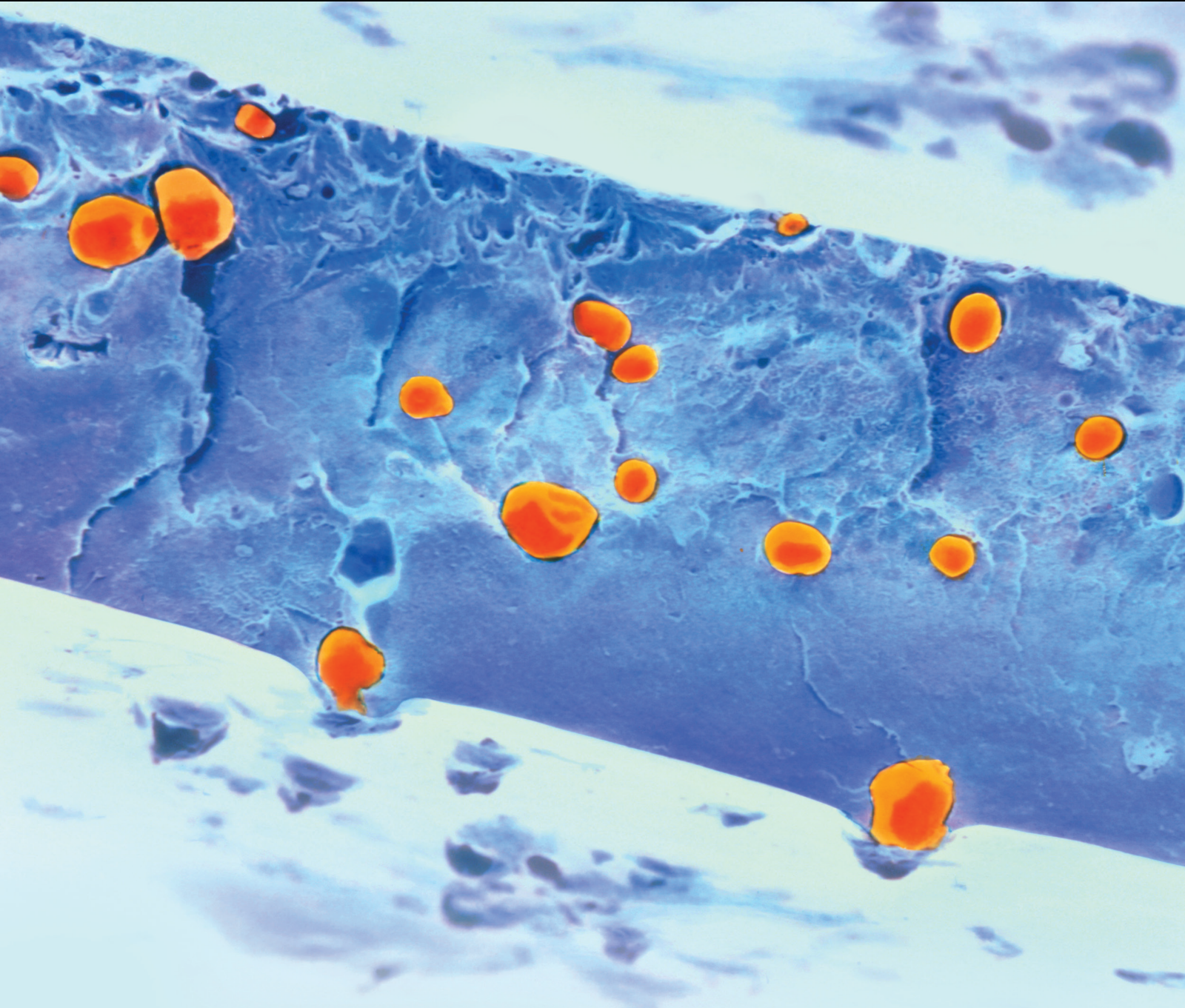


Polymer Composites using Recycled Natural Waste Materials

Lead Guest Editor: Jose# Luis Rivera-Armenta

Guest Editors: Ana Beatriz Morales-Cepeda and Doina Dimonie





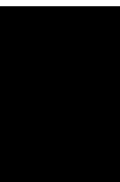
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International Journal of Polymer Science

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Research Article

Starch-Based Fishing Composite Fiber and Its Degradation Behavior

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The starch-based fishing composite fibers were prepared by one-step reactive extrusion and melt spinning. The effects of starch contents on the microstructural, thermal, dynamic mechanical, and mechanical properties of starch-based composite fibers were studied. And the degradation behaviors in soil of the fibers were also investigated. The compatibility between starch and HDPE is improved significantly by grafting maleic anhydride (MA) using one-step reactive blending extrusion. As the starch content increased, the melting temperature and the crystallinity of the fibers gradually decreased due to fluffy internal structures. Dynamic mechanical analysis showed that the transition peak α in the high-temperature region was gradually weakened and narrowed with increasing starch content; moreover, a shoulder appeared on the low-temperature side of the α peak was assigned to the β -relaxation related to starch phase. In addition, the mechanical results showed the significant decrease in the breaking strength and increase in the elongation at break of the starch-based composite fibers as the starch content increased. After degradation in soil for 5 months, the surface of the composite fibers had been deteriorated, while flocculent layers were observed and a large number of microfibrils appeared. And the weight loss rate of the starch-based composite fibers (5.2~34.8%) significantly increased with increasing starch content (50~90 wt%).

1. Introduction

Abandoned, lost, and discarded fishing gears (ALDFGs), also known as “ghost fishing” gear, can cause considerable ecological and economic losses [1]. Due to the continuous growth of fisheries and the transformation of fishing gear materials from natural materials (e.g., wood and cotton) to poorly degradable synthetic materials (e.g., polyethylene, polypropylene, nylon, and polyester), the amount, distribution, and environmental impact of ALDFGs have significantly increased over the last few decades [2, 3]. Some researchers indicate that about 640 t of fishing gear is lost in the ocean every year [4]. Indeed, white pollution and ghost fishing caused by nonbiodegradable fishing gear have attracted wide attention as public environmental awareness and requirements for environmental quality have improved [5, 6]. Thus, the research on the environment-friendly and biodegradable fishing materials has become an important means to protect the marine ecological envi-

ronment and prevent ALDFGs from causing harm to marine life.

Starch has attracted considerable attentions due to its natural abundance, low cost, and complete biodegradability [7–11]. Unfortunately, the mechanical properties and hydrophobicity of starch materials are poorer than those of synthetic plastics. Some authors have tried to overcome these weaknesses by blending starch with a polymer with good mechanical properties, while maintaining the biodegradability of the product [12–16]. Raquez et al. [17] have focused on the grafting of maleic anhydride (MA) onto the polymeric backbone using reactive extrusion methods. Such reactions promoted by MA moieties reduced the intrinsic viscosity of the blends, expecting an improvement in its processability. Pervaiz et al. [18] found that water absorption was reduced significantly after blending starch facilitated with green polyethylene and MA by reactive extrusion. Reactive extrusion is the simplest and most cost effective method for carrying out this reaction. The grafted MA can react with the hydroxyl

groups of starch macromolecules to form covalent bonds, and thus, they provide better control of the size of phase and strong interfacial adhesion and improve the stress transfer between the component phases [17, 19]. Researchers in the past have reported the modified starch foams [20], films [21, 22], and molding products; however, rare studies are found on starch-based fiber or monofilament, which is required for fishing net and rope.

In this current work, we attempt to prepare starch-based composite fibers using plasticized cassava starch and high-density polyethylene (HDPE) via one-step reactive extrusion with maleic anhydride (MA) and the melt spinning method. The grafting MA is expected to influence remarkably the microstructure, thereby leading to the changes in properties. In view of the fact that starch content is one of the important factors that strongly influence the morphology and properties of blends [15, 16, 20–23], we try to design composite fibers with different starch content to examine the effect of starch content on the physicochemical parameters and soil degradation for composite fibers.

2. Materials and Methods

2.1. Materials. Plasticized cassava starch (STR) was obtained from Zhangjiakou Yujing Starch Factory. The thermoplastic cassava starch was prepared by blending with cassava starch, low-density polyethylene (LDPE), plasticizer, and glycerol. The weight ratio of starch/LDPE is 9, and its density was 1500 kg/m³. HDPE (5000S) with an MFI 0.9 g per 10 min and density 950 kg/m³ was supplied by Sinopec Yangzi Petrochemical Company, China. Maleic anhydride (MA) was purchased from Sigma-Aldrich (Shanghai) Trading Co., Ltd. Dicumyl peroxide (DCP) and soybean oil were obtained from Shanghai Chemical Reagent Company, China Pharmacy Group.

2.2. Preparation of Starch-Based Fishing Composite Fibers by One-Step Reactive Extrusion. Plasticized cassava starch, HDPE (according to the experimental formulations shown in Table 1), MA, DCP, and soybean oil were added to premix, and then the mixture extruded in a twin-screw extruder for melt blending. MA and DCP were used as monomer and initiator at the 2.5 wt% and 0.25 wt% level based on starch. The temperatures of zones ①, ②, ③, ④, ⑤, ⑥, and ⑦ in the extruder were 130, 148, 155, 160, 160, 160, and 160°C, respectively. The twin-screw aspect ratio was 1:28, and the screw speed was 250 rpm corresponding to a mean residence time of around 5 min. Starch and HDPE were combined by reactive blending with MA agents during the melt extrusion process (Scheme 1). Then, the mixture was extruded from the spinneret. The diameter of the spinneret was 1 mm. The extruded as-spun fibers were drawn three times, and the total drawing ratio is 7.5–8, under which the composite monofilaments are continuously melt-spun. The temperatures of the draft water bath were 95, 98, and 98°C. The starch-based composite fibers were obtained by winding up the melt spinning tow with a reeler. Plasticized cassava starch was added to the starch-based composite fiber systems at proportions of 0 wt%, 50 wt%, 80 wt%, and 90 wt% and designated as HDPE,

TABLE 1: Composition of starch-based composite fibers.

Samples	Starch weight (wt%)	HDPE weight (wt%)
HDPE	0	100
STR-50	50	50
STR-80	80	20
STR-90	90	10

STR-50, STR-80, and STR-90, respectively (Table 1). For comparison purposes, the STR/HDPE fiber (50 wt% starch and 50 wt% HDPE) without adding MA was prepared in the same way.

2.3. Soil Degradation of Starch-Based Composite Fibers. Starch-based composite fibers were dried in an oven at 80°C for 48 h and then weighed (M_0). Next, the composite fibers were buried 10 cm under the surface of the soil for 5 months. The soil humidity is 20%. The fibers were retrieved and then soaked into purified water for 24 h. After washing with purified water, the samples were dried at 80°C for 48 h and weighed (M_d). The weight loss rate of the fibers was calculated according to Equation (1).

$$\text{Weight loss rate (\%)} = \frac{M_0 - M_d}{M_0} \times 100\%. \quad (1)$$

2.4. Characterization. SEM instrument (S4800, JEOL Ltd., Japan) was used to observe the surface and fractural morphologies of the composite fibers. Here, the surface of each sample was completely dried, quenched with liquid nitrogen, and sprayed with gold. The sample was then fixed on the sampling stage using conductive glue and placed in the observation chamber of the scanning electron microscope for imaging.

Differential scanning calorimetry (DSC) was applied to investigate the melting and crystallization behavior of the monofilaments using the DSC thermal analyzer (204F1, Netzsch Instruments, Germany). The sample was heated from 0°C to 150°C at a rate of 10°C/min, and the nitrogen flow was set to 50 mL/min.

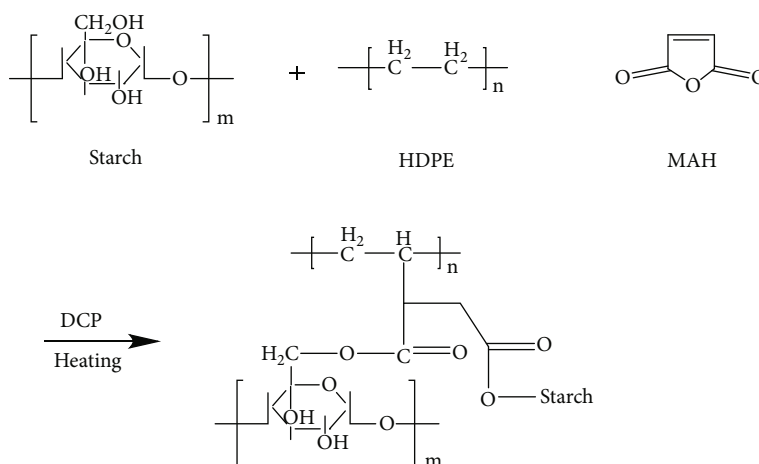
The crystallinity (X_c) of the samples was calculated according to Equation (2).

$$X_c = \left(\frac{\Delta H_f^{\text{obs}}}{\Delta H_f^0} \right) \times 100, \quad (2)$$

where ΔH_f^{obs} is the measured enthalpy of melting, ΔH_f^0 is the enthalpy of melting of the completely crystalline polymer, and ΔH_f^0 is the enthalpy of melting of HDPE (293 J/g) [24].

Dynamic mechanical analysis (DMA) was used as a mode of tensile clamp (242C, Netzsch Instruments, Germany) under the frequency of 1 Hz and the amplitude of 30 μm for all samples. During analysis, the temperature was increased from –184°C to 150°C at a rate of 3°C/min.

The tensile properties were investigated using the electron tensile tester (4466, Instron Instruments, USA) at a crosshead speed of 300 mm/min on a 500 mm long specimen



SCHEME 1: Schematic representation of synthesis procedure for MA grafting STR/HDPE.

according to SC/T 5005-2014 under ambient conditions. Results are the average of at least 10 specimens.

Fourier transform infrared (FT-IR) spectroscopy was conducted to characterize the microstructures of the starch-based composite fibers (6700, Nicolet Instrument, USA). For the attenuated total reflectance (ATR), an additional solid probe system was applied. The samples were scanned over the wavenumber range of 700–4000 cm^{-1} at a resolution of 4 cm^{-1} .

3. Results and Discussion

3.1. Morphological Structure of Starch-Based Composite Fibers. Figure 1 shows the FT-IR spectra of the composite fibers with different starch contents. There were three characteristic peaks of starch, with those at 1110 cm^{-1} and 1157 cm^{-1} attributed to C–O–H bond stretching, and that near 1025 cm^{-1} attributed to the stretching vibration of C–O in C–O–C groups [22, 25]. It can be seen that these absorption peaks are not detected in the FT-IR spectra of HDPE, so these peaks belong to starch, and the characteristic peak intensity gradually increases with the increase of starch content. Strong absorption peaks were observed near 2916, 2848, and 1460 cm^{-1} , which could be, respectively, assigned to symmetrical and asymmetry stretching vibration of C–H bonds, bending vibration of C–H bonds [26]. With the increase of starch content, the content of HDPE in the composite fiber decreased, and these absorption peaks strength decreased significantly. Compared to STR/HDPE fiber without MA, the –C=O stretching vibration peak was observed at 1720 cm^{-1} for composite fibers with grafting MA due to esterified starch by MAH. The characteristic peak at 1270 cm^{-1} represents C–O in the O–C=O bonds present in the ester structure [27]. For the STR/HDPE fiber without MA, a relevant band from 3200 to 3400 cm^{-1} could be observed due to the stretching of inter- and intramolecular bonding hydroxyl groups of granular starch [17]. When MA was used as a grafting agent, weak peaks at 3200 to 3400 cm^{-1} appeared due to the reaction between starch and MA groups.

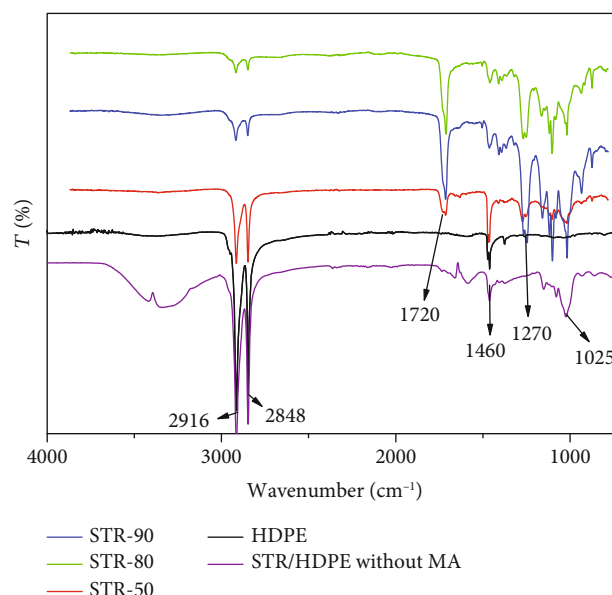


FIGURE 1: FT-IR spectrum of starch-based composite fibers.

It is necessary to study the morphology of composite fibers since many properties depend on it. SEM images of the starch-based composite fibers are shown in Figure 2. The STR/HDPE fiber without grafting MA displayed an obvious phase separation phenomenon (Figure 2(b)). The starch particles were not completely demolished and some of them were removed from the surface of the fiber during the fracture of the specimen, leaving some cavities in the fracture surface. The interfacial adhesion between starch and HDPE was poor due to the structural difference of dissimilar polymers [18]. However, after adding MA, the sample revealed a homogeneous fractural surface and compact structure (Figures 2(c) and 2(d)). There was no apparent phase interface between starch and HDPE in STR-50. Thereby, the compatibility between starch and HDPE is improved significantly by grafting MA using one-step reactive extrusion.

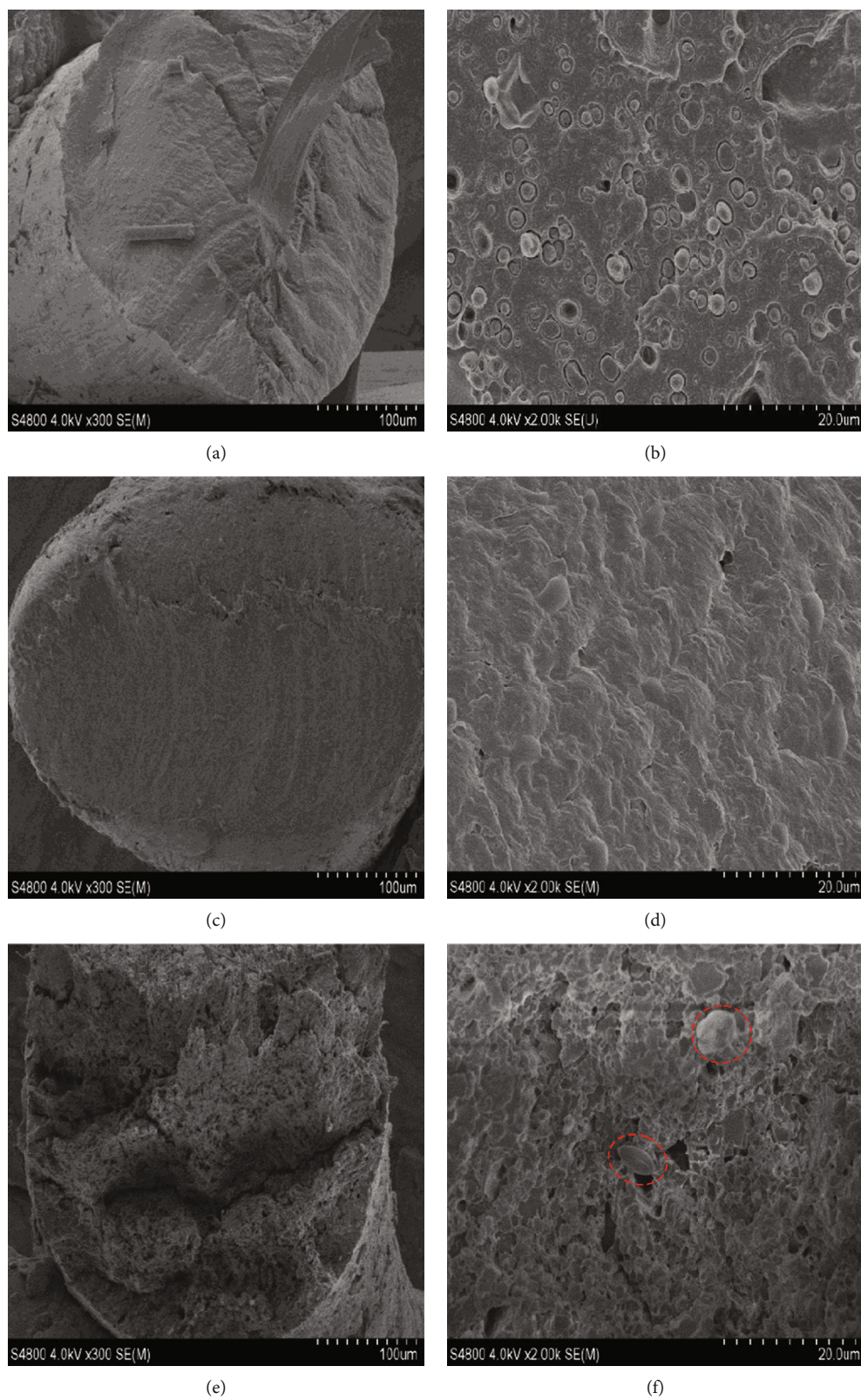


FIGURE 2: SEM images of starch-based composite fibers. (a) STR/HDPE fiber without adding MA at 300x. (b) STR/HDPE fiber without adding MA at 2000x. (c) STR-50 at 300x. (d) STR-50 at 2000x. (e) STR-90 at 300x. (f) STR-90 at 2000x.

This indicated that the compatibility of the composite fibers with adding MA was improved. However, it was noted that the internal structure of the composite fibers gradually became fluffy as the starch content increased (Figures 2(e) and 2(f)). As the starch content of the samples increased, the starch granules were congregated during the plasticization extrusion to become agglomerates. The presence of starch granules was attributed to the interaction of hydrogen bonds between molecules.

3.2. Thermal Properties of Starch-Based Composite Fibers. DSC thermograms were used to analyze the thermal properties of the starch-based composite fibers, and the results are shown in Figure 3. X_c of polyethylene in the composite fiber samples was calculated by the melting enthalpy, as shown in Figure 4. The melting temperature (T_m) of polyethylene in the starch-based composite fibers gradually decreased, thus improving the processability of the STR/HDPE composites. Importantly, the X_c of the samples decreased, and the crystal melting peak narrowed as the starch content increased. Compared to pure HDPE, the X_c of STR-80 decreased by 53.9%. This is because the introduction of starch reduces the order of polyethylene and destroys the crystal perfection of polyethylene, resulting in a decrease in the crystallinity and T_m of polyethylene as the starch content of the composite fibers increases. In addition, it was noted that the DSC curve of HDPE and STR-50 had only one heat absorption peak, but STR-80 and STR-90 showed another inflection point at about 96°C. It is speculated that the absorption peak is the endothermic peak of starch gelatinization, which is caused by the double conversion of starch gelatinization from polycrystalline state to amorphous state and from granular state to gelatinization state [28].

3.3. Dynamic Mechanical Properties of Starch-Based Composite Fibers. The dynamic mechanical properties of the starch-based composite fibers were studied, and the change curves of E' and $\tan \delta$ of the fibers were obtained at temperatures ranging from -184°C to 150°C (Figure 5). Results showed that E' of the starch-based composite fibers significantly decreased compared with that of HDPE fibers. When the temperature was 30°C , E' of the STR-90 was 0.1 GPa, indicating a decrease of 79% compared with that of pure HDPE (Figure 5(a)). The transition peaks α and γ of HDPE and the starch-based composite fibers were detected over a wide range of temperatures; here, the transition peak γ at the low-temperature region corresponds to the glass transition peak of polyethylene [29–31]. The peak temperature of γ remained essentially unchanged with increasing starch content, thus indicating that the effect of starch content on glass transition is not significant.

The transition peak α at the high-temperature region is related to the movement of restricted segments near the crystal region of polyethylene and a complex multiple relaxation, which gradually weakens and narrows as the starch content increases. Moreover, with increasing starch content, the α peak transition of composite fibers moved to lower temperature. The DSC results showed that the X_c of the composite fibers decreased and their crystal melting peak narrowed as

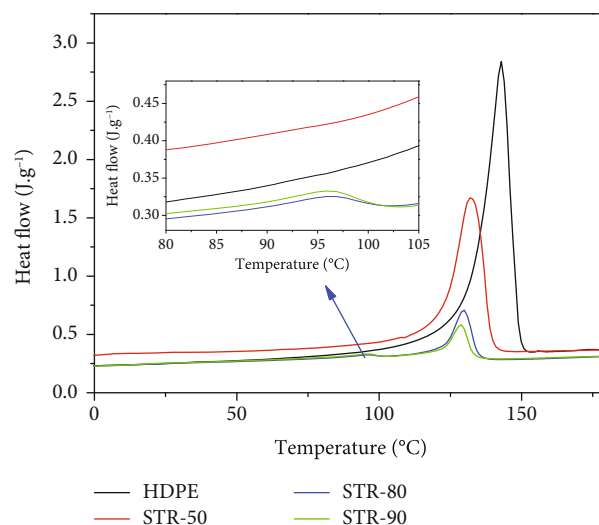


FIGURE 3: DSC analysis curves of starch-based composite fibers.

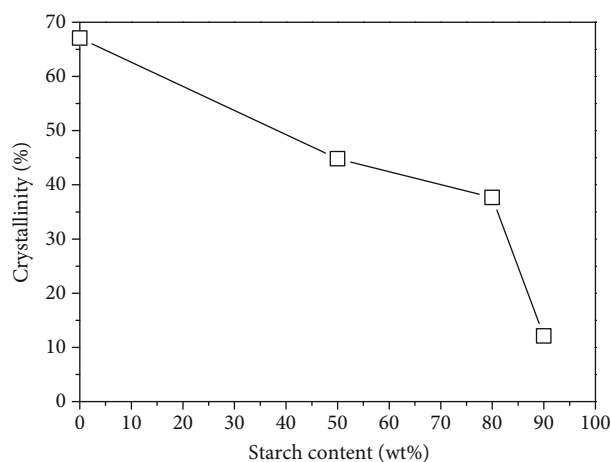


FIGURE 4: The X_c of polyethylene for starch-based composite fibers.

their starch content increased. Therefore, restricted segments near the polyethylene crystalline region decreased, consistent with the results of Abdul Wahab et al. [32]. It was noted that STR-80 and STR-90 revealed three transition peaks, while HDPE and STR-50 revealed two transition peaks. A shoulder appeared on the low-temperature side of the α peak. The shoulder in the DMA curves of the composites was assigned to the β -relaxation related to the starch phase, consistent with the results of our previous study [33]. The α and β peaks of STR-50 merged into one peak, thereby indicating that the compatibility of the composite fibers is improved when the starch content is 50 wt%. The result was in agreement with SEM analysis.

3.4. Mechanical Properties of Starch-Based Composite Fibers. Figure 6 shows the mechanical properties of HDPE and starch-based composite fibers. Compared to pure HDPE fiber, the breaking strength of the starch-based composite fibers significantly decreased. Importantly, with increasing

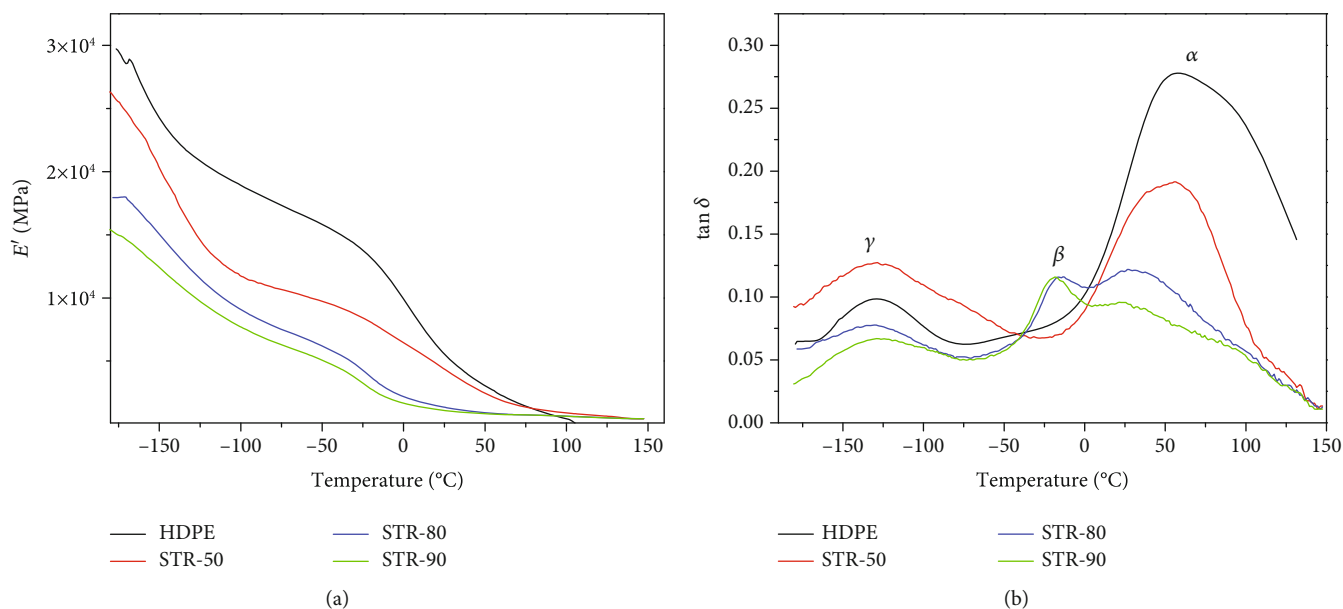


FIGURE 5: Starch-based composite fibers (a) E' and (b) $\tan \delta$ vs. temperature.

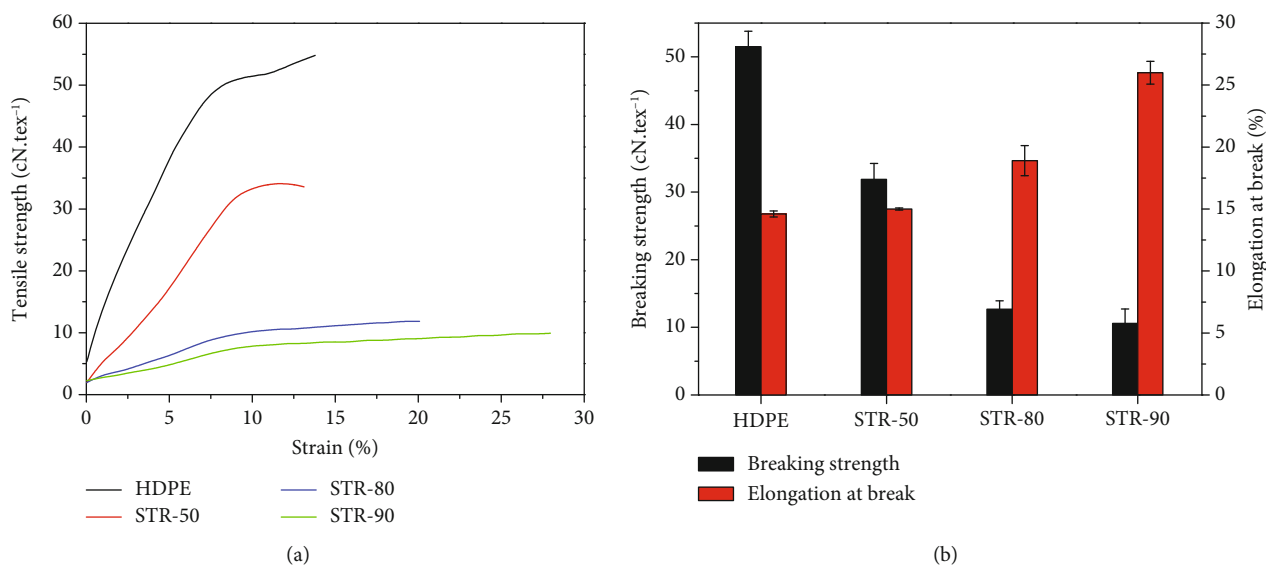


FIGURE 6: (a) Tensile strength-strain curves and (b) breaking strength and elongation at break of starch-based composite fibers.

the starch contents, the notable decrease in breaking strength and the increase in elongation at break can be observed in the starch-based composite fibers. Such a phenomenon was also reported in HDPE/starch blends in our previous study [33]. Differences between the tensile strength and elongation at break of the samples can be discussed in terms of their morphologies [34]. On increasing the content of starch, the mechanical properties worsened dramatically, especially the tensile strength for samples STR-80 and STR-90. This is ascribed to their internal structure became fluffy and the presence of starch granules. These features may form a stress concentration region, resulting in a significant decrease in mechanical properties of STR-80 and STR-90. Moreover,

for the STR-80 and STR-90, it was clear that with the increase in starch contents, the length of the rubber plateau became longer (Figure 6(a)), which represented the typical pattern of rubbery starch plastic materials reported previously [35].

3.5. Soil Degradation Behavior of Starch-Based Composite Fibers

3.5.1. *Effects of Soil Degradation on the Structural Morphology of Starch-Based Composite Fibers.* SEM photographs demonstrated degradation of starch within the fibers; here, Figures 7(a) and 7(b) refer to the surface of STR-80 before and after soil degradation, respectively,

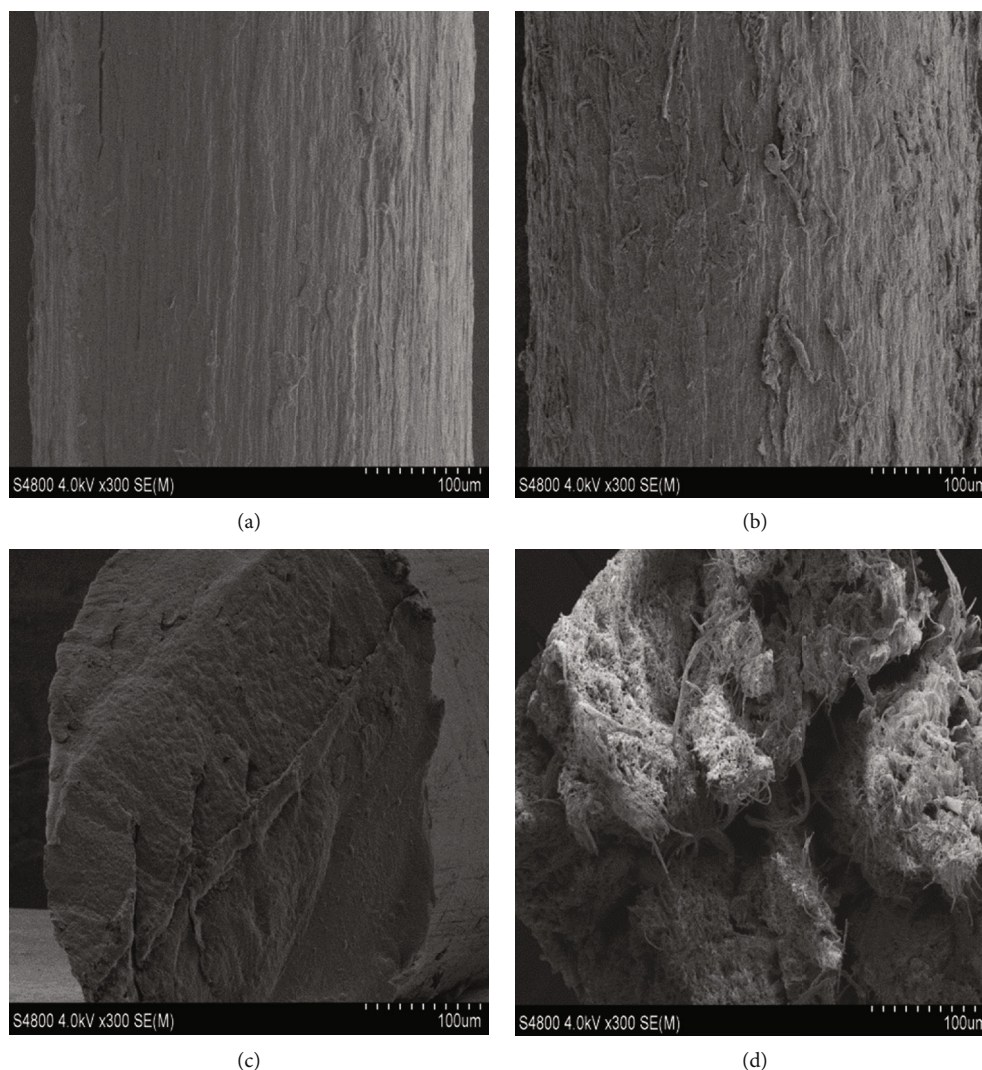


FIGURE 7: SEM images of starch-based composite fibers before and after biodegradation in soil. (a) Surface of STR-80 before soil degradation. (b) Surface of STR-80 after soil degradation. (c) Fractural structure of STR-80 before soil degradation. (d) Fractural structure of STR-80 after soil degradation.

while Figures 7(c) and 7(d) refer to the fractural section of the fiber sample before and after soil degradation, respectively. Before soil degradation, the surface of the composite fibers was smooth, no evident delamination could be observed, and the internal structure was compact. After soil degradation, some flocculent layering can be found on the surface of the composite fiber (Figure 7(b)). Moreover, disintegration of starch brought about changes of the internal structure. Many filamentous flocculent and spongy structures were observed on the fractural surface of the composite fiber (Figure 7(d)). The internal structure became collapsed after soil degradation, thus indicating that the starch-based composite fiber was eroded and degraded by microorganisms in the soil.

FT-IR was used to characterize microstructural changes in the starch-based composite fibers before and after soil degradation. Figure 8 shows the IR spectra of STR-50, STR-80, and STR-90 before and after soil degradation. After soil degradation, peak intensities of composite fibers after soil

degradation at 2916 and 2848 cm^{-1} were both improved greatly. The increase in the intensity of these peaks was owing to the break of the polyethylene chain in degradation progress, which resulted in the increase in the terminal group numbers [36]. Moreover, the $-C-O$ stretching vibration absorption peak near 1025 cm^{-1} was enhanced too. As indicated above, the band at 1025 cm^{-1} was attributed to the stretching vibration of $C-O$ in $C-O-C$ groups, and the degradation of starch led to the increase in the intensity of this peaks. Similar variations before and after degradation for starch/polyethylene film were reported by Wang et al. [22]. Hence, both starch and HDPE in the composite fibers exhibited varying degrees of degradation.

3.5.2. Weight Loss Rate of Starch-Based Composite Fibers. Figure 9 shows the rates of weight loss for the starch-based composite fibers after 5 months of soil degradation. The rates of weight loss for HDPE, STR-50, STR-80, and STR-90 were 0, 5.2%, 29.9%, and 34.8%, respectively. The weight loss rate

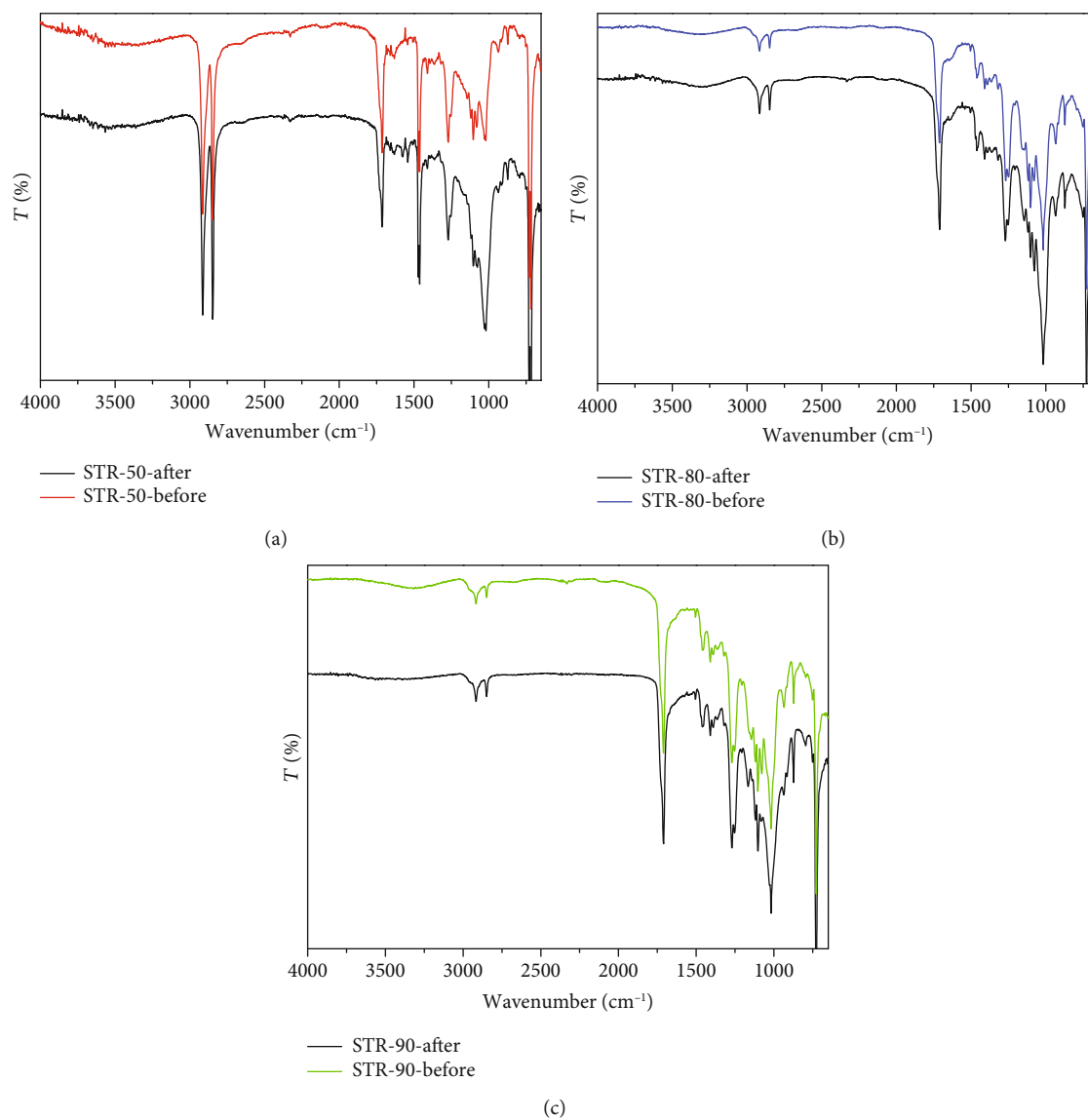


FIGURE 8: FT-IR spectrum of starch-based composite fibers before and after soil biodegradation.

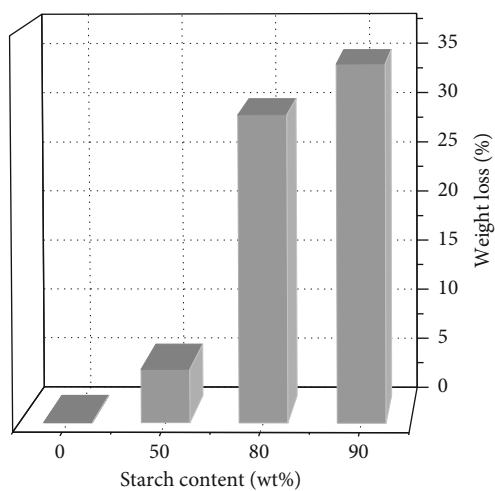


FIGURE 9: Weight loss of starch-based composite fibers after 5 months in soil degradation.

of the starch-based composite fibers significantly increased with increasing starch content. Starch fibers may be decomposed into oligomers, such as maltose and glucose, and, eventually, CO₂, H₂O, and other low-molecular weight compounds under the action of microorganisms. The presence of starch contributes to the multiplication of microorganisms that could easily destroy the structure and morphology of the composite fibers. FT-IR results showed that both starch and HDPE in the composite fibers exhibited varying degrees of degradation. However, the degradation of HDPE is only manifested as the break of the macromolecular chain but no weight loss. Bulatović et al. [37] found that thermoplastic starch was first degraded within the blend, which was facilitated access to the microorganisms of other ingredients in the blend, encouraging the biodegradation of other components. Although final values of weight loss are lower than expected in the composite fibers, indicating starch removal continues past 5 months.

4. Conclusions

Starch-based composite fibers were successfully prepared by one-step reactive extrusion and melt spinning technology. FT-IR and SEM data supported the fact that MA had been grafted as a potential compatibilizer for STR/HDPE systems. The STR/HDPE composite fibers with MA showed more homogeneous compared with the composite fibers without MA. The effect of starch contents on comprehensive morphological, thermal, and mechanical properties and soil degradation behavior was also studied. The starch contents had an important influence on the mechanical performance of the composite fibers due to the fluffy internal structure, the decrease of X_c , and small restricted segments near the crystalline region. In terms of soil degradation, SEM images of the polymers indicated surface deterioration. The weight loss rate of the composite fibers significantly increased with increasing starch content.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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Review Article

Polymer-Based Composites: An Indispensable Material for Present and Future Applications

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Right from the early days, polymer materials have been discovered as being beneficial for various applications but a poor understanding of these materials greatly handicapped their usage. However, with a change in this trend, polymer materials have gradually displaced other materials in most applications. In recent times, due to improved research and knowledge, polymer-based materials are the first choice materials for several applications and are now replacing other materials rapidly. More advanced materials from polymers are being developed daily as a substitute for other materials even in areas where polymers are considered not to be suitable in the time past. More recently, polymers have replaced metals and ceramics in applications like constructions, aerospace, automobiles, and medical. It is no doubt that this trend will continue due to the inherent properties of polymers and sustainability potential. Today, most of the limitations of polymers are being taken care of in the formulation of composite materials. Besides, the adaptation to positive environmental influence is being handled by scientists and researchers. Hence, this review reveals core areas of application of polymer-based composites and the significance of these materials to the advancement of humanity.

1. Introduction

In a world filled with various materials right from the beginning, we have had the opportunity of seeing materials transcend different eras to what it is today. Over centuries, man has had different materials to deal with right from the Stone age, to the Bronze age, to the Iron age, to the Glass age, to the Steel age, to the Aluminum age, and currently to the Plastic (polymer) age [1]. All these changes in material ages resulted as man's environment constantly evolved creating the need for improved materials to suit the present needs and applications. A polymer which is arguably one of the best materials ever due to its unique properties has gained predominance in vast areas of application. Little wonder, it is the material of the 21st century. For the material to adequately possess the required properties needed for top performance in diverse fields, polymers are usually reinforced with other materials to form composites. Hence, the formation of polymer

matrix-based composites (PMCs) has remained one of the most efficient methods to influence the properties of polymers [2]. These polymer composites could be of two matrix forms; thermoset or thermoplastic. Although thermoset-matrix based composites are generally more common, thermoplastic-matrix based composites are gaining increased attention due to their advantages such as lower cost of manufacturing, high strength, low moisture content, no curing, reprocessing flexibility, and high-temperature resistance [2, 3]. Polymer matrix composites can have either organic or inorganic polymer as the matrix and short or continuous fiber, particles of few millimeters to the nanometer range as the reinforcing material. The polymer matrix serves to firmly bond the fibers together, transfer loads to them, and uniformly distribute the load applied between them. While on the other hand, the fibers function as the major load-bearing component as a result of their higher strength and modulus. Based on the roles to be played by these

constituents, the properties of the individual constituents are known before selection and merging. Together, thus, they provide a series of exceptional properties which include lightweight, high stiffness, high specific strength, good resistance to fatigue, wear and corrosion resistance, easy fabrication, economic efficiency, high design flexibility, and desirable thermal expansion characteristics [2, 4, 5]. These properties make PMCs an in-demand composite type in numerous fields such as automobile, aerospace, medical, civil, electronics, communications, sports, marine, military, energy, industry, construction, and various household item applications [6]. When compared to metal-matrix and ceramic-matrix composites, polymer matrix composites are a lot easier to fabricate due to their relatively low processing temperatures. The ever-growing need for sustainability, innovations, and energy-efficient technology propels researchers and engineers to take to the production of natural biodegradable polymer composites in place of the synthetic ones in a bid to promote sustainable development. Natural fibers from plants and animals have gained much attention because of this. Examples include hemp, cotton, jute, flax, bamboo, sisal, kenaf, rice husk, ramie, abaca, sugarcane bagasse, coconut coir, Kevlar wool, keratin wool, hair, and silk [7–13]. Advanced composites majorly of biodegradable sources are considered as a better alternative to conventional materials due to their significant enhancement in mechanical, structural, and tribological properties [8, 14–16]. Natural fibers when used as reinforcements particularly in the nanometer range have been found to drastically improve the properties of the materials such as the strength, stiffness, fracture toughness, thermal stability, electrical conductivity, and wear resistance of materials making them highly suitable for application in diverse fields like construction, automobile, biomedical, marine, aerospace, and military [17]. For example, Singha and Thakur [18] synthesized natural fibers of Hibiscus Sabdariffa with phenol-formaldehyde resin matrix to form a polymer composite to analyze the tensile strength, compressive strength, flexural strength, and wear resistance properties of the material. The results showed that the mechanical and wear resistance properties increased up to 30% with the fiber reinforcement making it suitable in the automotive and other related industries. Prabhakar et al. [15] also reported the work of Arjmandi et al. [19] who investigated the use of the natural fiber of rice husk (RH) with different polymer matrices such as polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), and polylactic acid (PLA) to form polymer composites. The findings proved that the use of RH in PE helped to significantly improve the mechanical properties, making it a suitable composite material for building and construction. Likewise, Thakur et al. [20] used natural cellulosic fiber to reinforce resorcinol-formaldehyde. The resulting polymer composite was found to have improved mechanical and wear resistance properties thereby making it suitable for different industrial applications. Polymer biocomposites are reinforced with natural fillers like seed shells, animal fibers, and cellulose which make them to be preferred for biomedical applications due to their biocompatibility and resorbability [21]. Kevlar is an aramid fiber used as a reinforcement in polymeric organic matrix

composites and is gaining increased applications due to its outstanding properties such as high tensile strength, lightweight, stiffness, and thermal stability [22]. The use of Kevlar in composites helps to develop high-performance materials and allows for resource efficiency which makes it suitable for application in various fields like chassis, brake pads, and different body parts of vehicles, combat helmets, ballistic face masks, and bulletproof vests for defense, rotor blades of helicopters, radomes, landing gear doors, and propellers in aircrafts, bicycle tyres, ropes, and cables [12, 22, 23]. In the biomedical field, keratin-based biomaterials have received increased application for wound healing, drug delivery, and tissue engineering due to their intrinsic biological properties and excellent biocompatibility. Keratin is a fibrous protein that forms the major structural constituent of hair, feather, hooves, wool, and horn. It is abundantly available as a by-product from poultry and slaughterhouse [13, 24]. Research interest is increasing in the use of natural fibers such as sisal, jute, banana, coir, keratin, and cotton as reinforcements because of their lightweight, low-cost, eco-friendly, thermal, and acoustic insulating properties which makes them suitable for application in numerous industries which include consumer goods, biomedical industry, transportation industry, military, and civil structures [21].

To sustain the demand for light-weight materials for automobile applications and other commercial purposes, more research into the available polymer resources like waste plastics has been put into considerations. Recently, work was carried out to promote the use of secondary materials rather than creating new ones for the growing global demands for new materials. Besides, there is a need to intensify efforts towards identifying areas of applications suitable with the potentials embedded in derived materials [25–28]. This became necessary because of regulations in the developed nations for the inclusion of a high proportion of biodegradable materials in automobiles, aerospace, biomedical, and many other fields. In addition to the enhancement of the properties of some polymer composites, some natural fillers have also been reported to improve the mechanical properties and degradation of synthetic polymers, and this has been beneficial to the environment due to accelerated degradation [25, 29–32]. This paper focuses extensively on the benefits of fiber-reinforced polymer composites over conventional materials for applications in various fields.

2. Automobile Application

The automotive industry happens to be one of the largest consumers of PMCs which is a result of cost savings and its lightweight. The mechanical properties offered by PMCs are uniquely important in the design of vehicles to meet some of its very pressing requirements which include an overall reduction in the weight of automobiles [2]. The reason for this is that vehicle weight reduction will promote fuel efficiency as well as cause a reduction in the emission of exhaust thereby reducing air pollution. It is estimated that about 250 million barrels of crude oil can be saved from a 25% reduction in car mass, while fuel efficiency can be increased by 6%–8% for every 10% car weight reduction [2], [14, 33].

However, the passengers' safety must not be sacrificed in a bid to achieving these. This makes these three (lightweight, fuel efficiency, and passengers' safety) the most important factors to consider in the design of a vehicle [34]. Natural fiber polymer composites are the ideal materials for such applications due to their lightweight, high strength, high stiffness, design flexibility, high impact energy absorption, noise and vibration reduction, corrosion and abrasion resistance, lesser production cost, and biodegradability [33–35]. Figure 1 shows some of the numerous parts where PMCs are used in automobile manufacturing, which are door panel, bumper system, boot liner engine cover, refrigerated truck liners, connecting rod, dashboard, spoiler, seatback, pedal box system, wheel rim, fire engine, parcel shelves, chassis, and body stiffener [2, 14, 34, 36]. Examples of automakers, their models, and parts where they use PMCs are listed in Table 1 [35, 36].

The use of natural fiber polymer composites (NFPC) in automobile parts still holds some shortcomings due to issues such as high moisture absorption and high flammability. This makes it very crucial to address such issues to prevent the failure of these parts while in service. Hence, they are combined with synthetic fibers through hybridization techniques to form hybrid composites that possess more superior mechanical and structural properties and are more cost-effective [35]. From various researches and analysis, it is noted that the use of hybrid polymer composites in automobiles can bring about a significant reduction in weight of 20% to 40% while also having the potential to last 10 years longer than the conventional vehicles, thereby causing a new trend in materials selection for automobile application [5, 33, 35]. Recently, the use of recycled waste plastics in automobiles was investigated to arrest the pollution problems emanating from waste plastics. The research was carried out to propose the use of waste plastics in automobiles from where it was revealed that biofiller-recycled waste plastic-based composites were suitable for most automobile interiors such as door sills or the floor panel where moderate mechanical, good wear, and water resistance properties are desirable. The work presented that after reuse, the developed biocomposite will degrade easily due to aging when disposed off [25].

3. Aerospace Application

When it comes to the usage of advanced composites, the aerospace industry is one very big user. It is estimated that the aerospace industry consumes about 50% of the entire advanced composites production in the United States. Some of the reasons that spur the usage of these materials in the aerospace industry are similar to that of the automotive industry. Weight reduction, cost savings, and radiation shielding are at the forefront of concerns in this industry. The weight reduction is very crucial since it influences several factors such as fuel efficiency, speed, number of assembled parts, maneuverability, and increased range [5]. The lightweight of polymers provides the biggest advantages to the aerospace industry which are weight reduction and fuel savings. According to Koniuszewska and Kaczmar [37], American Airlines operates a fleet of about 600 planes and could

save up to 11,000 gallons of fuel per year by decreasing the weight of each aircraft only by 1 pound. Cost savings in aircraft production can be achieved by the use of fiber-reinforced polymer composites in place of metal alloys, reduced tooling cost, reducing the number of assembled parts which cuts down on the cost implication that comes with joining various parts together as well as in their maintenance. Besides these, property variation due to changes in environmental conditions can be achieved in advanced PMCs [5, 37].

Polymer matrix reinforced with nanofillers has been researched to provide improved radiation protection abilities compared to their metal counterparts. Aluminum which has previously been serving this purpose provides lesser attenuation characteristics due to its low electron density and production of secondary particles. The shielding effectiveness of polymer composite materials is attributed to their insulating nature as well as the possibility of designing them to possess high-Z fillers that are nontoxic and provide higher X-ray protection [38]. For example, silicone rubber finds application in aircraft due to its excellent performance at various temperatures, its resistance to irradiation, chemicals, and aging as well as its unique electrical insulation properties while the nanoparticles of carbon such as graphene, carbon nanotube, and carbon black provide excellent resistance to oxidation in the air [38, 39].

Based on the unique mechanical, electrical, and tribological properties of fiber-reinforced polymer (FRP) composites, other commendable benefits that come from using them in aircraft are their design flexibility, reduced scrap, improved corrosion and fatigue resistance, increased strength and stiffness, resistance to flame and heat for interior panels, improved damage and impact tolerance, durability, reduced noise level, vibration-damping properties, and fracture resistance. These make it possible for polymer composites to be used for components such as aircraft brakes, bulkheads, window frames, rotors, brackets, fuselage, aircraft wing boxes, airframe, fittings, blades, vertical fins, food tray arms, and tail assemblies [37, 40].

Hybrid composites have also recently been adopted since research has shown that they manifest enhanced mechanical properties required for aerospace applications. By using hybrid kenaf/glass fiber reinforced polymer composites, the specific strength and rain erosion resistance of aircraft are increased while carbon fiber reinforced silicon carbide when used to produce aircraft brakes tend to endure temperature as high as 1200°C [14]. Hybrid FRP composites are extensively used for various components in the A-series aircraft. In the A320 aircraft, about 800 kg weight is saved from using FRP composites when compared to aluminum alloy usage while also finding increased percentage application in the A330, A340, and the A380 superjumbo airliner [41]. Boeing B-787 Dreamliner is manufactured using a large number of polymer composites and is considered by design as a breakthrough in the aerospace industry [37]. Likewise, in the design and manufacturing of SARAS shown in Figure 2, a 14-seater aircraft in India, the use of PMCs helped to reduce weight by almost 25% over the metal alloys counterpart. By comparing the result, the mass of the metal alloys was



FIGURE 1: A vehicle showing numerous parts produced from PMCs [36].

TABLE 1: Automakers and parts produced from polymer matrix composites [36].

Automakers	Models	Parts
Volkswagen	Bora, Golf, Passat Variant	Seatback, door panel, boot liner, boot-lid finish panel
BMW	3,5,7 series	Door lining panel, seatback, boot lining
Opel	Vectra, Zafira, Astra	Door panel, headliner panel, instrument panel
Fiat	Marea, Brava, Punto	Boot liner, door panel
Audi	A2, A3, A4, A6, A8	Spare tire lining, door panel, hat rack, boot lining, seatback
Mercedes Benz	A-class, E-class, S-class	Seatback, door panel, cover panel, dashboard, windshield, engine cover, roof cover, instrument panel, bumper
Toyota	ES3, Brevis, Celsior, Raum	Spare tire lining, seatback, floor mat, door panel
Volvo	V70, C70	Natural foam, seat padding
Mitsubishi	Outlander and Eclipse cross	The instrument panel, cargo area floor, door panel
Daimler Chrysler	A, C, E, and S class	Door panels, car windshield, dashboard, and pillar cover panel
General Motors	Cadillac De Ville, Chevrolet Trail Blazer	Seatbacks, cargo area floor mat
Peugeot	406	Front and rear door panels, seatbacks, and parcel shelves
Ford	Mondeo CD 162, Focus	Door panels, boot-liner, door inserts, and floor trays
Renault	Twingo and Clio	Rear parcel shelf



FIGURE 2: The SARAS 14-seater aircraft [37].

33.5 kg while that of PMCs was 25.2 kg. The PMCs also had a single body part and no fastener present as against the 31 different parts with a total of 3400 fasteners obtained from using the metal alloys [37, 41].

4. Biomedical Application

The medical field is recognized as the leading industry with the most recent advances in the use of polymer composite materials. The use of these materials for biomedical applications is a result of their outstanding properties which include compatible mechanical strength, biodegradability, precise control, biocompatibility, biomimicry, compactness, and bioresorbability among others. Biopolymer materials can smartly imitate the morphological characteristics of living materials due to their biocompatibility. Their areas of application include but are not limited to wound dressing, medical devices, tissue engineering, dental usage, oral tissues, protein immobilization, drug delivery, regenerative medicine, bones and ligament application, blood vessels, antimicrobial materials, and surgical implants [42]. The biomedical field utilizes natural polymers such as chitosan, collagen, guar gum, alginates, agar, pectin, psyllium, pullulan, starch, and cellulose as well as synthetic polymers like polyamide (PA), polyglycolic acid (PGA), polylactic acid (PLA), polycaprolactone (PCL), polylactic-co-glycolic acid (PLGA), and polyestaramides (PEA) while also using fibers as its major form of reinforcement [42–47]. More detailed use of polymer composites for biomedical applications is presented in a broad term as hard (bone) and soft (skin) tissues.

4.1. Bones. The bone is a morphological component that can adapt and remodel itself to fit into any mechanical surroundings it finds itself. It is made up of hydroxyapatite (HA) nanocrystals, bone cells, mucopolysaccharides, collagen fibers, and blood vessels. Hydroxyapatites are continuously used for grafts and bone fillers and can easily be obtained from the waste bones of animals [48]. Their continuous usage is inclusive of their osteoconductivity property which enables the quick development of osteoprogenitor cells. Hence, they serve as bone fillers to aid bone fracture repair which is one of the most sensitive disorders common to bones. Both natural and synthetic degradable polymer composites are extensively used as scaffolds for bone repair due to their excellent mechanical and biological properties [42]. Having established the use of these materials as biomedical materials, sustainability and environmental impact were also considered, and hence, environmentally sustainable processes for the synthesis of HA have been developed and used for the production of hydroxyapatite powders (HAp) [49, 50]. Currently, HAp are being synthesized from both plants and animals using all the existing manufacturing processes [51].

From the investigation of Akagi and his coworkers who compared the effectiveness of HA/PDLLA and b-TCP scaffolds used for bone implant and repair, they were able to conclude from the result obtained that HA/PDLLA composite scaffolds, when used for bone implants, produce better bone repair because of their new bone formation process, biodegradability, minimal risk of residual scaffold left with the

composite as against b-TCP scaffold, and their improved cell infiltration shown by immunohistochemistry staining. This result was obtained from the surgical operation carried out on the right and left limbs of the dogs in which a section of their tibial bone was replaced with the HA/PDLLA and b-TCP scaffolds. The HA/PDLLA and b-TCP scaffolds were implanted into the right and left limbs, respectively, shown in Figure 3 [52].

4.2. Skin. The skin is the first immune system organ of the body as well as one of the most important parts of the body. This arms it with the responsibility of preventing pathogens and antigens from getting into the body. Nevertheless, they are still exposed to severe conditions such as skin infections, burns, and necrosis. Hence, skin regeneration using biodegradable and biocompatible polymer composites is of great interest to researchers. Also, since polymeric materials have been researched to be very suitable for drug delivery systems, they are extensively used as drug delivery materials. For instance, polymer-based hydrogels are used as carriers for drug molecules such as anticancer, antibiotic, and antifungal drugs. Also, polymeric materials are used for wound dressings to provide a shield to wound sites and to help quicken the healing process as well as for tissue engineering to help reproduce lost or damaged tissues by facilitating the development of new cells [53]. Table 2 presents some of the different polymer-based composites used for biomedical applications [42].

5. Civil Application

Over the past few decades, the construction industry has sought new materials and design processes to enhance the structural, mechanical, and environmental performance of buildings and bridge constructions around the world. The traditional materials, steel, concrete, and cement have been serving long enough but not adequate in meeting certain mechanical and environmental requirements, hence creating the need to research new materials that could provide such requirements [54]. Concrete and cement which are most generally used as construction and building materials, respectively, have posed various limitations to the development of novel structures globally, while steel has also been disappointed under certain conditions. Some of the shortcomings of these conventional materials are that cement production gives rise to serious environmental concerns as one tonne of cement production generates about one ton of carbon dioxide and also deteriorates quickly at the outer surface when exposed to alkaline or acid environment [55]. Furthermore, cement concrete exhibits high porosity, cavitation, low flexural strength, low abrasive resistance, low tensile strength, longer setting time, low durability, etc. When infrastructures are left unattended over a long period, these setbacks become overwhelming in the face of different kinds of degradation [54]. Some of the causes of structural degradations are environmental exposure, substandard materials usage, poor design, poor quality construction, etc [56, 57].

In the modern days, fiber-reinforced polymer composites (FRPC) have been researched to be excellent material

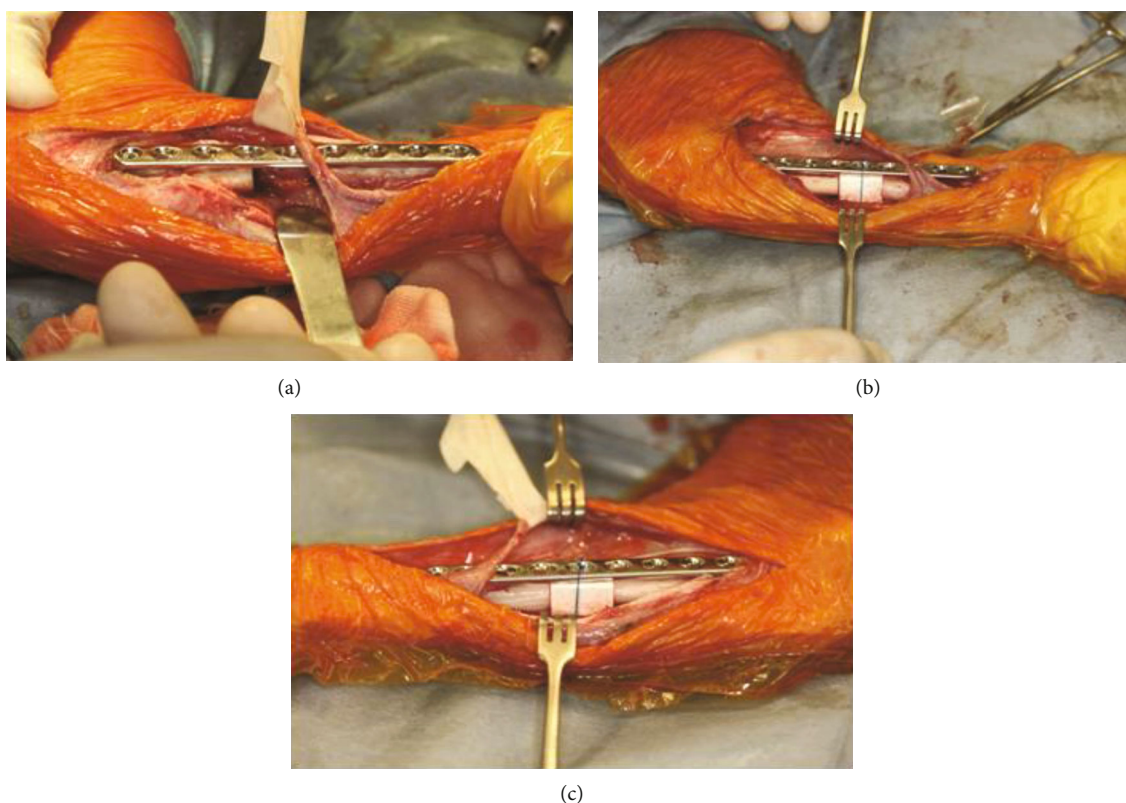


FIGURE 3: Images of surgical operation. (a) The central region of the tibia was removed using an oscillating bone saw (black arrow). (b) The HA/PDLLA composite was inserted into the space created (white arrow). (c) The b-TCP composite was inserted into the space created (black arrow) [52].

TABLE 2: Polymer composites for biomedical applications [42].

Polymer composites	Biomedical application
Modified HA/chondroitin sulfate	Skin
Glycoaminoglycoside/collagen	
AL/ibuprofen	
Polypropylene carbonate (PPC)	Bone
Silk fibroin (SF)/ alginate (AL)/HA	
Poly(lactide-co-glycolide) (PLAGA)/calcium phosphate	
PLA/ethylcellulose(EC)/ hydroxyapatite (HA)	
PCL/bioactive glass (BG) nanoparticles	Wound dressing
Kaolin/polyurethane	
Nanocellulose/poly(vinyl pyrrolidone) (PVP)/ SF/graphene oxide (GO)	
Banana peel powder/CS	
HA/PLA	Oral tissues
Polyglycolic acid (PGA)	
Poly(lactic-co-glycolic acid) (PLGA)	
Chitosan	Blood vessels
PCL/gelatin	
PVA/bacterial nanocellulose	

substitute for numerous civil engineering applications due to their unique properties which include high strength, lightweight, resistance to corrosion, improved ductility, workability, reduced cost, and improved aesthetic provision. As against the common construction materials, FRPCs help to provide increased strength-to-weight ratio and increased stiffness-to-weight ratio [54]. For example, polymer concrete can be used to replace cement concrete considering its increased strength, good resistance to corrosion, abrasion, and chemicals, improved ductility, high durability, low permeability, decreased maintenance requirement, low cure shrinkage, good adhesive property, eco-friendly characteristic, higher vibration damping property, excellent weathering property, and thawing and freezing resistance. These properties make polymer concrete highly suitable for a variety of civil engineering applications ranging from underground construction, bridge deck, building cladding, floor drains, sewer pipes, utility box, filtration slabs for drinking water, precast product, manholes, industrialized flooring, floor drains, hydraulic structures, for repair and maintenance purposes, for precast and cast purposes, trench lines, geothermal energy process, acid tanks, airport runway, etc. Also, it is noteworthy to mention that in the development of polymer concrete, epoxy resin is mostly used as the binder while a broader choice of materials is used as fillers. They include palm oil fuel ash, PET fibers, silica fume, bagasse ash, fly ash, marble waste, calcium carbonate, etc [55].

Advanced composite materials are of key essence to the construction industry. To prevent corrosion which is a major cause of concrete degradation, FRPC sheets are used to control the effect of corrosion, improve the structural strength, and repair concrete columns by wrapping them with the sheets. The concrete columns also experience increased energy absorption, shear capacity, load-carrying capacity, and damage control. They are also used for strengthening highway structures, beams, bridge structures, slabs, railway structures, walls, and beam-column joints [57, 58]. Swamy et al. [59] further explain the advantages of substituting steel plates for FRPC plates for reinforced concrete beams.

6. Marine Application

In more recent decades, the marine industry has experienced an extensive usage of advanced composites due to the excellent engineering properties that they offer. Weight and cost savings as well as environmental sustainability are the major drivers that have led to an increase in the use of these materials for various marine sectors [60, 61]. The use of conventional materials and some advanced composites all through various marine sectors has progressively led to an outcry on the environmental impacts caused by these materials which is facilitated much more by the aggressive environments they find operation in such as saltwater. The increasing concern for promoting a sustainable environment has led to the legislation of stricter manufacturing and maintenance policies by various regulatory bodies [61]. This has forced manufacturers to employ new innovative materials and processes while also understanding the life cycle of their products in a bid to simultaneously develop high engineering performance

components and ensure an eco-friendly environment. These demands have progressively required the incorporation of biodegradable polymer matrix composites (eco-composites) as they aid material recycling, the reduction of toxic and hazardous materials, waste, and polluting air emissions while offering outstanding mechanical properties [7, 25, 61, 62].

One such material classification is the fiber-reinforced polymer composite (FRPC) materials which can efficiently use a biosourced thermoplastic such as polylactic acid (PLA) or other thermoplastics such as polyamide or polypropylene. Presently, there is a need for a further shift to this choice of materials from epoxy and vinyl ester resins with carbon, glass, and aramid reinforcements [60, 63, 64]. However, these materials have still been experimented to be of better service than the traditional materials due to deterioration. According to Mouritz et al. [65], studies were carried out to compare the cost, weight, and structural performance of large patrol boats made using steel, aluminum, or sandwich. The studies found that the structural weight of a patrol boat made of glass-reinforced plastic (GRP) sandwich composite material should be 10% lighter than an aluminum boat and 36% lighter than a steel boat of similar size. Also, the use of hybrid composites such as hybrid glass-carbon reinforced polymer composite (GCG2C)s best helps to retain over a long period, the mechanical properties needed by materials for efficient performance in the marine industry. Hybrid (GCG2C)s possesses a very high flexural strength of 462 MPa with the lowest water absorption tendency. Likewise, hybridized flax and carbon fiber composite can be used to replace aluminum 6061 for structural materials as it offers about 141% improvement in vibration damping properties, 252% improvement in tensile strength with 49% reduction in weight. The use of jute and carbon fibers as reinforcements for hybridized composite structures also help to improve vibration-damping properties and economic and environmental sustainability [14].

Some of the outstanding properties of advanced composite materials promoting their usage in the marine industry are good strength-to-weight and stiffness-to-weight ratios, high durability, increased dimensional stability, increased range, flatness for stealth requirements, design flexibility, reduced fuel consumption, manufacturing and maintenance costs, lower electrical and magnetic signatures, increased speed, reduced wear, low moisture absorption, corrosion, impact, and resistances, increased vibration damping characteristics, sound barring, resistance to aggressive seawater, improved efficiency, high load-bearing capacity, lower inertia, increased buoyancy, and high level of acoustic transparency [14, 63, 65], [66]. Therefore, because of these excellent properties, marine sectors such as the boat and ship construction sector, renewable energy sector, offshore structural sector, and repairing sector [66] largely use them for fittings and internal equipment such as valves, ducts, pumps, heat exchangers, pipes, naval vessels, boats, small ships, superstructures, masts, decks, bulkheads, machinery, propellers, rudders, propulsion shafts, for warship equipment like destroyers, frigates, for fittings, hovercraft, corvettes, torpedo tubes, antenna trunks, engine components, tanks (water, fuel, lube oil), ferries, rotor blades, for gas pipelines, for hulls, for

pillars, for floating platforms such as tendons, risers, and support structures, for sailboats, yachts, and barges, topside structures, railings, radomes, tidal and wind turbine blades, and sonar domes [14, 61, 65, 66].

7. Military Application

The military industry is considered to be a big fan of nanotechnology for application in weaponry, communication, and protection. Over the years, staggering growth in the use of nanomaterials has been witnessed in the defense and military space in a bid to significantly improve the performance of military devices as well as increasing personnel comfort and survivability chances. Figure 4 shows the various nanomaterials used in defense and military sectors. Polymer nanocomposites (PNCs) have experienced a tremendous rise in their use in various military and defense sectors such as sensing, military medicine, smart structures and textiles, power generation and management, military weapons, and aerodynamics. PNC is a class of polymer composites having its polymer matrix reinforced with particles at the nanoscale (nanoparticles) thereby possessing excellently improved fatigue and fracture resistance. PNCs are used for producing military devices, materials, and structures that are lighter, smaller, cheaper, more accurate, smarter, and stronger [67, 68].

This industry is largely connected to the transportation industry in general. They are inseparable because the military and defense fields continuously and unavoidably make use of vehicles, aircraft, ships, and drones for their effective operations. This gives rise to the need for specific requirements such as fire-retardation, shock absorption, electromagnetic shielding, sensors, high-temperature resistance, vehicle liners for protection, actuators, ballistic performance, electrical energy storage (capacitors), and microwave absorption, in military vehicles, ships, and aircraft as they are being used for special purposes compared to civilian ones [69]. In military ships, for example, a ship production company, Ingall's Shipbuilding, achieves some of these requirements by making use of carbon-reinforced vinyl ester resin and phenolic fiberglass laminate panels to completely build the deckhouse and roof, respectively. In other ship parts, polymer composites are used for making the antennas, masts, and transparent radars. Likewise, the Lockheed Martin F-35 Lightning fighter aircraft has parts like the fuselage, wings, horizontal, and vertical stabilizers to be made of carbon fiber-reinforced polymer (CFRP) composites to make for extra toughness and durability [37].

In the area of soldiers' protection, PNCs are efficiently used for making body armor, smart textiles, gloves, and boots. Polymer matrix when reinforced with nanomaterials like Kevlar and graphene help to produce exceptionally strong, smart, and lightweight high-technology battle suits. When shear thickening fluids (a fluid containing a dispersion of nanoparticles) such as silica nanoparticles in polyethylene glycol are further applied, they will lead to the production of more flexible, dense, and stronger body armors. These body armors aid flexible movements of the wearer, protect the body against chemicals and toxins, and resist the impact of

high-speed bullets as well as protection against blunt weapons like bars, stones, and sticks [67–69]. Figure 5 shows a typical example in Russia's recent battle suit made of PNCs. The "Star Wars" high-tech armor capitalizes on the unique properties of graphene nanofiller which possesses excellent strength (it is 100 times stronger than steel), lightweight, high hydrophobicity capacity, high stamina, excellent electrical and thermal conductivity, and ballistic capacity. The armor consists of a tinted night vision helmet, radio cable, exoskeleton layer, gloves, padded khaki, and firearm [67]. More on the benefits of graphene, nanofillers in polymer composites for military applications are extensively covered by some previous researchers [70–76].

8. Future Trends

It is evident that the application of polymer matrix composites is now dominant across various industries and sectors as they significantly help to improve the performance and efficiency of materials across these diverse fields due to their outstanding properties. Presently, polymer-based composites are being used in every area of human activities without exception, some of which are in transportation [14, 37], civil construction [77, 78], biomedical [45], military [67, 69], sport and leisure [79, 80], food and packaging [81–83], and electrical and electronics [84, 85]. Therefore, there are needs to look into the advancement of these materials in the future to consider what the future has to offer. How can polymer solve future challenges among competing for future materials? Nanotechnology has been identified as one of the ways forward in which by combining the benefits in nanotechnology with the advantages in polymer-based materials, more advanced and dynamic materials will be achieved. Going by the present events, it was assumed that future trends in the use of PCMs will depend ultimately on the use of nanomaterials as reinforcements to meet the ever-evolving and dynamic requirements of different fields. This assumption was based on the premise that nanofillers greatly aid good interaction between the polymer matrix and the reinforcement that usually resulted in outstanding material properties. The sole incorporation of nanotechnology for the production of these advanced composites will provide the materials with further improved properties required for ever-increasing properties needed for satisfactory performance. The communication, electronics, energy, household, packaging, sports, and leisure industries are not left out in the application of polymer nanocomposites as they are also already fully involved in the use of advanced composites for various applications. For example, in the sport and leisure industry, an Australian surfboard manufacturing company, Samsara Surfboards is producing sustainable and eco-friendly surfboards of ultrahigh performance. The surfboard is made of commingled flax/PP, commingled flax/PLA, and flax fibers thereby making it to be highly environmentally friendly throughout its lifecycle. Also, the German company AX-Lightness GmbH, who is the major supplier of the Formula One sector with polymer composite materials, produced high-tech mountain bikes with wheels from epoxy prepregs and woven carbon fiber as polymer matrix and reinforcement, respectively [37]. In

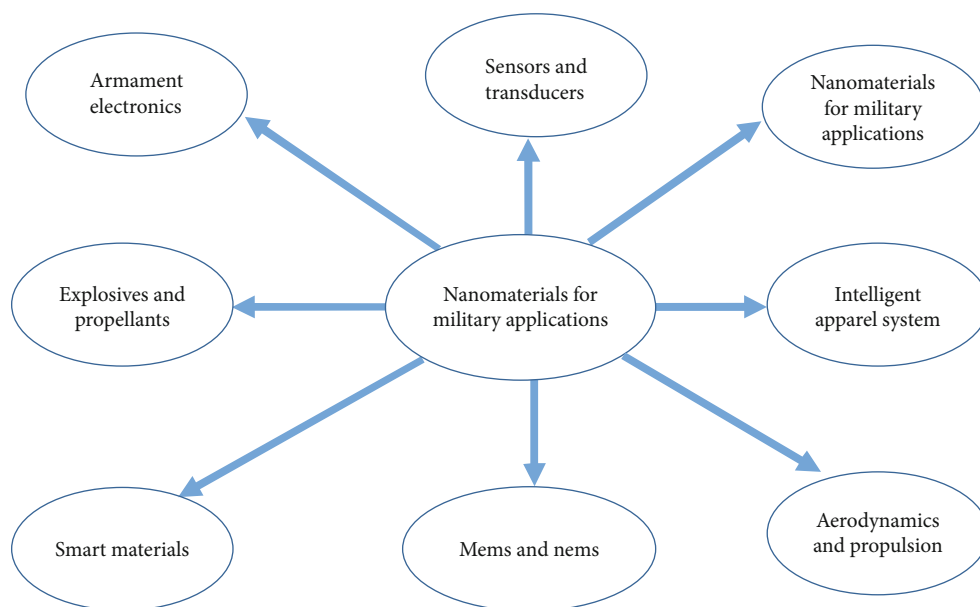


FIGURE 4: Various nanomaterials used in defense and military sectors [67].



FIGURE 5: Russian advanced high-tech amour item that includes an exoskeleton or the outer layer, designed to boost strength and stamina [67].

the area of electrical and electronics, PNCs can be used for making switchgear, panels, connectors, insulators, capacitor covers, headphone covers, and Li-ion battery covers [3].

9. Conclusion

Knowledge and information are powerful weapons that have been changing the course of mankind in the areas of science and engineering. These have been effectively communicated through research and developments that are readily available for readers to consider for application. This review has provided more information regarding the various areas of applications and challenges with polymer-based composites. The work revealed the prospect in polymer matrix composites as indispensable materials for the future whereby only modifications and adaptations will be the trends in the use of polymer-based composite materials. Hence, more research to overcome the present challenges in the areas of applications and environmental impact needs to be intensified.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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