A comprehensive review of mechanical and tribological behavior of bio-polymer composites

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Abstract

In the present study, the mechanical and tribological behaviors of bio-polymer composite materials are reviewed. Focusing on the critical findings of research studies in this field, this study explores diverse features, such as biodegradability, renewability, low density, non-abrasiveness, and suitability for a broad range of applications. Insights are provided into the effects of various factors (e.g., load, sliding speed, and temperature) on friction and wear performance. The contributions of fiber and filler modifications to improved mechanical attributes are also highlighted. This study emphasizes the use of natural fiber-reinforced bio-polymer composites, which are environmentally friendly and cost-effective alternatives to synthetic fiber-reinforced plastics. This study underscores the need for further research to understand property–structure relationships to optimize composite properties, which will open new possibilities for boosting the adoption of bio-polymer composites in diverse applications.

Keywords: Natural composite, mechanical properties, green composites, tribological properties

1. Introduction

Composites [1][2] play essential roles in material science, particularly biopolymer composites, which have attracted increasing attention. These composites combine two or more unique natural materials to create recognizable interfaces [3]. They are widely regarded because of their structural potential and tribological, thermal, and electrical properties. This feature allows biopolymer composites to be used in various applications [4]. A diverse range of biopolymers, including thermoplastics, thermosetting plastics, and elastomers, serve as the basis for the development of biopolymer nanocomposites. Properly designed nanocomposites exhibit superior performance. Nanotechnology has led to the development of biopolymer matrix-based nanocomposites[5]. Parts produced using biopolymers to create structural components exhibit an impressive strength-to-weight ratio.

Polylactic acid (PLA) enhanced with nanocellulose is an excellent example of this phenomenon. This enhancement has led to the development of lightweight yet solid automotive parts that decrease vehicular weight and augment fuel efficiency[6]. The improved efficiency of energy applications is equally impactful. For instance, the inclusion of these enhanced materials in wind turbine blades creates more durable components that yield higher energy outputs. A standard biopolymer nanosystem requires the addition of natural nanoparticles to a biopolymer resin, which is further reinforced with natural fibers such as hemp, flax, or jute. This combination is processed via extrusion or compression molding techniques to create the final biopolymer nanocomposite. This is a sustainable alternative to conventional composites and is suitable for many industrial applications [7].

Biopolymers have attracted significant research attention because of their potential applications in the healthcare, pharmaceutical, electronics, automotive, and other fields. These are natural polymers that are produced by living organisms and are pivotal elements in maintaining ecological balance [8]. Owing to their biodegradability, sustainability, and non-toxicity, they are considered environmentally friendly substitutes for artificial non-biodegradable polymers. These polymers are derived from various sources, including animals (e.g., silk, wool, DNA, and chitin), plants (e.g., cellulose, pectin, and starch), and microorganisms. Biopolymer synthesis, mainly through condensation polymerization and the subsequent addition of monomer units, results in high-molecular-mass configurations [9]. Bespoke biopolymers can be developed for specific applications by modifying the synthetic process. Their applications have spread across many fields, including medicine (tissue engineering and drug delivery), food packaging, agriculture (biofertilizers and biopesticides), and wastewater treatment. Biopolymers constitute a vital and versatile resource, and the magnitude of their potential is only increasing as they gain further recognition for their industrial and environmental advantages. Their crucial role in maintaining ecological equilibrium underscores their relevance in driving environmentally friendly initiatives [9].

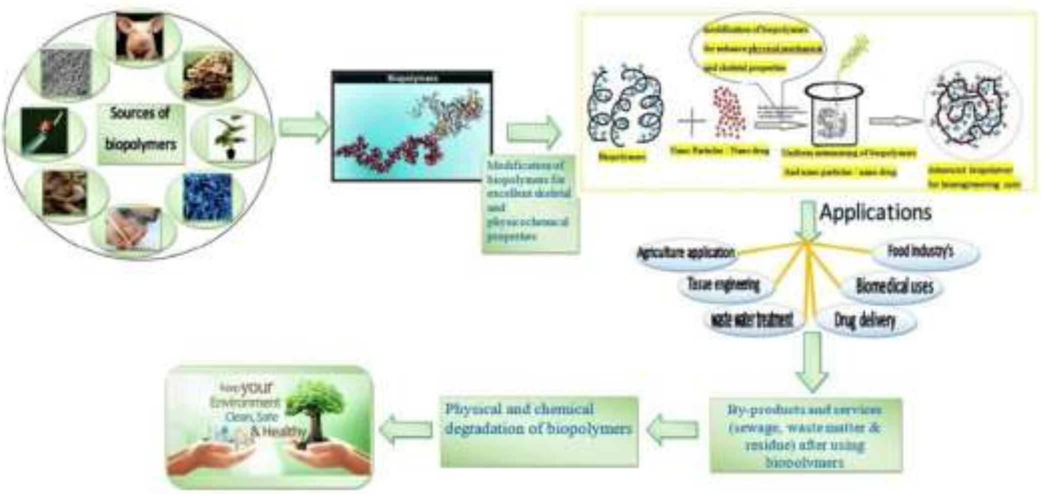

Fig. 1 Sources, synthesis, and applications of biopolymers[10]

Biopolymer nanocomposites are fundamentally multiphase solid materials in which at least one phase has dimensions smaller than 100 nm. Owing to intensive research and development, nano-reinforcements in biopolymers have attracted significant attention[11]. The key advantages of these nanocomposites include enhanced mechanical strength, toughness, increased wear resistance, and improved thermal and electrical conductivity by adding a minimal amount of nanoparticles by weight. Biopolymer composites can be classified based on their matrix as natural polymer matrix composites and synthetic biopolymer matrix composites[12]. Biopolymer nanocomposites are increasingly used in engineering applications in which tribological properties are crucial. To enhance these properties, natural fibers such as flax, hemp, and jute, as well as nanoparticles such as nanocellulose, nanoclay, and biochar, are incorporated into the biopolymer matrix. Incorporating nanoparticles, such as nanocellulose or nanoclay, in small quantities significantly enhances the mechanical properties. This enhancement is primarily due to the improved load-bearing capacity of the reinforcement components, which reduces wear by limiting the action of abrasive mechanisms. These advanced materials offer a sustainable alternative with superior performance characteristics, making them suitable for multiple industrial applications, including automotive parts, packaging materials, and medical devices.

The present study was meticulously organized to scrutinize a wide range of parameters in the literature. Specifically, it focuses on investigating the mechanical and tribological properties of biopolymers. These parameters were examined in depth to identify methods for improving the quality standards of composites. This study emphasizes the importance of understanding the behavior and attributes of biopolymers and devising conclusive strategies for improving composite quality. The primary goal is to improve the quality of these materials, thus enabling potentially revolutionary applications in numerous fields.

2. Review of mechanical and Tribological behavior of bio-polymers

2.1 Mechanical behaviour of bio-polymer composite materials

The mechanical attributes of biopolymer composite materials are remarkable. These substances offer an exceptional combination of robustness and adaptability. Their ability to withstand stress, compression, or distortion has vast potential applications. Importantly, these materials ensure environmental sustainability because of their bio-derived nature. The enhanced physical properties, coupled with the prospect of biodegradation, highlight the appeal of these composite materials. The applications of biopolymer composites span various sectors, from construction to packaging. Efforts to improve the configuration of these materials and optimize their performance are ongoing. Therefore, this field presents an exciting platform for technological advancement and eco-friendly practices. Researchers have reported studies on biopolymers and their mechanical parameter enhancement; the details are provided below.

Sang-Young Kim et al. [13] studied the mechanical properties of materials from vinyl ester epoxy resin combined with glass fiber-reinforced fillers. They utilized two processes, vacuum infusion and hand layup, to prepare the samples. Their analysis of the tensile strength, compressive strength, and in-plane shear properties revealed that the samples processed using the vacuum infusion method exhibited superior mechanical attributes compared to those produced via the hand layup process. This can be explained by the increased porosity of the hand layup technique, which negatively affects the physical properties of the end product. Mouritz et al. [14] presented an in-depth analysis of fiber-reinforced polymer composites usage in naval vessels. These materials offer an excellent strength-to-weight ratio and support various applications, including reducing vessel weight, increasing speed, reducing fuel consumption, augmenting corrosion resistance, and reducing maintenance costs. Insightful research provides valuable contributions to the advancement of naval shipbuilding technology.

Selvaraju et al. [15] presented an innovative application of CFRP and GFRP in marine structures. This study highlights critical applications, including naval boats and submarine tanks. The authors argue that these materials reduce weight, enhance corrosion resistance, and increase the strength-to-weight ratio, thereby offering significant advancements and potential applications in the marine industry. Vallbo [16] analyzed transportation components made from a vinyl ester matrix, PVC core material, and carbon fiber reinforcement and demonstrated promising results. This revealed enhanced mechanical and electrical properties, lighter weight, lower fuel consumption, greater environmental sustainability, and increased payload capacity. The authors presented a study to advance efforts to improve transportation design. Further research on these findings and their practical applications is required.

2.2 Tribological (Friction and Wear) behavior of bio-polymer composite materials

Biopolymer composite materials exhibit noteworthy tribological behavior. Friction and wear have immense potential in various applications owing to their biodegradability and renewability. These materials are subjected to mechanical pressure, resulting in friction and subsequent wear. Understanding the tribological properties of biopolymer composites enables the engineering of optimal materials for specific applications. Therefore, studying their tribological behavior is important for advancing sustainable technologies. These biocomposites can replace conventional materials, reducing their environmental impact while improving technological performance. Extensive research in this field has led to the development of eco-friendly and efficient solutions. Some studies reported in the literature that focus on tribological behavior are discussed as follows.

Chun et al. [17]scrutinized nanoclay's mechanical performance within epoxy composites across various compositions, with nanoclay's percent by weight varying from 0 to 4%. Notably, a direct relationship between the nanoclay concentration and the robustness and wear resistance of the material was observed, albeit contingent on the extent of agglomeration of the nanoclay clusters within the composite. Jawahar et al. [18]reported a detailed analysis of pristine polyester, conventional clay-filled composite, and polyester infused with nanoclay. Intriguingly, the study revealed that the nanocomposites outperformed the rest, with a significant improvement of up to 20% in flexural properties and 85% in wear properties. Based on this study, there is clear value in further exploring nanocomposite applications. Lingaraju et al. [19]examined the mechanical and tribological properties of hybrid polymer composites with nanoparticles. Their findings indicated that incorporating nanoparticles, such as silica and clay, into the glass fiber-reinforced epoxy composite from 0% to 3% by weight, significantly boosted properties such as tensile strength, impact strength, hardness, and wear rate. This surpassed the performance of the original composite material.

Xin-Rui et al. [20] assessed the interplay of friction and wear in various compositions of Polyimide (PI) with short carbon fibers (SCFs), micro SiO2, and graphite particles. Their findings indicated an enhancement in the tribological attributes when SCF and graphite particles were mixed with PI, whereas the addition of SiO2 to PI induced opposite effects. The most promising outcomes were obtained when PI was mixed with SCF, graphite, and micro SiO2 particles. Dong et al. [21]studied polymethyl methacrylate/styrene and multiwall carbon nanotubes, offering significant findings. Utilizing CNT composites varying from–0-3 % in increments of 0.5 %, they noted an increase in microhardness as the CNT percentage increased; interestingly, the friction coefficient and wear rate decreased with increasing CNT concentration. The combination with 1.5% CNT was superior, exhibiting the highest wear resistance and negligible friction coefficient. Thus, their research provides valuable insights into the field of materials engineering.

3. Discussion on results

The field of material research is witnessing increased attention towards biopolymer composites. Two or more unique natural materials present a recognizable interface. Their structural, tribological, thermal, and electrical properties have great potential for a wide range of applications. The fundamental components of these nanocomposites are biopolymers, such as thermoplastics, thermosetting plastics, and elastomers. These composites exhibit superior properties when designed efficiently, making them suitable for various industrial applications. For instance, polylactic acid (PLA) integrated with nanocellulose can be used to create lightweight and robust automotive parts that enhance fuel efficiency. Additionally, such composites infused into wind turbine blades can aid in generating higher energy yields.

Biopolymers are natural polymers derived from living organisms and are crucial for maintaining ecological balance. Properties such as biodegradability, sustainability, and non-toxicity make them environmentally friendly alternatives to non-biodegradable artificial polymers. The sources of these polymers are extensive and range from plants and animals to microorganisms. The development of biopolymer nanocomposites is a multistep process in which natural nanoparticles are added to a biopolymer resin. This is then reinforced with natural fibers, such as hemp, flax, or jute, and processed via extrusion or compression-molding techniques to create the final product. Such composites, also known as nanoparticle-reinforced biopolymers, have received considerable attention because of their enhanced mechanical strength, toughness, and wear resistance.

This study conducted an in-depth analysis of the mechanical and tribological attributes of biopolymers[22]. Understanding these parameters can help develop strategies for improving the quality standards of composites, further revolutionizing their applications in multiple fields. Research has shown that biopolymer composite materials offer a unique blend of robustness and adaptability to environmental changes. They can withstand stress and distortion, making them ideal for applications across sectors such as construction and packaging. To improve the performance of these materials, Kim et al. [13] found that samples processed using the vacuum infusion method presented superior mechanical attributes compared to those developed using the hand layup process. The tribological behavior of these composite materials also shows immense potential, particularly in terms of their friction and wear properties. This understanding is of utmost significance for creating optimal and sustainable technological solutions. According to a study by Xin-Rui et al. [20], the tribological properties of these materials were enhanced when short carbon fibers and graphite particles were mixed. Thus, the potential and versatility of biopolymers, combined with their ecological benefits, present a promising roadmap for environmentally friendly initiatives.

4. Conclusions

Biopolymer composites, which are combinations of multiple natural materials, exhibit remarkable structural potential and various properties, making them invaluable for numerous applications. Being environmentally friendly, biodegradable, and non-toxic, these substitutes for artificial non-biodegradable polymers are crucial for ecological equilibrium and environmentally friendly initiatives. They have found significant use in the healthcare, pharmaceutical, and electronics industries, among others. Biopolymer nanocomposites with enhanced mechanical strength, toughness, wear resistance, and other qualities are particularly useful in industries where tribological properties are essential. In addition to their remarkable mechanical properties, these bio-derived materials offer environmental sustainability and applications across sectors, from construction to packaging. Studying the tribological behavior of these materials is of immense importance for advancing sustainable technologies. These findings indicate that these composites can replace conventional materials, thereby reducing environmental impact and improving technological performance.

5. Future scope of work

The future holds great promise for continued research and exploration of biopolymer composites, such as graphene and basalt, starch/polyvinyl alcohol (PVA), and PLA/natural fiber composites. Their distinctive properties have expanded their potential applications in diverse fields, such as healthcare and electronics. The biodegradability and non-toxicity of these composites make them eco-friendly alternatives, contributing positively to sustainability initiatives. Enhancing the mechanical strength, toughness, and other properties by incorporating nanoparticles presents vast potential for innovation. Applications extend from the creation of lightweight and fuel-efficient automotive components. Future work will reveal more of their benefits and open the versatility of this field, as it continues to provide valuable contributions to industry and the environment.

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