers been used as reinforcements, their common attributes and uses are presented in Table 1 while Table 2 highlights the strengths of common examples.

Table 1: Types of synthetic fibers, characteristics and areas of application [29]–[31]

Synthetic Fibers	Characteristics	Applications
Nylon	It is a polyamide which is made from petroleum It is highly lustrous and elastic It is stain resistant, durable and has lightweight Does not absorb moisture	Used for non-absorbable sutures Used for vehicle seatbelts For making filter cloths, sleeping bags, sieves, parachutes
Rayon	It is absorbent and comfortable It is soft and dries easily	Used for preparing viscose-rayon absorbent wool and surgical dressing Used for making fabrics
Polyester	Contains an ester group in the main chain Possesses high strength and resistance to shrinkage It is soft and very durable It is inelastic	Used for making industrial ropes and pet bottles Used for making floor coverings, upholstery and clothing
Acrylic	Possesses lightweight It is flexible and soft Resistant to chemicals and stain	Used for making home furnishings Used for making fabrics

Table 2: Common examples of synthetic fibers and their strengths [32]

Synthetic Fibers	Young's Modulus	Strength-to-Weight	Fiber Strength	Laminate Strength
E-glass	30–40	564	3450	1500
Carbon fiber	125–181	1013	4127	1600
Kevlar	70.5–112.4	993	2757	1430
Epoxy	3	28	-	12–40

Despite the desirable properties obtainable from synthetic-based polymer materials, major problems associated with synthetic polymers and their composites persist. These problems include but not limited to limited and depleting petrochemical resources, continued carbon footprint from their usage, non-biodegradable and recycling challenges, creation of huge plastic wastes, cost-intensive and high consumption of energy required for their fabrication processes since a lot of pressure and heat is usually needed [33]. These challenges make it difficult for researchers to consider them viable and sustainable alternatives that can leave the environment in a safer condition. Hence, the need for the development of green composites materials for applications across various industries.

3 Advanced Classifications of Composites

Awareness of possible classifications for composite development is essentials for the possibility of solving existing and future material challenges for diverse applications. Polymer composite researches are usually formulated based on the available class of starting materials and, this usually serves as a guide for the research focus. Material classification is knowledge-based, and it varies with time. At the inception, composite material classification was basically on matrices and reinforcements. However, due to technological advancement, new possible classifications have begun to emerge. Some of these classifications are not well pronounced but are adopted. Hence, the advancement in polymer-based composites can be classified based on;

1) Constituents (matrix and reinforcement)
2) Mode of reinforcements (single and hybrid)
3) Constituents surface morphology (modified and unmodified)
4) Origin (natural, synthetic, and semi-synthetic)

Each of these general classifications can further be sub-divided into a more enlarged category. Polymer-based composite classifications have helped in recognizing some essential properties expected of composites materials in their group. However, in spite of this, all the problems associated with meeting material needs have not been met. Hence, there is a need to advance this area of materials development with more novel materials formulations and production processes. This can only be achieved by a proper understanding of the parameters to transform and, thus, more classifications.

Two or more of the classifications usually exist in any developed polymer composites; however, to adopt any of them, the researchers' interests are paramount.

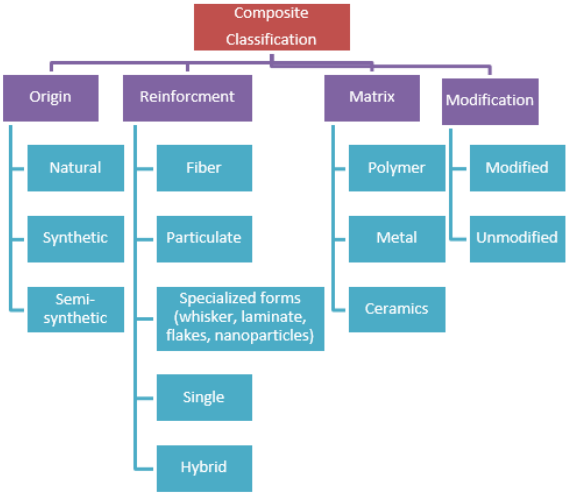

Figure 1: Advanced classifications of composites.

The most outstanding classification based on interest is often used while other possible classifications are less voiced. Hence, more attention needs to be given to the class of starting raw materials being used for the development of any composites. It should be noted that, the advancement in classification of polymer-based composites will aid expansion and improvement in the development of novel materials needed for various applications now and in the future. Figure 1 showed the expanded composite classification.

3.1 *Classification based on constituents*

This is the most basic form of classification that applies to polymer composites and all composites in general. The basis for the formation of any composite in the first place is the blending of two or more constituents together to form a single material that has distinct and improved properties when compared to the properties of the individual constituents that make up the composite material. Therefore, the first classification of polymer composites is based on matrix and reinforcement, as no composite can be formed without both constituents' presence.

3.1.1 Matrix

In any composite, the matrix is the main constituent and, by nature, the more abundant material existing in the composite material. Simultaneously, the reinforcement

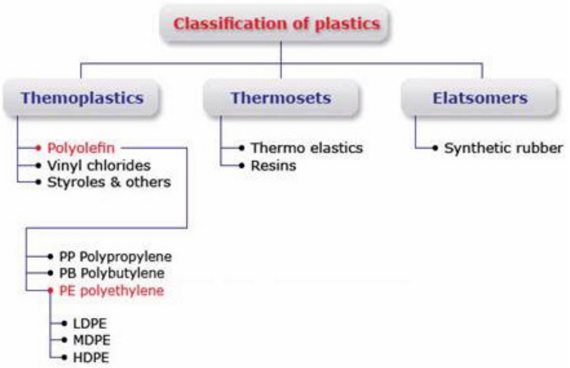

Figure 2: Classifications of plastics [34].

can be said to be the supporting phase existing in the composite. Both the matrix and the reinforcement play crucial roles in the composite material that enable the material to possess the desired properties. The functions of the matrix in the composite are to hold the reinforcement phase in place, provide protection to the reinforcement against mechanical damage and chemical attacks, distribute and transfer stress to the reinforcement under applied loads, and provide rigidity and shape to the material [35]. For polymer-based composites, the main matrixes are;

1) Thermosetting
2) Thermoplastics
3) Elastomer hermosetting

At the inception, thermosetting plastics were reinforced until recently, where thermoplastics and elastomers were also given more attention. Thermosets possess a three-dimensional molecular structure that is usually formed after curing. They include high flexibility and strength and do not melt at elevated temperatures. They are suitable for polymeric material applications that require elevated temperature and chemical resistance. Thermoplastics possess one-dimensional or two-dimensional molecular structures and melt at elevated temperatures, making their original properties recoverable on cooling. They are suitable for applications that require high damage tolerance and recyclability [25], [36]. Elastomers are one of the early-discovered and largely used materials for different applications. Elastomers are a class of polymers that exhibit extraordinary reversible extension 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. The classification of the matrix based on these polymeric materials is as shown in Figure 2 while Figure 3 showed some typical products to depict their areas of applications.

Figure 3: Typical applications of plastics [34].

3.1.2 Reinforcement

Reinforcement provides support to the system by serving as the load-bearing phase of the material. The reinforcements help significantly to improve the material's overall properties [37]. This combination makes it possible to develop tailor-made materials that are required for specific applications in various industries. The classification of reinforcement concerns the shape of the materials. Thus, they can be;

1) Fibers
2) Particulates
3) Special forms (whiskers, flakes, laminates, and nanomaterials
4) Mode of reinforcements (single and hybrid)

To successfully develop a polymer composite with the desired properties needed for a specific application, it is important to determine the exact combination of matrix and reinforcement that will deliver the intended properties. The inherent properties of the individual constituents influence the composite's properties, making it different for various designed materials. For this reason, researchers need to understand the properties of individual constitutes that will make up the polymer composite.

3.1.3 Classification based on origin

Any polymer matrix composite's origin or source can be attributed to either of three different sources: natural, synthetic, or semi-synthetic polymers. The formation of any composite is derived from any of the above sources. Just as the name implies, natural polymers are gotten from natural sources of animals, plants, or other living species [38]. Examples include bones, wood, cellulose, lignin, protein, chitosan, alginate, and starch. Natural polymers are characterized by a large variety of complex structures and various physiological functions. Due to their outstanding properties, natural polymers have a dominant and wide range of applications in the biomedical and pharmaceutical industries as they contain bio-functional molecules that ensure biomimicry and bioactivity [26], [27]. Other properties include lightweight, low cost, availability, and design flexibility, making them suitable for automobile, aerospace, and military applications. However, they possess lesser mechanical strength when compared with synthetic polymers. This is why the formation of semi-synthetic polymers which is the combination of natural and synthetic constituents is employed to design materials of desired mechanical and environmental properties for diverse applications. Synthetic polymers are a group of polymers synthesized in the laboratory by the polymerization of simple chemical molecules. Examples are polyethylene, nylon, synthetic rubber, and polyvinyl chloride [38]. Synthetic polymers possess higher mechanical strength and can be produced in large uniform quantities. Their degradation rate, mechanical properties, and porosity can be tuned to meet specific requirements. The apprehension associated with synthetic fibers is the increasing demands for environmentally friendly materials with drastically reduced environmental impacts. Also, cost and supply of petroleum-based resources are of great concern. This has given tremendous rise to semi-synthetic polymers, which helps to meet mechanical and environmental properties requirements. They are derived from naturally occurring polymers but undergo chemical and/or physical modification or treatment. Simply put, they are produced from a combination of natural and synthetic polymers. Common examples of semi-synthetic polymers include cellulose acetate, cellulose nitrate, viscose rayon (cellophane), and vulcanized rubber [38]. In a polymer based bio-composite, either matrix or reinforcement or both can have a natural, synthetic or semi-synthetic source. Hence, when green composite is the focus, natural or semi-synthetic sources play a major role in the formulation.

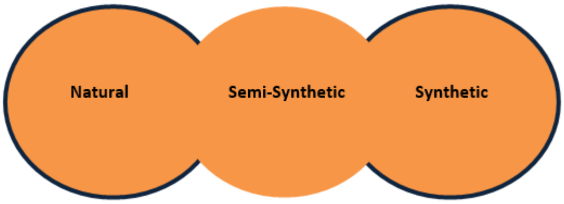

Figure 4: Classifications of composites based on origin.

Recently, researchers' interest in materials development is on the source or origin of the basic raw materials. Thus, from the modern trends in polymer composite materials development, composites can be best classified based on the origin of the raw materials selected as the constituents as; natural, synthetic, or semi-synthetic as shown in Figure 4. Due to global environmental concern and Government regulations in many developed nations in recent times, researchers have given serious attention to green composites. This development has made all other classifications to be linked with this classification. This current developments have advanced the field of polymer composites nowadays.

3.2 *Classification based on the mode of reinforcements*

There are two modes of reinforcement in polymer composites; single and hybrid reinforcements. The present trend in polymer composites development is mainly in the use of hybrid reinforcements because of their increased potential. Single reinforcement involves using only one reinforcing phase added to the polymer matrix to provide improved properties to the material. However, to meet specific requirements, particularly, in mechanical and environmental qualities, researchers now utilize the benefits of hybrid reinforcement, which is a combination of two or more reinforcing phrases that are added to the polymer matrix. For single reinforced polymer composites, the reinforcement used can be either natural or synthetic. The hybrid reinforced polymer composites offer a wider variety of reinforcing phases that can be a blend of natural base, synthetic base, or a combination of natural and synthetic bases. Hybrid reinforcements provide a significant enhancement in the thermal, damping, dynamic, tribological, mechanical, and water absorption properties of polymer composites compared to single reinforcement [39]. The reinforcing material used can be of different forms; fibers, particles, or specialized (whiskers, flakes, laminates, and nanoparticles). The philosophy of the used of hybrid reinforcement has improved the enhancement of polymer composite properties.

Particulate-reinforced polymer composites have been proven to be a less effective means of strengthening the composites. Primarily, they achieve more gains in stiffness than in strength and toughness. Consequently, the overall improvement in the composite properties is less than that achieved using fiber as the reinforcement. The primary benefit of particle reinforced polymer composites is their ease of production, forming, and low cost. They are used in application areas where high wear resistance levels are required, such as road surfaces. The addition of gravel to cement as filler material essentially helps to increase the hardness of the cement.

Fiber-reinforced polymer composites are preferred as the reinforcing material for load-bearing applications because of their higher mechanical strength. Natural and synthetic fibers are widely applied in polymer composite development. They possess lightweight, high specific strength, low density, high temperature, and corrosion resistance, among other highly desired properties [34]. Some of the advantages of natural fibers are that they are abundantly available in nature, are renewable and biodegradable, have low cost, low wear of tooling, and low density. The density of natural fibers is about 40–50% lower than that of most synthetic fibers, making it possible to reinforce polymeric materials without significantly affecting their density [34]. These advantages make them highly suitable in various industries like automobile, aerospace, marine, construction, military, biomedical, electronic, packaging, and sports industries [40]. However, the major drawbacks of natural fibers against synthetic fibers are their higher moisture absorption rate and lower mechanical strength [34].

On the other hand, synthetic fibers possess enhanced mechanical strength, which is a major requirement for any application. This is the underlying factor for their continuous use. Other benefits include high chemical resistance, low water absorption, and excellent dimensional stability. Despite these, the growing concerns of environmental friendliness and other discouraging factors of synthetic fibers such as high cost of production, availability, and non-renewable nature necessitate the production of green and cost-friendly polymer composites. Common examples of synthetic fibers are glass fiber, carbon fiber, and aramid fiber [34]. Major types of natural and synthetic fibers are shown in Figure 5 [15].

Figure 5: Examples of natural and synthetic fibers [19].

3.3 *Classification based on modification*

More recently, the treatment and modification of the reinforcements used in various polymer composites are gaining more ground. This is basically because researches show that the properties of the developed polymer composites are significantly enhanced by such modifications. The research findings of Mohan *et al.* gives a typical example [41]. They investigated the use of short banana fibers as reinforcement in an epoxy polymer matrix to prepare three types of composite cylinders using the resin impregnation method. The banana fibers used as reinforcement for the first composite cylinder were untreated, for the second cylinder, the reinforcement was treated with alkaline (NaOH) while that of the third cylinder was infused with nanoclay particles. The flexural, tensile, compressive, energy absorption and interfacial characteristics were studied. The results obtained showed that the compressive yield stress, modulus, and strength of the nanoclay infused composite cylinder was 17%, ~2 times, and 43% higher than that of the untreated banana fiber composite cylinder. The energy absorption properties were also found to be about two times higher than that of the untreated composite cylinder with greatly improved load transfer and fiber-matrix interfacial characteristics due to the nanoclay particles infusion. The alkaline treated polymer composite cylinder possessed properties improvement above that of the untreated composite cylinder but below that of the nanoclay infused particles [41]. Therefore, the experiment of Mohan and his colleagues proved that the treatment and modification of polymer composites are very useful in achieving desired properties in materials for advanced applications. This makes the modification and unmodification of polymer composite a crucial form of classification especially with regards to advanced applications.

Several types of research have been conducted with modified and unmodified matrix and/or reinforcement but these researchers have not considered the classification of composites based on the various modifications being carried out on the constituents. Many comparative investigations between modified and unmodified composites materials are available in the literature with lots of promising results [1], [2], [31], [32].

4 The Dynamics Nature of Reinforcement Weight Fraction on Performances of Polymer-based Composites

The performance of composite materials in service can be enhanced by incorporating different forms of reinforcements whereby the improvement will now depend on the processing method, type of surface condition, weight fraction, and mode of dispersion of the reinforcements among many others. The flexibility of the manufacturing process for composites development has made it possible to control the structure and properties of the developed composite materials. Hence, it becomes easier to traverse between the benefits and shortcomings inherent in any constituents and the ensuing composite materials. Various researchers on composite developments have come up with varying weight fractions that gave the optimum properties for different applications. These findings were based on the complexity of the composite constituents such as particle sizes, fiber lengths, manufacturing processes, etc adopted.

In the work that was carried out by Mansor and co-workers [42] to investigate the influence of chemically modified alfa fiber on flexural properties of unsaturated polyester-based composites, the filler content was fixed at 40 wt%. This showed that 40 wt% reinforcement was the best content to give the optimum result. Araujo *et al.* [43] studied the effect of coupling agents on the thermal behavior of natural fiber high density polyethylene-based composite. The composite formulation was based on 20 wt% Kerala fiber to show that this wt% was the optimum in this design. In the work by Abdelmouleh *et al.* [44], natural rubber-based composites were developed by direct dispersion of cellulosic fibers in the natural rubber latex. It was reported that fiber loading cannot exceed 27 wt%. Punyapriya and Acharya, [45] investigate the wear behavior of bagasse fiber-based polymer composites using 20 wt% bagasse fiber. It was discovered that as the load and grit size increase, the wear rate increases. However, 20 wt% was used as the optimum weight fraction.

The use of natural fiber to reinforce natural rubber has been studied by many researchers [38], [46], [47]. The results of Binoj [48] when moringa oleifera fruit pod was examined for possible applications in polymer-based composite materials showed that the optimum content was 20 wt%. The mechanical properties of polyester composites were studied using bagasse particulate of 75 μm particle sizes. The results obtained showed that the mechanical properties of the developed composites were greatly enhanced by the bagasse fiber reinforcement. It was discovered that most of the properties were optimum when 10 wt% reinforcement was used [49]. Also, an investigation into the use of extracted submicron agro-waste-based silica particles from rice husk ash in high-density polyethylene (HDPE) based composites revealed that composites with 10 wt% SiO_2 have the best thermal degradation temperature [8].

The properties of jute-plastic composites were investigated for their suitability in the automobile industry by Al-Oqla and Sapuan [6] while Mohanty *et al.* [50] examined the influence of jute fiber on the mechanical properties of biodegradable polymer (Biopol). From the results, tensile strength was improved by 50% while flexural and impact strengths were enhanced by 30% and 90%, respectively compared to pure Biopol. The results from these authors did not specify or laid much emphasis on the weight fraction or other parameters that brought about the improvement, the interest was on the fact that enhancement was achieved. Hence, most researchers are interested in the improvement of the properties of the developed composites to meet the service requirements.

The common phenomenon here is polymer composite, however, due to the differences in materials combination and processing methods, varying weight fractions has brought about optimum properties within the same class of material. Polymer composite is a compound name that needs to be proven further for more effective application by working on the possible subset that can emerge from the multifaceted material. Therefore, going by the submissions of the various authors from literature, it has been revealed that weight fractions have no fixed value for the enhancement of the properties of reinforced polymers. Rather, a wide range of values depends on many variables considered/adopted. Many research findings on weight fraction have always been reported thus; as the reinforcement content increases, properties under investigation either increase or decrease as illustrated in Figure 6. In the development of composite materials, the inclusion of the reinforcement usually tends to increase the effect and performance of matrix properties in a bid to achieve the overall desired properties required of the composite material.

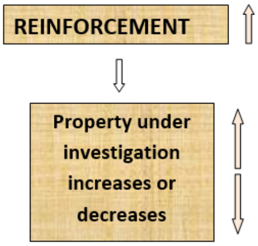

Figure 6: Correlation between reinforcements and influences on composites performance.

For this reason, researchers should be cautious in selecting the particular matrix and reinforcement materials that need to be combined to achieve the properties needed for any specific application. The underlying philosopy was that weight fraction that will yield optimum results varies in composite development and the values obtained depends on many other variables or inputed parameters.

The rule of mixture in composite development gave a range of values such as 40 : 60 or 30 : 70 for reinforcement to the matrix. But due to the level of the present advancement in composites development and the future challenges and competitions in the marketplace, a better and more concise approach is needed. Presently, this rule did not take adequate care of the emergency of nanoparticles which tend to be more effective at low weight fraction (1–5%) of the reinforcement to the matrix (99–95%). It is a necessity to begin to consider how to improve on the existing basic or conventional mode of operation in composite development. Acceptable improved template for optimum enhancement from the various reinforcements being used are necessary. More research is expect to provide close range of values for different categories of reinforcements that are available at present. Some of the drawbacks emanating from the type of matrix and reinforcement selected which has to be overcome are, the interfacial adhesion, size and shape of the reinforcement, type of surface modification carried out, manufacturing process adopted and density of the reinforcement as well as manufacturers' experience.

The advent of nanoparticles and nanomaterials is a clue to this anticipation. With nanomaterial, a small amount of reinforcement is what you need to achieve the optimum performance expected of microparticles with large filler content from the same material. The prospect from the rule of mixture for composites development was that higher volume fraction should yield better performance; however, the reverse was the case when the nanoparticle is involved. The work by Gangoiti and Peruzzo [51] presents the production of polyurethane composite foams based on modified canola oil or castor oil as the polyol and cellulose nanocrystals (CN) as the nanofiller at 0.10–0.50 wt%. The results revealed that the addition of CN affects density and mechanical properties based on selected polyol. Also, evaluation of the proliferation of cells grown on different foams revealed that the presence of CN significantly increased the cell viability for samples containing 0.25 and 0.50 wt% of CN. Similarly, the addition of nanocrystals cellulose to different polymer matrices has been studied broadly in the past and polyurethane foam was no exception. Reports from these works presented that cellulose nanocrystals incorporation affected the cell size, mechanical properties, dimensional stability, and water uptake of the foams [42]–[44].All these points to the changing trends following modern technological advancement.

5 Modification of Composite Constituents; Matrix and Reinforcement

Enhancements of composites' properties have led to the development of many approaches that include polymer and fiber modifications. Though they are commonly referred to as surface modifications buy in reality, the bulk modification does take place since the surface cannot be isolated from the inner part during treatments.

5.1 *Polymer modification*

Many of the inherent advantages of polymers such as low cost, controllable crystallinity, ease of processing, physical, chemical, and mechanical stability has made polymers to be applicable in diverse areas. However, this fundamental material has its inherent limitations, hence; current investigations have revealed that polymer structures and properties can invariable impacts their durability and functionality by modifying the surface conditions of the polymers [45], [52]. Investigations have shown that the performances of polymer-based composites are greatly influenced by the modification technique and the adopted processing variables. These various polymer surface modification methods are classified as chemical, physical, optical, and thermal methods each having its benefits and drawbacks [36].

Polymer modification is usually carried out to influence essential short and long-term properties that are desirable for their expected areas of applications. Surface treatments also expand the areas of polymer applications due to tenable bulk properties induced. The basic principles for surface treatments are achieved in a wide range of processes. These processes are put in place to control wetting, the surface energy, to improve or impair its adhesive, to ensure absorption or releasing of properties when exposed to ionic, chemical, or light-based treatment processes. These processes assist in the reconditioning of the surface energy of polymers by adding functional groups to the materials [53]. In the same vein, treatment with dry or wet abrasives can be used to achieve surface roughness through chemical or mechanical abrasion processes in which the top layer of the polymers is reformed [54]. These processes impact micro and nano-scale roughness on the surface of the polymer and allow anti-wetting and anti-fouling. Roughness and energy of the surface of the polymer can be modified in various ways like physical methods, chemical etching, and more advanced non-invasive methods like corona, laser-induced patterning, plasma treatment, and UV irradiation techniques.

Selection and modification of polymers for different applications are made easy due to the existence of an extensive spectrum of physical and chemical properties of different groups of polymer materials. For example, for applications that require good mechanical properties, tunable degradation rates, non-toxicity, low immunogenicity, and, biodegradable aliphatic polyester can be selected. This type of material is desirable in the area of tissue engineering [17]. The quest for material that can support higher melting and freezing temperatures in refrigeration and air conditioning systems with improved surface properties led to the development of shape stabilized poly(ethylenealt-maelic anhydride) composites. The polymer was blended and processed with a nano-diamond as a phase change material [23]. Polymers like cotton fiber are from vegetable fibers with lots of porosity due to countless polar hydroxyl groups present and, hence, highly hydrophilic. The adequate hydrophilicity of polymers makes them a suitable candidate for the separation of oil-water. Also, in oil and gas filtration units, they perform very well as antifouling material [55]. Surface-treated polymers are used to prevent membrane fouling infiltration and water harvesting systems [24]. Despite the relevance and benefits of high hydrophilicity in biopolymers, their shortcomings have led to the modification of their cellulose structures. These modifications are carried out using the favorable treatment for the polymer surface with fluorine-based chemical reagents. The low surface energies of the reagents allow them to generate functional surfaces. Thus, silanes treatments have been used to modify many cellulose nano-fibers to make them functionally hydrophobic.

Several advancements in biomedical applications have been achieved by treating polymers. Such materials have been applied in bioengineering based on their superior antibacterial and cytotoxic properties [56]. These materials have been deployed in places where harmonized drug release and improved biocompatibility without any change in the bulk properties of the polymer are needed [36]. They are used in reconstructive medicine where enhanced absorption, connection, and functionality of bioactive compounds to surfaces are desired. For example, designing surfaces for creating optimum designs and controlled topography in polymer, laser-induced surface modification methods were used. Likewise, The work of Heitz *et al.* showed that the modification of poly-tetrafluoroethylene using ultraviolet (UV) treatment yielded increased adhesion and better proliferation of the human vascular cells. Exposure of polymer substrates to UV treatment and nanoparticles simultaneously in vacuum was reported to improve surface adhesive properties of carbon atoms in the polymer with the nanoparticles [21].

Based on polymer surface adaptation, advancements in several attributes to improve its functionality have been made. It was discovered that no two polymer surface reform processes affect the material equally.

Table 3: Polymer surface modification methods and their influence on properties [36]

S/N	Method	Influence on Polymer Properties	Reference
1	Physical	Roughness	[22]
2	Wet chemical	Hydrophobicity, conductivity, molecular weight, and crystallinity	[17], [23], [24]
3	Corona	Surface energy, adhesion, antifouling, permeability, and sterility	[21], [22], [56]–[59]
4	Plasma	Adhesion, roughness, and surface energy	[60], [61]
5	Ultraviolet	Curing, adhesion, surface energy, light absorption, and density	[62]–[65]
6	Annealing	Crystallinity, elasticity and cross-linking	[53], [66]
7	Patterning	Structure, adhesion, hydrophilicity, hydrophobicity, photoluminescence, and density	[67]–[70]

There is always variation in either the lifetime of the induced property or its effect on the materials concerned, thus, it is important to understand this to determine the most relevant process for a specific application. Table 3 showed the major polymer modification methods and the affected properties of modified polymers [36].

5.2 *Fiber modification*

Natural fibers are characterized by their microstructural compositions; this, in turn, determines their tensile properties. The higher the cellulose content, the higher the tensile strength, and the lower the lignin content, the higher the tensile strength [15]. Fiber surface modification is essential for proper interfacial adhesion between contacting fiber and polymer surfaces in composite development. Since the two constituents represent different phases, there is a need to adapt the two phases in a way that will encourage proper bonding at the interphase.

Specifically, interphase as the name implies is the region around which the matrix and the reinforcement (fiber) meets and interacts. As they interact under load, stress transfer is from matrix to reinforcement (fiber). However, natural fibers exhibit weak interphase bonds under loading conditions due to the presence of hydroxyl groups that makes them hydrophilic in contrast to the matrix (polymers) which are hydrophobic. This has made the study of interphase behavior and microstructural constituent to be an important factor in assessing the capability of composites [71]. Hence, there have been developments of several pretreatment procedures to tackle the challenge of poor or weak interphase, therefore achieving good or strong interphase adhesion. These pretreatment procedures which include acetylation, silane coupling, preheating, and alkalization have proved effective in achieving good or strong interphase adhesion properties by revamping the fiber surface and its internal structure [72]. Modifications of fiber structure and composition are affected by the presence of functional groups in the chemicals used for pretreatments [73]. Table 4 gives the list of common natural fiber modification processes.

Other treatment protocols like maleated coupling agents [74], permanganate [75], stearic acid, triazine [76], unsaturated fatty acid, and unsaturated triglyceride esters derivatives [73] have been utilized. The major objective of surface treatment protocols for bio-fibers aside from strengthening stress transferability is to enhance interphase bonds between fiber and matrix.

Table 4: Treatment methods and their influence on constituents and composites [63]–[65]

S/N	Treatment	Functional Properties
1	Alkali	Lignin content reduction. Improvement in fiber-matrix heat resistance, thermal stability, and interfacial adhesion
2	Acetylation	Enhancement of flexural and tensile strengths
3	Plasma	Hydrophobicity improvement
4	Methacrylate	Tensile and Flexural strength Improvement
5	Mercerization	Moisture regain reduction and improvement in the mechanical properties
6	Isocyanate	Surface modification
7	Grafting	Improvement in hydrophobicity, mechanical and ultraviolet protective properties
8	Enzyme	Lignin content reduction
9	Ozone	Modification in contact angle and surface energy
10	Peroxide	Reduction in moisture regain
11	Benzoylation	Hydrophobicity improvement
12	Silane	Enhancement in hydrophobicity and mechanical properties
13	Sodium chlorite	Improvement in tensile properties

Apart from fiber treatments, other factors usually influence the composite capabilities due to the role of fiber where the following are prominent; fiber directional organization [77] toughness and vigor of the fiber [78] physical (elasticity and bending) properties of the fibers [79]. Interphase bonds strength of the fibers [80], moisture absorption [81], impurities [82] and volume fraction [83]. Thus, fiber treatment protocols are put in place to promote the positive influence of these factors as presented in Table 2.

Oladele *et al.* [84] evaluated the effect of surface treatment on mechanical and thermal properties of Bagasse fiber (BF)/calcium carbonate hybrid reinforced polypropylene composites by mercerizing it with sodium hydroxide and conclude that the mercerization enhanced the mechanical and the thermal properties. The results revealed that pretreatment protocol (mercerization) could be employed to improve the mechanical and thermal properties of composites. The research was carried out on the impact of surface treatments via alkalization on the flexural properties of bio-fibers reinforced polyester-based composites. It was discovered from the results that, there was an improvement in bending characteristics of the composites from treated fiber compared to the ones that were not treated [42]. In another study, maleic anhydride grafted polypropylene (MA-g-pp) was utilized to strengthen the interphase bonds between the matrix (polypropylene) and the reinforcement (bamboo fiber). The results showed that mechanical properties were improved alongside thermal stability [85].

Cordeiroa *et al.* studied the effects of surface modification done with alkaline on the selected properties of natural cultivated fibers (from Iran) [86]. He and his coworkers concluded that alkaline treatment eliminated some undesirable chemical components present in the facet of the fibers. These undesirable chemical components are aromatic moieties and uranic acid which are extractives and hemicellulose, respectively.

Non-wood fibers have exhibited different reactions to chemical treatments as chemical effects on them are stronger. Thus, there is an enhancement in crystallinity with minimal improvement in surface adhesion potential. Hence, alkaline treatment can improve bio-fibers wettability.

This was illustrated succinctly by Le Troedec *et al.* [87] when he and his coworkers investigated the effects of surface treatments via sodium hydroxide (NaOH), calcium hydroxide $Ca(OH)_2$, ethylene diaminetetraacetic acid(EDTA), and calcium chloride ($CaCl_2$) chemicals on the selected properties of composites. They concluded that chemical treatments affect the interaction of fiber surfaces as they exhibited better properties compared to when they were not treated. Specifically, it was observed that 6% of Sodium hydroxide (NaOH) treatment helped to remove the amorphous compounds leading to the purification of the fibers. The purification of the fibers unanimously intensified the crystallinity of the fiber bundles. The ethylene diaminetetraacetic acid (EDTA) treatment detached the fibers and consequently calcium ions associated with pectins.

Van de Weyenberg *et al.* [88] studied the impact of flax processing variables on the mechanical properties of flax fiber-reinforced epoxy composites. It was revealed that long flax slivers may not give superior composite properties. Though, enhancement in flexural properties can be achieved by chemical treatments. Transverse strength was improved by 250% while transverse modulus was by 500%. Likewise, the longitudinal properties of the composites showed improvements of over 40%.

Ahmad *et al.* [89] investigated coating effects of Acrylonitrile Butadiene Styrene (ABS) on oil palm empty fruit bunch fibers and concluded that coating strengthened the fiber capability. The coatings helped in the elimination of water take up and the possibility of bio-fiber degrading when in contact with soil. Thus, enhancing the elasticity and tensile strength of treated fibers compared to when they were not treated.

Many researchers [71], [72] have investigated the influence of alkali treatment coupling agent (maleic anhydride) and chemical treatments (acetylation) on the elimination of moisture take-up of natural fiber polymer composites. They ensured that impurities were eliminated viz-a-viz the chemical treatments as they increase the roughness of the fiber surfaces. The mechanism behind the elimination of the moisture absorption is the obliteration of the OH functional groups as expressed in Equation (1) [73], [78].

$$\text{Fiber-OH} + \text{NaOH} \rightarrow \text{Fiber-O}{-}\text{Na+} + H_2O \tag{1}$$

The moisture absorption properties of oil palm empty fruit bunch (OPEFB) in diverse temperatures were evaluated by Sreekala and Thomas [90]. Likewise, they investigated the influence of different alterations on the fiber modifications like coating with latex, irradiation with gamma, treatment with silane, mercerization, and acetylation on the water uptake properties, they found out that the alteration process proved effective in curbing the rate of water uptake. Further research showed that oil palm empty fruit bunch (OPEFB) - Sisal fiber hybrid composites enhanced the decrease in water uptake of the composite. The mechanism behind this process is the increase in the surface area leading to enhanced mechanical interconnections and increasing the adhesive behavior of the fiber surface [91]. Shinoj *et al.* [78] worked on reducing the water diffusivity of agave fibers by modifying the fibers with styrene, acetic anhydride, acrylic acid, and maleic anhydride, and discovered that the modifying purpose became successful.

In another study [92], the commingling method was employed in the fabrication of jute yarn reinforced polypropylene composite. The aim was to investigate its viscoelastic behavior. The behavior was investigated under varying fiber weight ratios and different surface treatments such as maleic anhydride-modified polypropylene, toluene diisocyanate, potassium permanganate (VII), and stearic acid. They discovered that as the fiber content increase, there was a decrease in the elastic modulus and subsequently an increase in the storage modulus of the composites. Nevertheless, the chemical treatment enhanced the storage and elastic modulus of the composite compared to when they were not treated. Contrary to these findings, another researcher discovered that the stress relaxation rate of oil palm empty fruit bunch-sisal fiber hybrid composite decreases as the fiber weight ratio increases [93]. Thus, composites constituent modifications have been used to enhance various desirable properties in composites development. Therefore, this classification cab be further exploit for improved performance of polymer based composites.

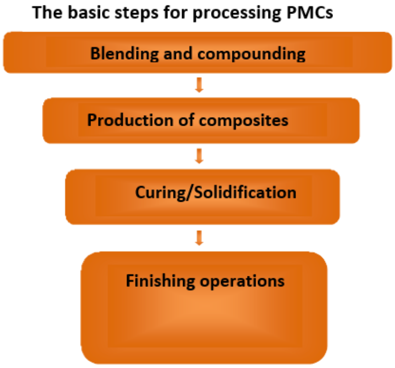

Figure 7: Basic steps for processing PMCs.

6 Processing Techniques for Polymer Matrix Composites

The manufacturing process adopted in the production of polymer matrix composites (PMC) has a great influence on the ensuing properties. Production route, interphase, and composition play a vital role in the performance of fiber-reinforced plastics thus, following the golden rule; where the direction of the arrow implies the direction of influence.

Process → Structure → Property → Application

Hence, the selection of appropriate processing methods is paramount to obtaining high-quality and viable products. The basic steps involved in the processing of PMCs are shown in Figure 7 while Table 5 presented the common processing methods and the polymers that are usually processed.

Table 5: Processing Techniques for Polymer Composites [94]

S/N	Process	Application
1	Resin transfer molding	Commonly used for liquid polymers; sisal fiber-polyester based composites [95],glass fiber/carbon nanotubes-epoxy based composites [96]
2	Filament winding	Commonly used for liquid polymers; E-glass fiber epoxy tubes [97], kevlar fiber monofilament/epoxy composite [98]
3	Injection molding	Commonly used for solid polymers; jute-synthetic cellulose fibers based hybrid PP composites [99], cellulose fiber-reinforced polylactide (PLA) composites [100]
4	Extrusion	Commonly used for solid polymers; polycaprolactone/multi-walled carbon nanotube composites [101],kenaf fiber/high-density polyethylene (HDPE) composites [102]
5	Pultrusion	Commonly used for both liquid and solid polymers; chemically modified soy-based epoxy resins [103], carbon-reinforced PP pre-impregnated materials [104]
6	Compression molding	Commonly used for both liquid and solid polymers; sugarcane bagasse cellulose/HDPE composites [105], multiscale carbon fiber/epoxy composites [106]
7	Prepreg	Commonly used for both liquid and solid polymers; tape lay-up carbon fiber-Triple-A polyimide-based composites [107], glass fiber-PP based laminates composite [108]

Table 5 gives a list of some processing procedures for bio-fiber reinforced polymers for biocomposite production. An appropriate production process is essential for the adaptation of materials into the desired shape in single processing procedures with little or no waste. Several factors have to be considered in choosing the right forming or processing technique. These include among others, the size and geometry of the finished product, design complexity, type, production capacity, quality of the parts and atmospheric stability of the polymer matrix [12], [94]. To date, many production processes have been developed to produce advanced fiber reinforced polymer biocomposites. This development was because bio-fibers are mechanically anisotropic materials. However, among these production methods, screw extrusion is the most widely used. Besides the essential factors stated above, the economic viability in terms of the speed of forming techniques and the cost of production are essential criteria in industries. Table 6 gave a collection of several processing techniques for Polylactic acid (PLA) based composites. The Table displayed the variability of the manufacturing processes and, hence, the need for more critical investigations.

Table 6: Typical preparation methods for Polylactic acid-based biocomposites [109]

Natural Fibers	Resin	Fabrication Methods
Bamboo/ Cellulose	PLA	Injection molding
Hemp	PLA	Roller carding + Compression molding
Banana	PLA	Melt blending + Injection molding
Ramie	PLA	Two-roll plastics mill + Hot pressing
Coir	PLA	Hand lay-up + Hydraulic press
Durian Skin	PLA	Screw extrusion + Injection molding

Current development is on the application of hybrid processes where manufacturing technologies are being merged into a single continuous process. This process has proven to be an efficient means to improve the performance and shorten the process chains of the developed materials [110].

These hybrid manufacturing processes for the production of composite materials will experience modifications in the future and, it will remain an interesting field of activities. Figures 8–10 [15] are some of the available manufacturing processes for polymer-based composites.

7 The Effects of Various Natural Fibers on the Properties of Reinforced Polymer Composites

Many researchers have investigated the suitability and competitiveness of bio-fibers as reinforcement in polymers [100], [101]. Some researchers focused their efforts on the modifications of fiber surface and manufacturing processes in improving fiber/polymer compatibility while some studied and compared different bio-fiber-based composites and their suitability for various applications [111]–[114]. Table 7 provides information on some vegetable fibers that are available globally.

To illustrate the dynamics of the agro waste products, researches were carried out using groundnut shell, rice husk, and coir pit as reinforcements in the epoxy matrix, respectively. They exhibited different results with the use of 30% of the respective particles and 70% of epoxy due to the differences in their constituents. Rice husk-epoxy composites exhibited the best values in impact, flexural and tensile properties. This performance was due to better chemical constituents present in rice husk compared to others. Also, particulate

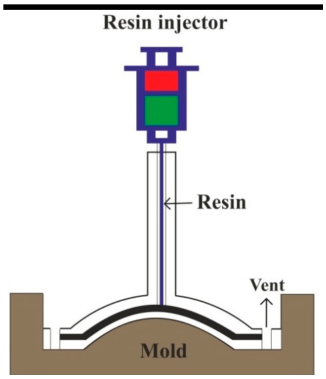

Figure 8: Resin transfer molding process [12].

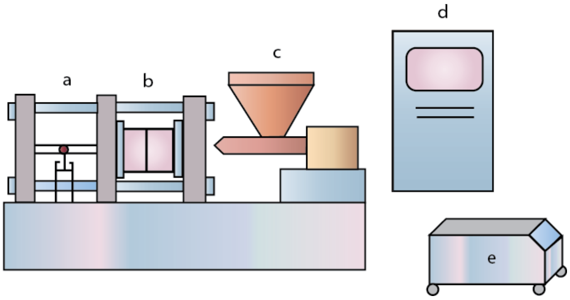

Figure 9: Sections of an injection molding machine: a) Clamping unit; b) Molding unit; c) Plastication unit; d) Control panel; e) Temperature controlsystem [12].

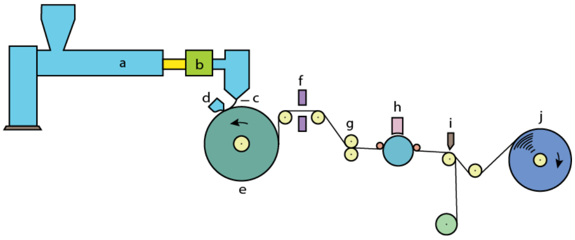

Figure 10: Extrusion molding machine units: a) Extruder; b) Filter; c) Slot die; d) Air knife; e) Cooling roll; f) Film thickness measuring device; g) Tension rolls; h) Corona treatment; i) Edge treatment; j) Winding [12].

rice husk and boiled eggshell were mixed to form hybrid reinforcement in polymer to investigate further the influence of the agro-wastes. The results showed that hybrid reinforcements presented higher values relative to individual reinforcements [110], [115]. These results showed that there is no established condition(s) for the enhancement of polymer properties by these agro wastes. Table 8 showed the results

Table 7: Selected vegetable fibers properties and their availability in the world [111]

Vegetable Fiber	Basic Properties	Availability in the World (10^3 ton)
Wood	Wood fiber has a high level of total porosity and in most cases a very high level of air-filled porosity and a rather low level of water.	1,750,000
Bagasse	The modulus of bagasse fiber was relatively high compare to other bio-fibers and the dimension affects its reinforcing potentials. Its average length and diameter are 1.2 mm and 15 µm, respectively with an aspect ratio of 80 [116].	75,000
Bamboo	Numerous micro-gaps are present in the bamboo fiber. These micro-gaps cause it to be soft compared to other bio-fibers and increase its moisture absorption. However, it is a highly elastic, hygroscopic, natural deodorizer, possesses good resistance against UV light, hypoallergenic, bacteriostatic, antibacterial, and antifungal.	30,000
Cotton	Cotton fiber has an excellent absorbency.	18,500
Jute	Jute fiber exhibits good insulating properties, high specific strength, and aspect ratio [1].	2,300
Kenaf	Kenaf fiber has a high specific strength and low density [1].	970
Flax	Flax fiber has high strength and stiffness with low density [1].	830
Grass	Grass fibers exist in different parts of plants as sclerenchyma elongated cells usually in stems and leaves. They are mechanical support that can be found in the ground, vascular tissues, or dermal tissues.	700
Sisal	Sisal fiber has high tensile strength and tenacity. It is a fiber with high abrasion, saltwater, acid, and alkali resistance. Sisal fiber is easily cultivated [1].	375
Hemp	Hemp fiber has good tensile and insulating properties [114].	214
Banana	Banana fiber is similar to bamboo and ramie fibers in appearance but has better fineness and spinnability compared to them.	200
Coir	Coir is tougher with high resilience than most bio-fibers. It is free of chemical modification and its resistance to salt water was strong [117].	100
Ramie	Ramie fiber is not a common bio-fiber compared with others due to the need for expensive pre-treatments [4].	100
Abaca	Abaca fiber has flexural strength similar to glass fiber,high tensile properties and they cannot be easily decomposed [118].	70

of the influence of different vegetable fibers on the epoxy matrix as invested by various researchers. The mechanical properties of these composite formations differ significantly due to the sensitivities of the agro-waste as natural composites. The vegetable fibers are of cellulosic fibers but yielded different results on the same matrix due to the variations in the amount of this cellulosic that are present in each of the fibers and some other parameters that influence the strength.

Table 8: Inconsistency in mechanical properties of bio-fiber-epoxy composites [119]

S/N	Composites Formation	Ultimate Tensile Strength (MPa)	Flexural Strength at Peak(MPa)	Impact Strength (kJ/m^2)
1	Coir-epoxy	23.68	46.63	26.43
2	Sisal-epoxy	37.40	52.8	56.70
3	Jute-epoxy	43.00	55.8	65.00
4	Banana-epoxy	59.00	76.53	149.66
5	Bagasse-epoxy	42.40	56.7	110.66
6	Flax-epoxy	59.85	75.40	191.71
7	Areca-epoxy	27.50	25.00	93.33
8	Ramie-epoxy	90.00	110.00	105.40
9	Lantana camara-epoxy	19.08	55.45	32.30
10	Pseudo stem Banana-epoxy	45.57	73.58	92.66
11	Groundnut shell-epoxy	18.09	28.00	24.17
12	Rice husk-epoxy	23.00	29.00	26.00
13	Coir pith-epoxy	9.00	23.00	18.67
14	Banana + sisal-epoxy	25.00	62.00	98.66
15	Luffa + Groundnut-epoxy	39.31	58.95	27.33

To validate this further, the effect of different natural fibers used as reinforcement on polypropylene as a matrix was evaluated in Table 9, and it was observed that the mechanical properties vary as a result of varying chemical constituents of bio-fibers similar to what was obtained in Table 8.

The morphologies of some selected eggshell particulate-sisal fiber (ESP-SF) hybrid-based epoxy composites were presented in Figures 11–13. They showed the SEM images from the low, medium, and high proportions of the reinforcements in the matrix which also represent fractured surfaces of the most improved composite samples from the mixture [120].

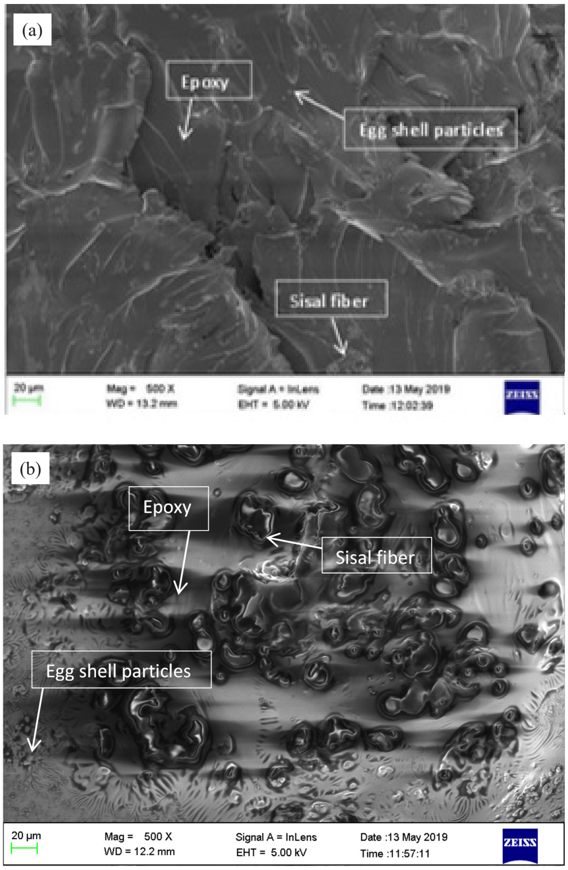

Figure 11: SEM image of low wt%; (a) calcined ESP-SF (b) uncalcined ESP-SF reinforced epoxy composites [120].

Table 9: The disparity in mechanical properties of some selected-fibre based polymer composites [111]–[113]

Type of Composite	Ultimate Tensile Strength (MPa)	Young's Modulus of Elasticity (GPa)	Flexural Strength at Peak (MPa)	Flexural Modulus (MPa))	Impact Strength (kJ/m^2)	Hardness (HR)
Jute-PP	23–29	1.6–2.4	45–54	1.7–2.8	30–51	76–91
Coir-PP	25–28	1.7–2.7	47–49	1.6–2.8	41–54	85–87
Abaca-PP	23–27	1.6–2.6	46–48	1.4–2.6	39–46	79–86
Bagasse-PP	17–22	1.2–1.4	21–34	0.8–1.6	3–6	-
Banana-PP	36–41	0.8– 1.0	-	-	10–13	-
Hemp-PP	27–29	1.6–1.8	-	-	-	-
Palm-PP	21–30	1.1–1.6	44–55	1.6–2.6	39–53	92–96

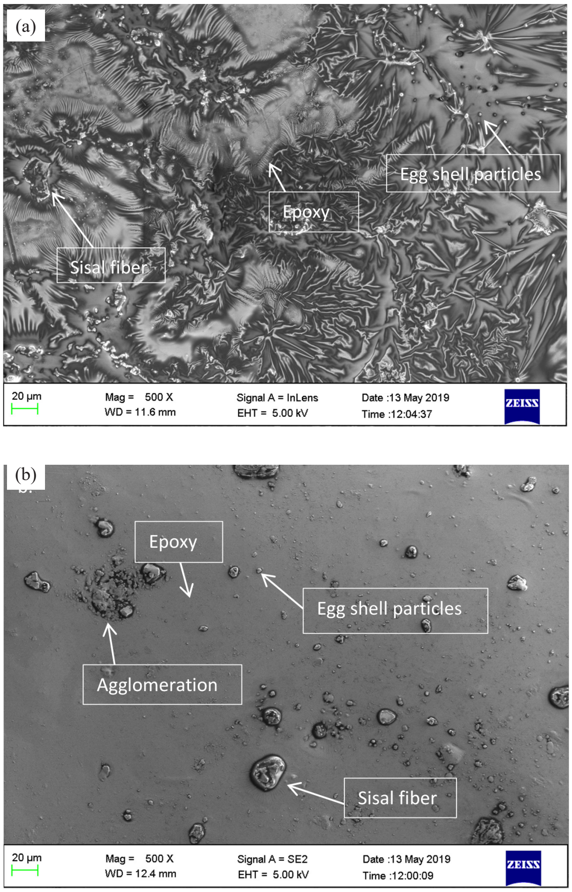

Figure 12: SEM image of medium wt%; (a) calcined ESP-SF (b) uncalcined ESP-SF reinforced epoxy composites [120].

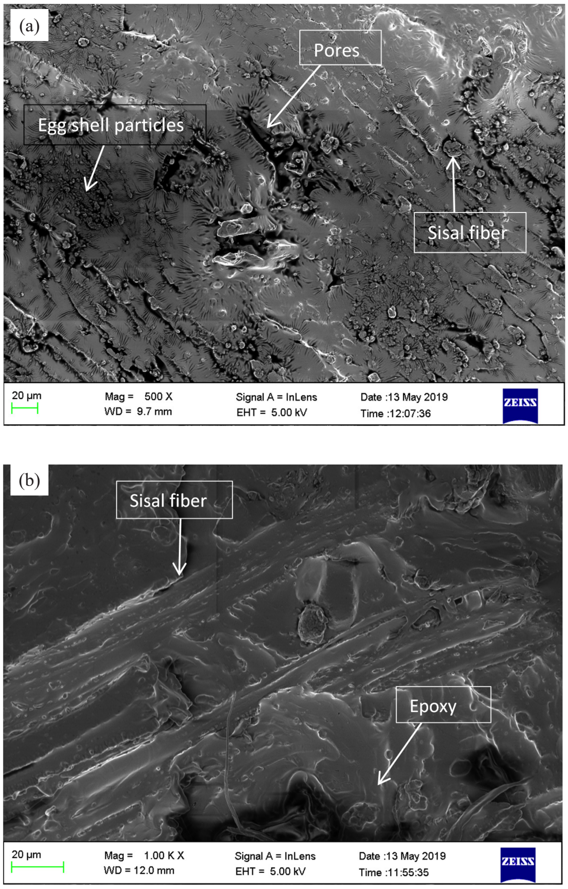

Figure 13: SEM image of high wt%; (a) calcined ESP-SF (b) uncalcined ESP-SF reinforced epoxy composites [120].

These were presented to show the prospective morphologies of the above-stated composite formulations in Table 6 and to support the results. Hence, finding like this will be reported in terms of the percentage improvement in mechanical properties that can be achieved from the addition of hybrid ESP-SF in epoxy composites. Hence, more attention is needed to be given to these trends for improved performance in composite development.

Occasionally, all properties are not usually enhanced from the same weight fraction in composites development as reported in this work. Likewise, all enhanced property values are not the same for different vegetable fibers when used in the same polymer matrix as shown in Tables 8 and 9.

8 Variation based on Inherent Fiber Properties

8.1 *Mechanical properties*

The mechanical properties of bio-fibers differ from one another due to the differences in their micro constituents especially the micro-fibrillar angle and cellulose content as presented in Table 10. High cellulose content with a low micro-fibril angle increases the mechanical properties of bio-fibers as reinforcement [121].

Table 10: Density and tensile properties of bio-fibers [122]

Bio-fiber	Ultimate Tensile Strength (MPa)	Young's Modulus of Elasticity (GPa)	Elongation at Break (%)	Density (g/cm^3)
Hemp	690	70	1.60	1.48
Kenaf	930	53	1.60	-
Flax	345–1035	28	2.70–3.20	1.50
Ramie	560	24–50	2.50	1.50
Bamboo	140–230	11–17	-	0.60–1.10
Jute	393–773	27	1.50–1.80	1.30
Coir	175	4–6	30.00	1.20
Banana	500	12	5.9	1.35
Cotton	287–597	6–13	7–8	1.50–1.60
Sisal	511–635	9–22	2.0–2.50	1.50
Oil palm	248	3	25	0.7–1.55
Pineapple	144	3	25	0.7–1.55
Bagasse	290	-	-	1.25

8.2 *Thermal stability properties*

Varying proportions of cellulose, hemicellulose and lignin are present in natural fibers in different percentages and hence, their thermal stability differs. Cellulose decomposes at 210 to 260°C, hemicellulose at 290°C, and lignin at 280–520°C, therefore, exhibiting diverse behavior under thermal effects [122]. This made it difficult to accurately predict the behavior of some systems because they consist of diverse chemical constituents.

Table 11 present the thermal stability behavior of some selected bio-fibers. It was revealed that the fibers followed a similar trend for thermal degradation except for wood fibers where the first decomposition stage exhibited a higher DTG peak than the other bio-fibers. Thus, it was concluded that at the second stage, the DTG shoulder was a result of degradation of cellulose, the main DTG peak was caused by the degradation of hemicellulose while the tail peak caused the end of lignin degradation [123].

9 Conclusions

This review revealed the potentials and future prospect in meeting the material demands. Though, many principles and processes has been adopted in solving the present challenges and there is hope that future challenges will be overcome by given more adequate attention to the parameters or variables that are involved. The article revealed the unlimited progress that can be achieved in natural fiber/particle reinforced polymer composites by working along the pathway of classification, constituent, modification and processing. The review showed that composite materials remain the class of materials with the highest sensitivities to changes at different levels in achieving materials for various applications; hence, more efforts are expected to be given to new innovative approaches in advancing this class of material. It is the most versatile class/group of materials; from natural to man-made and it is the most abundant material in natural form compared to other fundamental classes of materials: metal, ceramic, and polymer. This major reason has made man and researchers keep exploiting this group of materials to meet the human needs of all ages globally. The paper bring to the fore that, many materials challenges are still envisaged and the reason why modern approaches are essential in this most valuable class of materials. It showed evidence from the review that all future demand for advanced, sustainable and eco-friendly materials can be attended to by following the existing pathways that are highlighted in this review.

Table 11: Thermal degradation parameters of some common bio-fibers [116], [117]

Bio-fibers	Stage One		Stage Two					Stage Three
	Mass Loss (%)	DTG Peak	Tonset	Mass Loss (%)	DTG Peaks			Mass Loss (%)
					Shoulder (°C)	Main (°C)	Tail (°C)	
Jute	8	60	260	89	290	340	470	3
Cotton	4	55	265	91	280	330	410	5
Sisal	9	52	250	76	275	345	465	15
Wood	2	107	290	85	270	367	400	13

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