

Research Article

Cu Nanoparticle-Modified High-Density Polyethylene Monofilament and Its Antifouling Performance on Fishing Netting

Wenwen Yu , Yongli Liu, Lei Wang , and Jiangaoshi Shi 

East China Sea Fisheries Research Institute, Chinese Academy of Fishery Sciences, Shanghai 200090, China

Correspondence should be addressed to Jiangaoshi Shi; jiangaoshi666@163.com

Received 30 July 2019; Revised 22 October 2019; Accepted 4 November 2019; Published 25 November 2019

Academic Editor: De-Yi Wang

Copyright © 2019 Wenwen Yu et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Cu nanoparticles (CuNPs) were modified by organic surfactant, then CuNP-modified high-density polyethylene (CuNP/HDPE) monofilaments were prepared by melt spinning. The effect of CuNP content on the morphology and properties of nanocomposite monofilaments was investigated. FT-IR and dynamic light scattering proved the successful surface modification for CuNP. Scanning electron microscope was used to observe the dispersed behavior of the CuNP. When the CuNP content was less than 1.0 wt%, the CuNPs were well dispersed in these nanocomposite monofilaments, and the increase of crystallization rate, the breaking strength, and knot strength were observed by differential scanning calorimeter and tensile test. Therefore, nanocomposite monofilaments showed comparable properties at low CuNP contents. With increasing CuNP content, the width of $\tan \delta$ peak and ΔE_a for α -relaxation from dynamic mechanical analysis were increased, indicating more amorphous components near the crystalline regions. In addition, burst release of Cu ions in seawater was observed. The coupon tests demonstrated that CuNPs could significantly improve antibiofouling performance of CuNP/HDPE fishing netting. CuNP/HDPE fishing netting have a strong potential for using in marine antifouling mitigation.

1. Introduction

High-density polyethylene (HDPE) resin is the most commonly used materials in fisheries because of its excellent fishing performance, such as good toughness, high strength, low density, smooth surface, minimal hygroscopicity, good water filtration, wear resistance, and aging resistance [1–5]. HDPE monofilament is the preferred material for making trawls, purse seines, fixed nets, aquaculture cages, and various fishing nets [6–8]. The HDPE fishing gear possesses satisfactory economic efficiency, fishery harvesting performance, and operating efficiency. With the development of aquatic science, the industry establishes higher requirements for the performance of fishing gear. Ordinary polyethylene fibers can no longer meet the special needs of existing fishery specialization. The main problems of conventional polyethylene fiber netting materials for traditional aquaculture purse seines are as follows: on the one hand, conventional polyethylene netting materials are prone to be damaged under severe

sea conditions, such as typhoon [9, 10] and on the other hand, after placing traditional aquaculture purse seines equipped with ordinary fiber netting in the sea area for a period of time, they will be covered with marine fouling organisms. These organisms affect not only the exchange of water inside and outside but also the growth of cultured fish, causing these fish to become sick [11]. Moreover, drag acting on the net increases with increasing level of biofouling [12]. Even if antifouling coatings are used, the antipollution effect of the netting can only be maintained for 6–12 months [13]. The netting needs to be treated again after coating for a period of time, leading to complicated and costly operation. Therefore, higher requirements are placed on the mechanical strength and antifouling performance of fishing netting materials. Modification is the most economical and feasible way to improve the comprehensive and cost performance of conventional materials [14, 15].

Metallic Cu exhibits a relatively good inhibitory effect on bacteria and can simultaneously prevent the growth of

marine organisms. The application of Cu has achieved satisfactory results in the field of fishery engineering, especially in aquaculture cages or aquaculture seines [16, 17]. Long-term antifouling performance tests indicate that Cu and its alloys are resistant to fouling mainly due to corrosion to release Cu ions in seawater. Noteworthy, since the 19th century, dispersions of copper or copper oxide particles into organic matrixes have been employed as antifouling coatings by the paint industry. Such paints after immersion in seawater provoked massive release of copper but it quickly failed in a short time [18]. And the coating is easy to fall off and causes pollution. A worldwide attempt to eliminate or reduce the use of such large-scale coatings is being promoted [19]. However, Cu/polymer nanocomposites can be a valid option for antifouling purposes. The use of Cu nanoparticle- (CuNP-) modified polymer materials combines the excellent properties of both and obtains a composite material with low cost, low density, and excellent performance. The addition of CuNP to the polymer improves its mechanical properties and thermal stability and imparts certain antiseptic and antibacterial effects on the resin itself. Recently, many reports appeared in literature on the study for nanocomposites containing CuNP [20–24]. Molefi et al. [23] investigated polyethylene-/CuNP melt mixing with 0~5 vol.% CuNP, and they found that the tensile modulus generally increased with increasing CuNP content. When exposed to seawater, CuNP are oxidized into free Cu ions, which play a role in antimicrobial and antifouling [25, 26]. As we know, the distribution of CuNP can be improved after surface treatment. Anyaogu et al. [27] reported a functionalized CuNP/polymer composite based on surface-modified CuNP with acrylic monomers and observed the antimicrobial activity of CuNP/polymer composites.

In the present study, the nanocomposite monofilaments were prepared in such a way that surface-modified CuNPs were added to blending in melt spinning. The effect of CuNP content on morphology and properties of CuNP/HDPE nanocomposite monofilaments was investigated, and the Cu ion release characteristics of CuNP/HDPE nanocomposite monofilaments were explored by ultraviolet-visible spectrophotometer.

2. Experimental

2.1. Materials and CuNP/HDPE Nanocomposite Monofilament Preparation. HDPE (5000S) with the melt flow index of 0.9 g/10 min was supplied by Sinopec Yangzi Petrochemical Co., Ltd, China. CuNP with 20 nm was provided by Suzhou Canfuo Nanotechnology Co., Ltd, China. Tween-20 agent and ethanol were purchased from Sinopharm Chemical Reagent Co., China. The surface-modified CuNP was prepared by dissolving Tween agent in ethanol, stirred evenly for 5 min, and then added CuNP powders, shaken for 30 min, and stirred for another 1 h. The stirrer was washed and dried at 80°C under vacuum.

With spinning-grade HDPE as matrix, CuNP/HDPE nanocomposite system was obtained by adding surface-modified CuNP and other processing aids. These mixes were blended and extruded through a twin-screw extruder. Then,

the systems were treated by melt spinning, and CuNP/HDPE primary fibers were obtained by single-screw extrusion. CuNP/HDPE nanocomposite monofilaments were prepared by multistage draw production. The suitable spinning temperature was 250°C–270°C. The water bath temperature was 98°C, and the draw ratio was 8.0, under which the nanocomposite monofilaments are continuously melt-spun. The diameter of the nanocomposite monofilaments was approximately 0.20 mm. The weight ratios of CuNP to HDPE were 0.5 wt%, 1.0 wt%, and 2.0 wt%. Correspondingly, the nanocomposite monofilaments were named as CuNP/HDPE-0.5, CuNP/HDPE-1.0, and CuNP/HDPE-2.0, respectively.

2.2. Characterization. FT-IR spectra were measured using a Nicolet spectrometer (model 560, Nicolet Instruments, USA). The samples were scanned 32 times at a resolution of 4 cm⁻¹.

The particle size distribution of the suspended nanoparticles (dispersion in H₂O) was obtained by dynamic light scattering (DLS) (Brookhaven BI-200SM Goniometer, USA).

The microstructures of the monofilaments were examined using a scanning electron microscope (SEM) (6360LA, JEOL Ltd., Japan) operated at an acceleration voltage of 15 kV.

Dynamic mechanical analysis (DMA) was used a mode of tensile film clamp (242C, NETZSCH Instruments, Germany) under the frequency of 1 Hz and the amplitude of 30 μm for all samples. The samples were initially cooled from ambient temperature to -170°C and then held at this temperature for 10 min. Then, the samples were heated to 140°C at a heating rate of 3°C/min.

Thus, loss factor, tan δ, is expressed as follows:

$$\tan \delta = \frac{E'}{E''}, \quad (1)$$

where E' is the storage modulus and E'' is the loss tangent modulus. tan δ is the most fundamental dynamic property of a viscoelastic material.

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 samples were scanned at a heating and cooling rate of 10°C/min in nitrogen atmosphere. The degree of crystallinity (X_c) was calculated via the total enthalpy method, according to the following expression:

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

where ΔH_f^{obs} is the observed heat of fusion values and ΔH_f^0 is the specific enthalpy of melting for 100% crystalline polymer. The ΔH_f^0 value of 287 J/g was used for PE [28].

The tensile properties were investigated using the electron tensile tester (4466, Instron Instruments, USA) at a crosshead speed of 300 mm/min on a 750 mm long specimen

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

A linear wear tester machine (5750, Taber Instruments, USA) was employed to measure the wear resistance of monofilament samples. The test was conducted at 25°C under a pressure of 1.0 cN/dtex. The degree of wear resistance (W) is related to the wear broken times, expressed as follows:

$$W = \frac{\text{wear broken times}}{\text{line density}}. \quad (3)$$

The release of Cu ion of varying monofilament samples was investigated when exposed to artificial seawater. 2g monofilament samples were immersed in the 200 ml artificial seawater. Artificial seawater was prepared by using sea salt and distilled water according to ASTM standard D1141-98. Salinity was constantly monitored and held between 33% and 34%, and the pH was kept between 8.10 and 8.15. During immersion, the samples were gently stirred by a magnetic stirrer. The solubility of Cu based on inorganic speciation considerations is about 0.5 mg L^{-1} [29]. The Cu ion concentrations in seawater are far less than the saturation in the present study. Ultraviolet-visible spectrophotometer can be used to quantify the Cu ion concentration [30]. Absorbance measurements were made at 1 nm intervals from 350 nm to 600 nm. The absorbance was measured using a spectrophotometer (i8, Hanon Instruments, China) to established the standard curve of Cu ion.

Coupon test was carried out by replacing some cage netting with CuNP/HDPE netting in the shallow sea area of the South China Sea. The samples were drawn in 1-, 3-, and 6-month intervals. Four 0.5-square mesh samples were randomly cut from the CuNP/HDPE netting and HDPE netting at 1 m depth. The retrieved mesh was cleaned by immersing in the water to remove sediments and other dirt. Then, weights were taken to assess the accumulation of fouling organisms. Results are the average of four mesh samples.

3. Results and Discussion

3.1. Surface Modification of CuNP. CuNPs before and after surface modification are characterized by FT-IR (Figure 1). The modified CuNP shows a distinct absorption band between 1500 and 1700 cm^{-1} , corresponding to the stretching vibration of the -COO group in Tween agent. In addition, the broad absorption band at 3700–3000 cm^{-1} is assigned to the stretching vibration of the hydroxyl group (-OH). This band clearly migrates to high wave number after modification. Tween agent is speculated to be adsorbed on the surface of CuNP. Figure 2 shows the DLS analysis for before and after modification of CuNP. The particle size of CuNP is 20 nm. A large amount of agglomeration is found due to the high surface energy, and the average particle size is 170 nm. The average particle size of CuNP modified by Tween agent is 105 nm. It can be clearly seen that the tendency of agglomeration is weakened, resulting from the adsorption of surfactant. Surface-modified CuNP are used in our experiment given the importance of the dispersibility of the microspheres in the particle filling system.

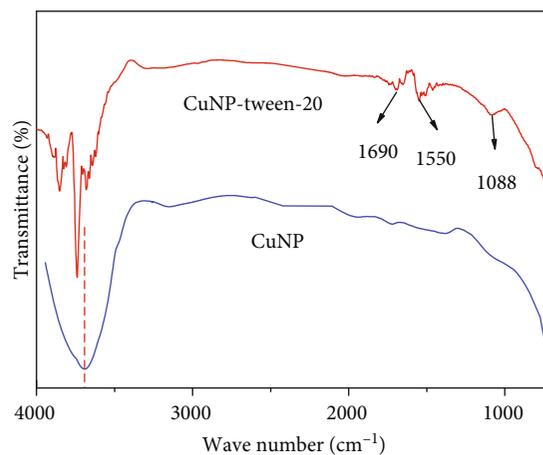


FIGURE 1: FT-IR spectra of CuNP and surface-modified CuNP.

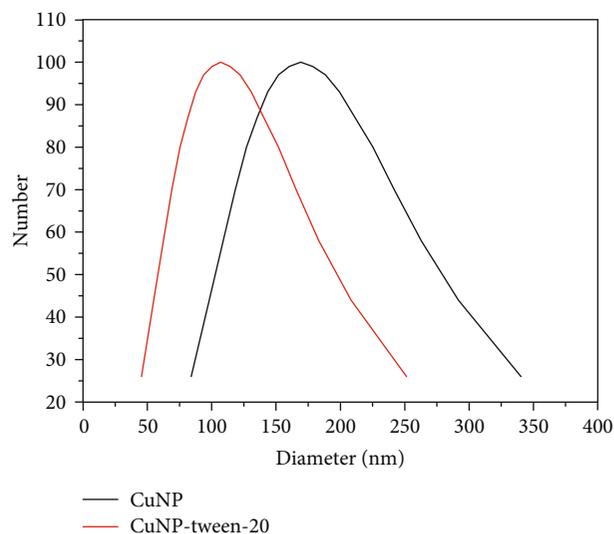


FIGURE 2: DLS profile of CuNP and surface-modified CuNP.

3.2. Microstructure. SEM images are used to visually assess nanofiller dispersion within the matrix. The morphology of CuNP/HDPE nanocomposite monofilaments is investigated by SEM, and typical images are given in Figure 3. CuNPs are dispersed in the HDPE monofilament matrix as microaggregates. When 0.5 wt% CuNPs are added and the dispersion size is about 200 nm, the dispersed particles are substantially spherical. When 2.0 wt% CuNPs are added and the dispersion size is about 300 nm–1.2 μm (Figure 3(c)), the aggregates show irregular and nonspherical structure. This finding indicates that CuNPs are not completely dissociated and dispersed because of the high melt viscosity during melt spinning. The aggregation of CuNP is also attributed to the strong van der Waals interactions between the nanoparticles.

3.3. Crystallization. The DSC heating curves of CuNP/HDPE nanocomposite monofilaments are shown in Figure 4(a), and the dependence of CuNP content on calculated X_c are plotted in Figure 4(b). The CuNP content has no significant effect on the melting temperature of HDPE matrix. As the CuNP

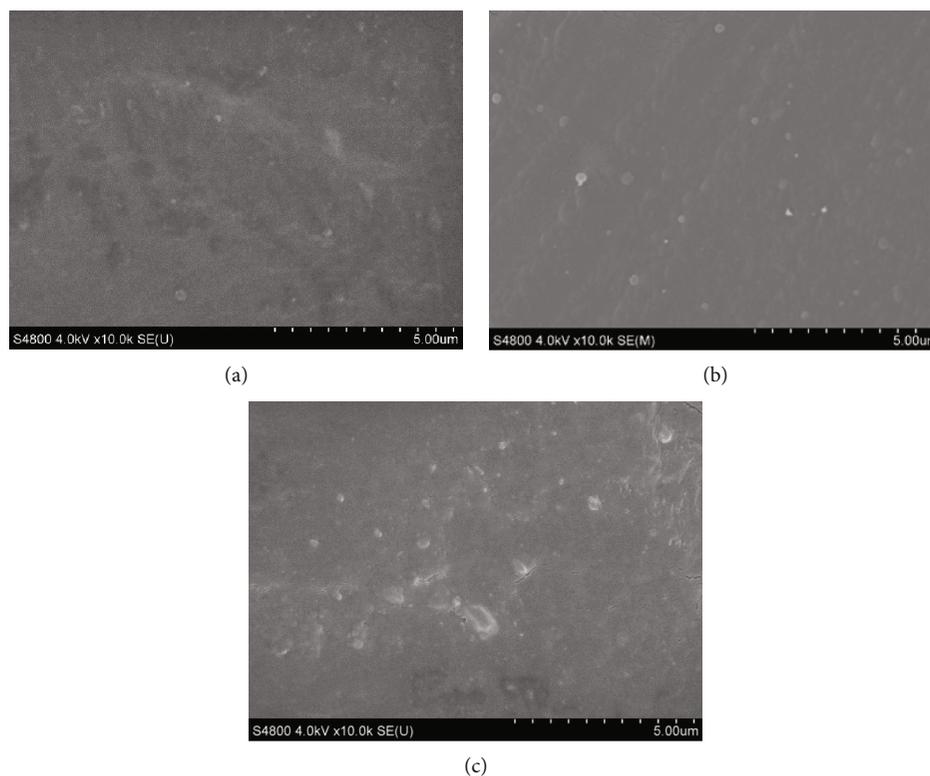


FIGURE 3: SEM image of (a) CuNP/HDPE-0.5, (b) CuNP/HDPE-1.0, and (c) CuNP/HDPE-2.0 nanocomposite monofilaments.

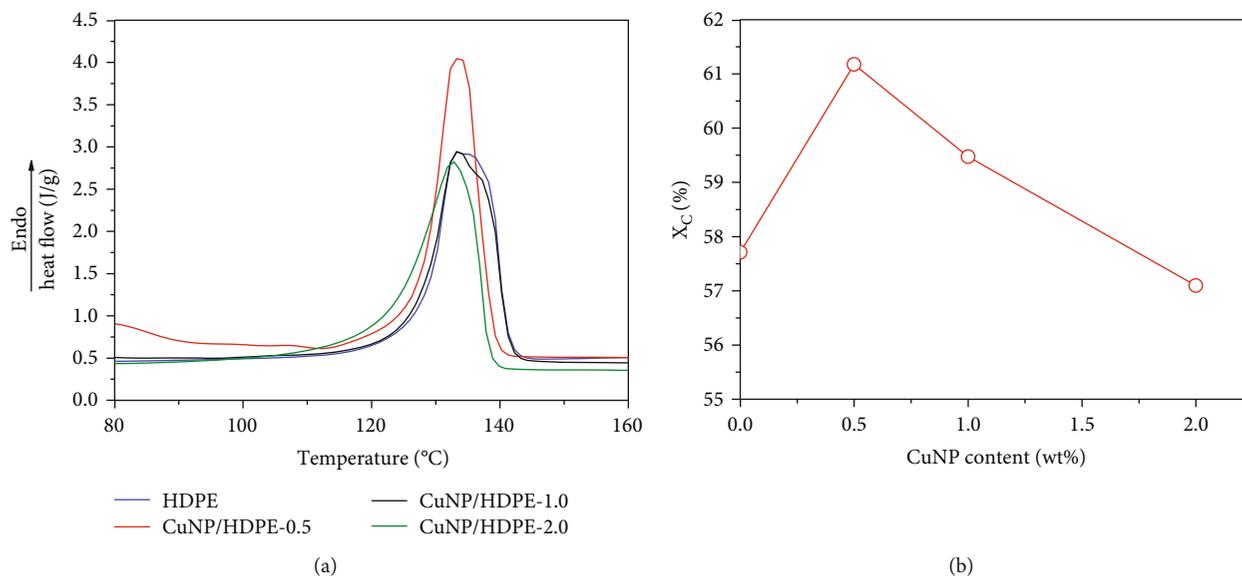


FIGURE 4: (a) DSC curves of nanocomposite monofilaments and (b) the dependence of CuNP content on crystallinity.

content increases, the X_c of the nanocomposite monofilaments increases first and then decreases. When the CuNP content is 0.5 wt%, CuNP/HDPE nanocomposite monofilament has the largest X_c of 61%. It should be noted that for other systems, an increase of crystallization rate also was observed for low concentrations of nanofiller [31, 32]. It

was argued that the nanoparticles could act as additional nucleation sites. On the other hand, the nanomaterials added hinder the crystallization of polyethylene segments. As the CuNP content further increases, the introduction of a large amount of CuNP causes agglomeration and reduces the interaction among HDPE macromolecular chains, resulting

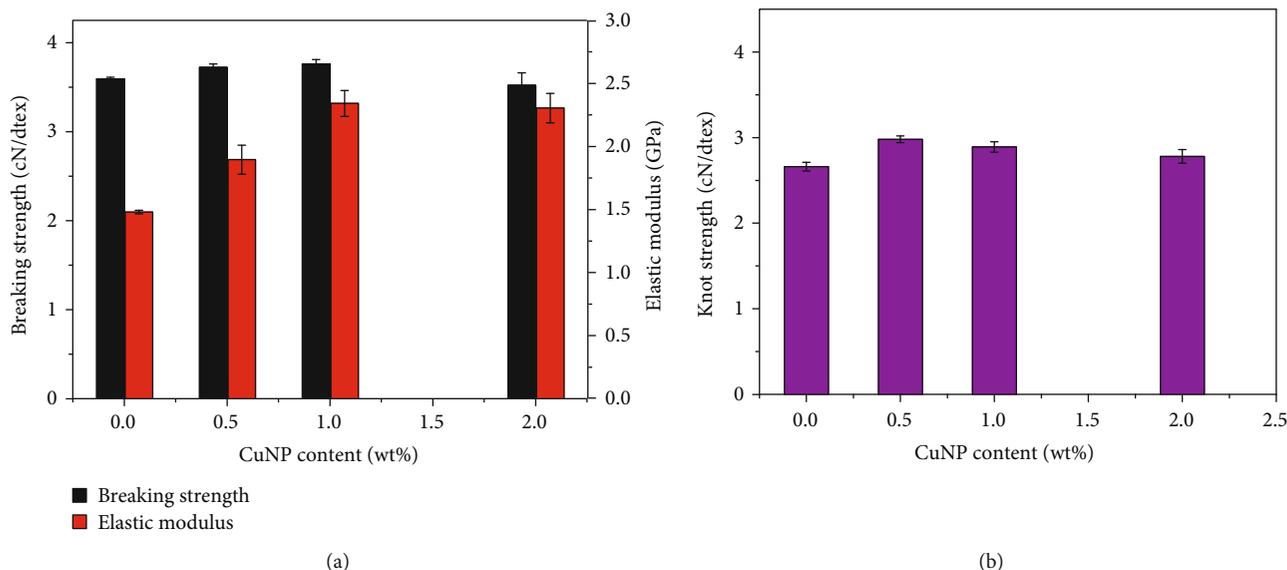


FIGURE 5: Dependence of (a) breaking strength and elastic modulus, (b) knot strength on CuNP content for nanocomposite monofilament.

in a decrease in the X_c of the CuNP/HDPE monofilaments. A similar behavior was observed for nanocomposites based on polyethylene containing other nanofillers [33, 34].

3.4. Mechanical Properties. The mechanical properties of CuNP/HDPE nanocomposite monofilaments were compared to analyze the effect of the CuNP content. Figure 5 shows the effect of the CuNP content on the mechanical properties of CuNP/HDPE nanocomposite monofilaments. All nanocomposite monofilaments show higher elastic modulus than pure HDPE monofilaments, and the elastic modulus of the nanocomposite monofilaments increases first and then decrease with increasing CuNP content (Figure 5(a)). A similar behavior has also been observed for nanoparticle-reinforced nanocomposites [35]. In general, the improvement of elastic modulus is attributed to the good dispersion of nanoparticles and good interfacial adhesion between the particles and the matrix so that the mobility of polymer chains is restricted under loading [36]. Knot strength is an important property for fishing netting and is associated with the toughness of polymer [37]. With increasing CuNP content, the breaking strength and knot strength of CuNP/HDPE nanocomposite monofilaments show the same trend as the elastic modulus. When the CuNP content is 0.5–1.0 wt%, the CuNP/HDPE nanocomposite monofilament exhibits better breaking strength and knot strength than pure HDPE samples. This finding is related to the dispersion state of nanoparticles and the microstructure of the aggregation state. When CuNPs are uniformly dispersed in the HDPE matrix with good interfacial bonding, significant nanoenhancement and toughening effects are produced, resulting in an increase of breaking strength and knot strength. When the CuNP content is 2.0 wt%, agglomeration is intensified, forming larger agglomerates that become defects. Moreover, a large stress concentration occurs when subjected to force, resulting in the decrease in the elastic modulus, breaking

strength, and knot strength. Therefore, the mechanical properties of monofilaments can be further optimized by adjusting the dispersion and aggregation microstructure of the particles.

3.5. Viscoelastic Properties. The viscoelastic properties of CuNP/HDPE nanocomposite monofilaments are studied by dynamic mechanical analysis. Figure 6 shows the temperature and frequency dependence of the dynamic mechanical properties of CuNP/HDPE nanocomposite monofilaments. The E' of the CuNP/HDPE nanocomposite monofilaments increases with increasing CuNP content (Figure 6(a)), which reflects higher elastic modulus of the nanocomposite monofilaments [38]. Two transition peaks are detected in HDPE and CuNP/HDPE nanocomposite monofilaments in a wide range of test temperatures (Figure 6(b)). The weaker peak appearing at low temperature corresponds to the glass transition of polyethylene [39]. With increasing CuNP content, the glass transition temperature (T_g) of CuNP/HDPE nanocomposite monofilament increases and the maximum loss factor ($\tan \delta_{\max}$) decreases. In general, the shape and position of $\tan \delta$ peak are closely related to crosslinking density and molecular structure [40, 41]. This finding shows that CuNP exerts a strong interaction with HDPE after surface modification. The increase in the CuNP content increases the binding of macromolecular chains, resulting in a decrease in $\tan \delta_{\max}$ and a tendency of T_g toward high temperature. The transition in high-temperature zone (α transition) corresponds to the movement of restricted amorphous structure near the crystallization zone of polyethylene [23, 38]. With increasing CuNP content, the α peak transition temperature (T_a) of CuNP/HDPE nanocomposite monofilament does not change much. When the CuNP content is 2.0 wt%, the $\tan \delta$ peak widens significantly, indicating more amorphous structure in the nanocomposite monofilaments. CuNPs exert a

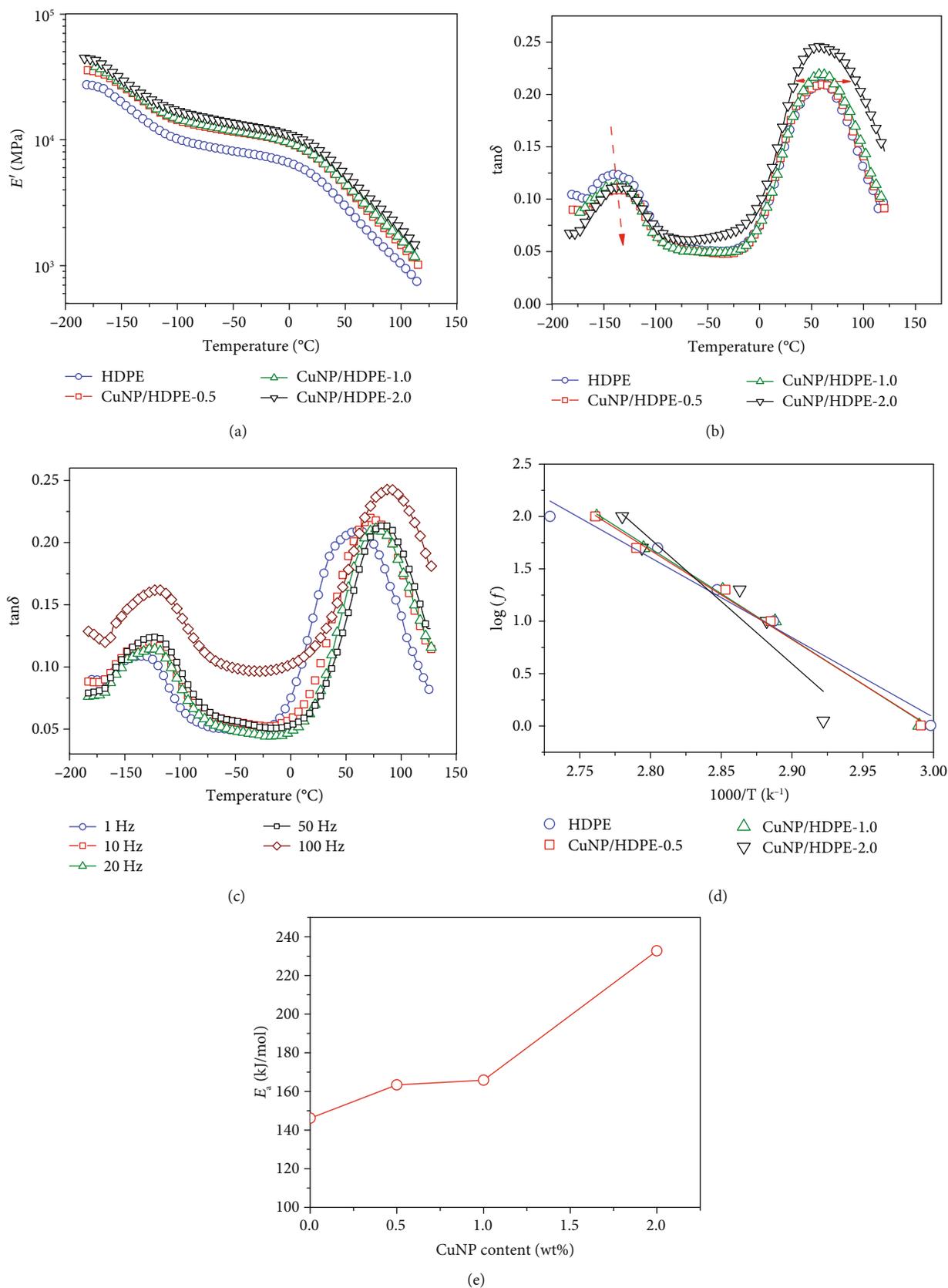


FIGURE 6: The relationship between (a) E' and (b) $\tan \delta$ of CuNP/HDPE nanocomposite monofilament and temperature; (c) the effect of frequency on the $\tan \delta \sim T$ spectrum of nanocomposite monofilament with CuNP content of 0.5 wt%; (d) Arrhenius plot for α -relaxation (solid line); and (e) the dependence of CuNP content on ΔE_a .

destructive effect on the crystalline structure of polyethylene and increase the mobility of the polyethylene molecular chain. This finding is consistent with the crystallinity results.

The T_a of CuNP/HDPE nanocomposite monofilaments move toward high temperature as frequency increases (Figure 6(c)). The relationship between f_{\max} and temperature is shown in Figure 6(d). The temperature dependence of f_{\max} of CuNP/HDPE nanocomposite monofilaments fits the Arrhenius equation.

$$f = f_0 \exp\left(\frac{\Delta E}{kT}\right), \quad (4)$$

where f_0 is the pre-exponential factor, ΔE is the activation energy, k is the Boltzman constant, and T is the temperature.

By fitting of the Arrhenius equation, the relationship between the corresponding activation energy of α -relaxation (ΔE_a) and the content of CuNPs can be obtained (Figure 6(e)). As the CuNP content increases, the ΔE_a value gradually increases, which is related to more limiting molecular motions near the crystalline regions.

3.6. Wear Resistance. Figure 7 shows the wear resistance of CuNP/HDPE nanocomposite monofilaments. The W (wear broken times per unit linear density of CuNP/HDPE monofilament) of CuNP/HDPE-1.0 is 115% higher than that of pure HDPE monofilaments under the same wear test conditions. The W of CuNP/HDPE-2.0 with the CuNP agglomeration only increases by 20.7% compared with that of HDPE monofilaments. Therefore, the content and dispersion form of CuNPs significantly affect the wear resistance of monofilaments.

3.7. The Release of Cu Ions in Sea Water. The Cu ions' concentration is determined according to the standard correspondence between the Cu ion concentration and the solution absorbance which measured by ultraviolet-visible spectrophotometer. As a matrix material, HDPE provides a permeability channel for Cu ions. At the same time, the barrier of the matrix to CuNPs can effectively control the release rate of particles thereby controlling the release of the Cu ions [42]. Nanocomposite monofilaments (0.5 and 1.0 wt%) of the same weight are immersed in quantitative seawater at room temperature to measure the concentration of Cu ions at different time periods and the Cu ion concentrations with different soak times are shown in Figure 8. Cu ion concentration increases with the increase of CuNP content. This is attributed to the increase in the amount of amorphous parts previously observed by DSC and DMA, and these amorphous parts could facilitate the diffusion of Cu ions. Such behaviors are in agreement with that of many other composites reported previously [43, 44], in which the ion release from polymer composites could be improved by lowering its crystallinity. The crystallinity affects the water uptake, which in turn controls the ion release. Moreover, the higher release of nanocomposite at higher CuNP content is also due to existing the larger amount of CuNP on the surface. In addition, it can be observed that CuNP/HDPE nanocomposite monofilament samples release a large amount of

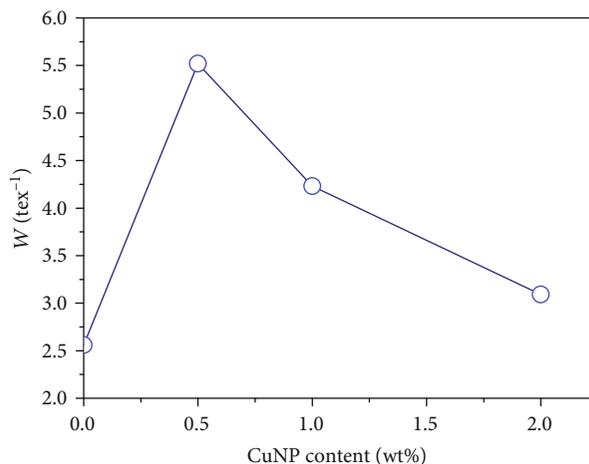


FIGURE 7: Comparison of the W of CuNP/HDPE monofilament as CuNP content.

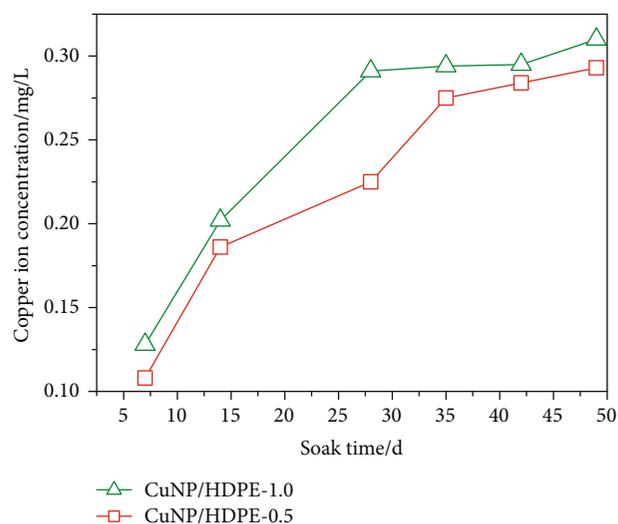


FIGURE 8: Relationship between Cu ion concentration and soaking time of nanocomposite monofilament.

Cu ions in the first few weeks. One month later, the Cu ion release rate becomes weaker. This is because of the “burst effect” of Cu ions for composites [45].

3.8. Evaluation of the Antifouling Effect of Fishing Netting. CuNP/HDPE-1.0 nanocomposite monofilaments with optimal overall performance were twisted into a 36tex \times 10 \times 3 netting twine to prepare knotted netting with a mesh length of 25 mm. Coupon test was used to evaluate antifouling performance from May to October 2018 in the shallow sea area of the South China Sea.

As shown in the photos of several sets of netting in Table 1, the attached fouling organisms on CuNP/HDPE netting are less than the HDPE netting at the same period of time. After six months, HDPE netting is completely covered by the attached fouling organisms, and the surface of the CuNP/HDPE netting also has some shellfish and algae attached. The netting of the same area is cropped and weighed. The results show that CuNP/HDPE nanocomposite

TABLE 1: Marine test results of CuNP/HDPE and HDPE fishing nets.

Netting	Soaking time/month		
	1	3	6
CuNP/HDPE nanocomposite netting			
HDPE netting			

mesh shows lower weight gain than the HDPE mesh (reduced by 32%). Hence, the CuNP/HDPE netting has a certain repellent effect on attaching organisms.

4. Conclusion

We can conclude that the content of CuNP has significant effects on the morphology and properties of CuNP/HDPE nanocomposite monofilaments. When the CuNP content was ranging from 0.5 wt% to 1.0 wt%, CuNP presented nano-scale and uniform distribution in the HDPE monofilament matrix. And the X_c , T_g , E' , and ΔE_a of nanocomposite monofilaments were higher than that of HDPE monofilament. Moreover, the mechanical properties and wear resistance of CuNP/HDPE nanocomposite monofilaments with low CuNP contents were superior to those of HDPE monofilaments. When CuNP content increased to 2.0 wt%, the mechanical properties and wear resistance decreased resulting from the aggregation of CuNP. In addition, Cu ion concentration increased with the increase of CuNP content, which attributed to the increase in the amount of amorphous parts. Burst release of Cu ions was observed in the first few weeks. Coupon tests observed that CuNP/HDPE nanocomposite mesh showed less weight gain than HDPE mesh during the same period of time; therefore, the CuNP/HDPE nanocomposite netting had better antifouling performance than pure HDPE netting. This study highlights the CuNP/HDPE netting to use as a potential fishing netting to prevent fouling in the aquaculture cage nets.

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

This work was supported by the National Natural Science Foundation of China (Grant Nos. 31502213, 31872611, and 31972844), Central Public-interest Scientific Institution Basal Research Fund, CAFS (Grant No. 2019CY0304), Special Scientific Research Funds for Central Non-profit Institutes (East China Sea Fisheries Research Institute, Chinese Academy of Fishery Sciences) (Grant No. 2019T04), and Earmarked Fund for China Agriculture Research System (Grant No. CARS-50).

References

- [1] S. Eichhorn, J. Hearle, M. Jaffe, and T. Kikutani, *Handbook of Textile Fibre Structure: Volume 1: Fundamentals and Manufactured Polymer Fibres*, Elsevier, 2009.
- [2] H. A. McKenna, J. W. Hearle, and N. O'Hear, *Handbook of Fibre Rope Technology*, Elsevier, 2004.
- [3] J. M. L. Ramos and C. V. Islands, *Chemical and Physical Properties of Synthetic Fibres Most Commonly Used in Fishing Gear, with Reference to Their Use in Cape Verde Fisheries*, UNU, Fisheries Training Programme, 1999.
- [4] J. Van Dingenen, "Gel-spun high-performance polyethylene fibres," in *High-Performance Fibres*, pp. 62–92, Woodhead Publishing, 2001.
- [5] P. C. Shannon and F. D. Ehrman, "High Density Polyethylene," US Patent No. 7,595,364, 2009.
- [6] S. N. Thomas and C. Hridayanathan, "Substitution of polyamide multifilament by polyethylene twisted monofilament in large mesh gill nets," *Fishery Technology*, vol. 39, no. 2, pp. 100–106, 2002.
- [7] K. Radhalekshmy and S. Gopalan Nayar, "Synthetic fibres for fishing gear," *Fishery Technology*, vol. 10, no. 2, pp. 142–165, 1973.
- [8] B. Meenakumari and K. Ravindran, "Tensile strength properties of polyethylene netting twines under exposure to outdoor and artificial UV radiation," *Fishery Technology*, vol. 22, no. 2, pp. 83–86, 1985.
- [9] M. Kaiser, B. Bullimore, P. Newman, K. Lock, and S. Gilbert, "Catches in 'ghost fishing' set nets," *Marine Ecology Progress Series*, vol. 145, pp. 11–16, 1996.

- [10] H. Moe, A. Olsen, O. S. Hopperstad, Ø. Jensen, and A. Fredheim, "Tensile properties for netting materials used in aquaculture net cages," *Aquacultural Engineering*, vol. 37, no. 3, pp. 252–265, 2007.
- [11] S. Dürr and D. I. Watson, "Biofouling and antifouling in aquaculture," in *Biofouling*, pp. 267–287, Wiley, 2010.
- [12] C. W. Bi, Y. P. Zhao, G. H. Dong, Z. M. Wu, Y. Zhang, and T. J. Xu, "Drag on and flow through the hydroid-fouled nets in currents," *Ocean Engineering*, vol. 161, pp. 195–204, 2018.
- [13] E. Almeida, T. C. Diamantino, and O. de Sousa, "Marine paints: the particular case of antifouling paints," *Progress in Organic Coatings*, vol. 59, no. 1, pp. 2–20, 2007.
- [14] N. Clough, *Fishing line and methods for making the same*, Google Patents, 2005.
- [15] S. Mishra, M. Misra, S. S. Tripathy, S. K. Nayak, and A. K. Mohanty, "Graft copolymerization of acrylonitrile on chemically modified sisal fibers," *Macromolecular Materials and Engineering*, vol. 286, no. 2, pp. 107–113, 2001.
- [16] C. Powell and H. Stillman, *Corrosion behaviour of copper alloys used in marine aquaculture*, International Copper Association, Ltd., New York, 2009.
- [17] M. R. Swift, D. W. Fredriksson, A. Unrein, B. Fullerton, O. Patursson, and K. Baldwin, "Drag force acting on biofouled net panels," *Aquacultural Engineering*, vol. 35, no. 3, pp. 292–299, 2006.
- [18] E. Lindner, "Failure mechanism of copper antifouling coatings," *International Biodeterioration*, vol. 24, no. 4-5, pp. 247–253, 1988.
- [19] N. Cioffi, L. Torsi, N. Ditaranto et al., "Copper nanoparticle/polymer composites with antifungal and bacteriostatic properties," *Chemistry of Materials*, vol. 17, no. 21, pp. 5255–5262, 2005.
- [20] L. Yu, S. Yang, H. Wang, and Q. Xue, "An investigation of the friction and wear behaviors of micrometer copper particle- and nanometer copper particle-filled polyoxymethylene composites," *Journal of Applied Polymer Science*, vol. 77, no. 11, pp. 2404–2410, 2000.
- [21] G. A. Gelves, B. Lin, U. Sundararaj, and J. A. Haber, "Low electrical percolation threshold of silver and copper nanowires in polystyrene composites," *Advanced Functional Materials*, vol. 16, no. 18, pp. 2423–2430, 2006.
- [22] Y. Gotoh, R. Igarashi, Y. Ohkoshi, M. Nagura, K. Akamatsu, and S. Deki, "Preparation and structure of copper nanoparticle/poly (acrylic acid) composite films," *Journal of Materials Chemistry*, vol. 10, no. 11, pp. 2548–2552, 2000.
- [23] J. A. Molefi, A. S. Luyt, and I. Krupa, "Comparison of the influence of copper micro- and nano-particles on the mechanical properties of polyethylene/copper composites," *Journal of Materials Science*, vol. 45, no. 1, pp. 82–88, 2010.
- [24] M. C. Vu, Q.-V. Bach, D. D. Nguyen, T. S. Tran, and M. Goodarzi, "3D interconnected structure of poly(methyl methacrylate) microbeads coated with copper nanoparticles for highly thermal conductive epoxy composites," *Composites Part B: Engineering*, vol. 175, article 107105, 2019.
- [25] T. Xu, H. Lei, S. Z. Cai, X. P. Xia, and C. S. Xie, "The release of cupric ion in simulated uterine: New material nano-Cu/low-density polyethylene used for intrauterine devices," *Contraception*, vol. 70, no. 2, pp. 153–157, 2004.
- [26] T. Kruk, M. Gołda-Cępa, K. Szczepanowicz et al., "Nanocomposite multifunctional polyelectrolyte thin films with copper nanoparticles as the antimicrobial coatings," *Colloids and Surfaces B: Biointerfaces*, vol. 181, pp. 112–118, 2019.
- [27] K. C. Anyaogu, A. V. Fedorov, and D. C. Neckers, "Synthesis, characterization, and antifouling potential of functionalized copper nanoparticles," *Langmuir*, vol. 24, no. 8, pp. 4340–4346, 2008.
- [28] S. Jose, A. S. Aprem, B. Francis et al., "Phase morphology, crystallisation behaviour and mechanical properties of isotactic polypropylene/high density polyethylene blends," *European Polymer Journal*, vol. 40, no. 9, pp. 2105–2115, 2004.
- [29] Woods Hole Oceanographic Institute, *Marine Fouling and Its Prevention*, US Naval Institute, Annapolis, 1952.
- [30] J. Bastidas, E. Cano, and N. Mora, "Copper corrosion-simulated uterine solutions," *Contraception*, vol. 61, no. 6, pp. 395–399, 2000.
- [31] K. Lu, N. Grossiord, C. E. Koning, H. E. Miltner, B. van Mele, and J. Loos, "Carbon nanotube/isotactic polypropylene composites prepared by latex technology: morphology analysis of CNT-induced nucleation," *Macromolecules*, vol. 41, no. 21, pp. 8081–8085, 2008.
- [32] D. Homminga, B. Goderis, I. Dolbnya, and G. Groeninckx, "Crystallization behavior of polymer/montmorillonite nanocomposites. Part II. Intercalated poly(ϵ -caprolactone)/montmorillonite nanocomposites," *Polymer*, vol. 47, no. 5, pp. 1620–1629, 2006.
- [33] A. Schönhals, H. Goering, F. R. Costa, U. Wagenknecht, and G. Heinrich, "Dielectric properties of nanocomposites based on polyethylene and layered double hydroxide," *Macromolecules*, vol. 42, no. 12, pp. 4165–4174, 2009.
- [34] P. J. Purohit, D.-Y. Wang, F. Emmerling, A. F. Thünemann, G. Heinrich, and A. Schönhals, "Arrangement of layered double hydroxide in a polyethylene matrix studied by a combination of complementary methods," *Polymer*, vol. 53, no. 11, pp. 2245–2254, 2012.
- [35] A. Yasmin, J. J. Luo, J. L. Abot, and I. M. Daniel, "Mechanical and thermal behavior of clay/epoxy nanocomposites," *Composites Science and Technology*, vol. 66, no. 14, pp. 2415–2422, 2006.
- [36] C. L. Wei, M. Q. Zhang, M. Z. Rang, and K. Friedrich, "Tensile performance improvement of low nanoparticles filled-polypropylene composites," *Composites Science and Technology*, vol. 62, pp. 1327–1340, 2002.
- [37] P. Pieranski, S. Kasas, G. Dietler, J. Dubochet, and A. Stasiak, "Localization of breakage points in knotted strings," *New Journal of Physics*, vol. 3, no. 1, p. 10, 2001.
- [38] W. Yu, L. Wang, and J. Shi, "Influence of drawing and annealing on the crystallization, viscoelasticity, and mechanical properties for middle-molecular-weight polyethylene fishing monofilaments," *Fibers and Polymers*, vol. 19, no. 5, pp. 1050–1056, 2018.
- [39] H. Nakayasu, H. Markovitz, and D. J. Plazek, "The frequency and temperature dependence of the dynamic mechanical properties of a high density polyethylene," *Transactions of the Society of Rheology*, vol. 5, no. 1, pp. 261–283, 1961.
- [40] R. Popli, M. Glotin, L. Mandelkern, and R. S. Benson, "Dynamic mechanical studies of α and β relaxations of polyethylenes," *Journal of Polymer Science: Polymer Physics Edition*, vol. 22, no. 3, pp. 407–448, 1984.
- [41] Y. Gao, R. Zhang, W. Lv et al., "Critical effect of segmental dynamics in polybutadiene/clay nanocomposites characterized

- by solid state ^1H NMR spectroscopy,” *The Journal of Physical Chemistry C*, vol. 118, no. 10, pp. 5606–5614, 2014.
- [42] A. B. Samui, J. G. Chavan, and V. R. Hande, “Study on film forming organo-copper polymer,” *Progress in Organic Coatings*, vol. 57, no. 4, pp. 301–306, 2006.
- [43] H. Palza, R. Quijada, and K. Delgado, “Antimicrobial polymer composites with copper micro- and nanoparticles: effect of particle size and polymer matrix,” *Journal of Bioactive and Compatible Polymers*, vol. 30, no. 4, pp. 366–380, 2015.
- [44] R. Kumar and H. Münstedt, “Polyamide/silver antimicrobials: effect of crystallinity on the silver ion release,” *Polymer International*, vol. 54, no. 8, pp. 1180–1186, 2005.
- [45] M. Bertuola, C. A. Grillo, and M. F. L. de Mele, “Eradication of burst release of copper ions from copper-bearing IUDs by a phytocompound-based electropolymeric coating,” *Materials Letters*, vol. 252, pp. 317–320, 2019.

