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Review article

From nanotechnology to environmental impact: a comparative study of synthetic and biopolymers- a review

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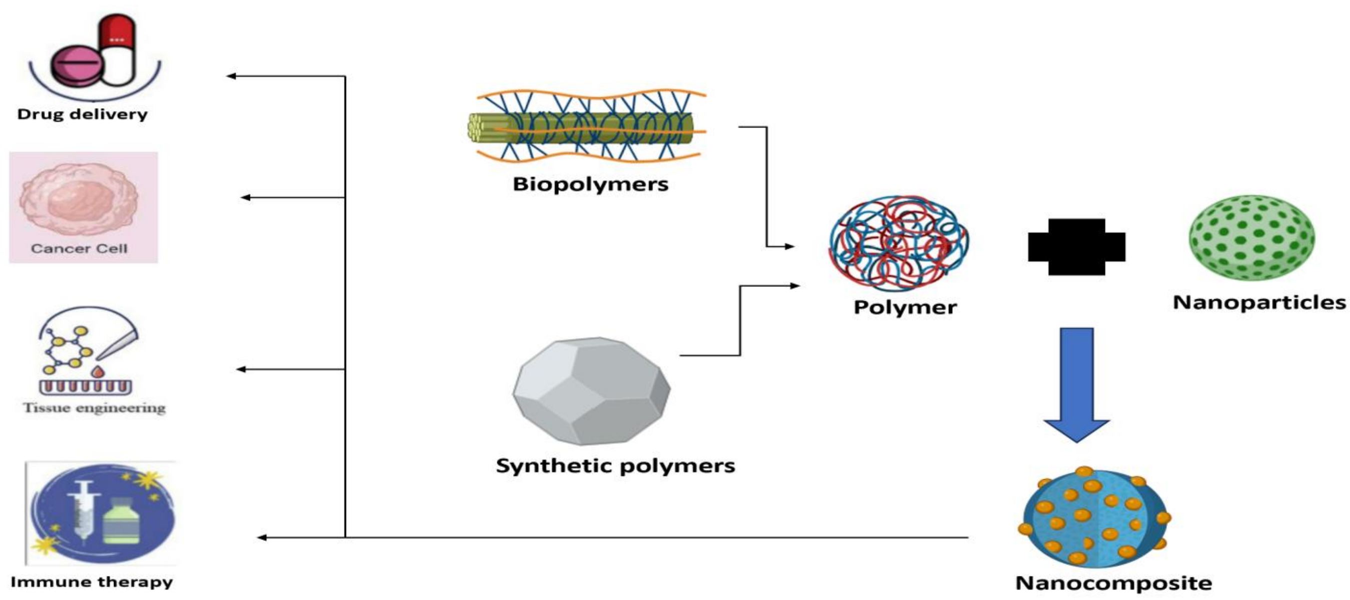
ABSTRACT

Synthetic polymers, celebrated for their superior mechanical properties and thermal stability, have become indispensable in fields such as medicine, packaging, and electronics. However, their poor biodegradability presents a major environmental challenge, significantly contributing to the escalating global plastic waste crisis. In contrast, biopolymers, derived from renewable resources, offer distinct advantages such as biodegradability and biocompatibility. These materials are gaining prominence in controlled drug delivery systems, tissue engineering, and environmental applications, aligning seamlessly with the principles of green chemistry and sustainable development. Despite these promising features, the extensive application of biopolymers is hindered by several challenges.



High production costs, limited scalability, and comparatively weaker mechanical properties restrict their utilization in broader industrial applications. Furthermore, advancements in biopolymer technology have yet to fully bridge the gap between performance and sustainability, necessitating innovative approaches to enhance their properties while maintaining eco-friendliness. To address these limitations, integrating synthetic and biopolymer-based technologies has emerged as a promising strategy. This hybrid approach combines the strengths of both material classes, providing opportunities for innovation while addressing critical sustainability concerns. Such integration has the potential to revolutionize material science, offering solutions that balance performance, cost-effectiveness, and environmental impact. This review comprehensively compares synthetic and biopolymers, critically examining their synthesis, properties, applications, and challenges. It highlights their roles in sustainable development and underscores the need for synergistic and creative solutions in material engineering. By focusing on recent advancements and future trends, this paper aims to provide insights into the strategic utilization of polymers to achieve long-term environmental and industrial goals.

Keywords: Synthetic polymer, Biopolymers, Nanotechnology, Nanoparticles, Drug delivery system.

INTRODUCTION

Several natural polymers such as cellulose, silk and natural rubber had existed in one form or the other right from the antiquity. The history of synthetic polymers reached to modern period in the beginning of twentieth century and was effectively affected to many disciplines. In the early twentieth century, it began with invention of Bakelite by the chemist Leo Baekeland the same year as 1907 and this formed a base and several synthetic polymers such as polyethylene, nylon, PVC among others flood the market. On the other hand, the use of biopolymers dates back to civilization of humans although its application in various areas has revolved around the modern society. Among the natural polymers which have been used in the past in such applications as in cloth making as well as in food include cellulose and proteins. The current interest in biopolymers can, therefore, be blamed on environmental problems arising out of the use of conveniences polymers such as plastics as well as the exhaustion of natural resources [1]. With regard to the sustainable material, the idea has directed focus on not only the biopolymers but also the research and development possibilities of the biopolymers.

Polymers are very large molecules that are produced from monomers which are units that are chemically linked and are large in size. Macromolecules possess the highest molecular mass, and the reason is that these polymers have special properties because of structural change. Natural polymers can be categorized into natural biopolymers and natural synthetic polymers while the second category includes: organic synthetic materials [2]. This has done a good job in articulating how polymer materials have become essential commodities in the society today due to their integration to almost all areas of human life. Its applications in many fields are immense: packaging, construction, automotive, electronics, healthcare requirements, textiles and some others. Thus, it would be quite reasonable to state that the especial proneterist of the polymers are versatility, high durability and comparatively low costs which make them the fundamentals of the contemporary production and designing. Thus, in the medical field, it is used in operation tools, prosthetic appliances, delivery equipment for drugs, dispensable treatments and the like. Polymer and silicone that are generally used and usually coated with substrates are also referred because it is non-active and tends to be flexible. Plastics currently in use in packaging since they are light, flexible and the creation of hermetic and moisture proof barriers. Polyethylene, polypropylene and PET are therefore the most commonly used packaging materials in the food packaging us, bottles and containers.

Depending on the source, polymers are classified by a.

Natural Polymers

Originated from animal and plant sources. These are in the form of cellulose, proteins and natural rubber among others the major roles of these are to provide strength, support and shape of the plants.

b. Synthetic Polymers: Products that are made from synthetic polymers using chemical reaction methods. It is comprised of polyethylene, nylon, polystyrene among other related products.

The fields of polymers synthetic and biopolymers also had remaining research works which in one way or the other were aimed at eradicating some of the flaws associated with them and at the same time enhancing their applications [3]. Concerning the synthetic polymers, other improvements under working that has been made and put into practice includes development of a technique that enhance the degree of recycling, having polymers that degrade and use of renewable resources in making the polymer[4]. New trends in the polymer recycling, the chemical recycling and depolymerisation techniques are also entering the stage and they seem to offer proper handling of the plastic waste. Regarding the bio-polymers what has been established is that this is being done to enhance the properties and characteristics of the end product, to reduce the cost of manufacturing the same as well as to look at new markets for selling the same. It has been evident that there are social advantages such as the constant enhancement of the synthesis process of biopolymers based on the agricultural refuse or genetically-engineered microorganisms, which in the long run strengthened economical factor of biopolymers. In addition, research that focuses on the biopolymer composites and chemically modifying them has improved on their properties to be able to substitute synthetic polymers in several uses [5]. Altogether one major difference between the synthetic and biopolymers refers to its impact on the environment. Nonetheless, synthetic polymers have superior mechanical properties and wear resistance and, at the same time, environmental problems arise. Such characteristics lead to persistent existence in various environments, hence they pollute and negative effects on the ecology [6]. People are now mindful that the waste plastics employed ad nauseam are threatening the aquatic and earth habitats alongside landfill centres, hence the search for improved plastics. These problems may be considered solved by biopolymers due to their character of degradability and origin from renewable resources. Plastics like PLA and PHA breaks down under environmental conditions hence would reduce the effect of plastics in the environment. Thirdly, cyclic aspects of biopolymer production based on renewable feedstock's; therefore, the increase of resource efficiency and the decrease of the use of fossil resources [7]. This review paper deals with the critical comparison of synthetic and biopolymers with their properties and applications.

Synthetic Polymers in Nanotechnology

Development of polymer Nan composites falls under nanotechnology. More exactly, these materials are a kind of polymer matrix that holds nanoparticles embedded, and any physical property, chemical, and mechanical of the polymer may be greatly improved. This hence includes elevation, improvements in thermal stability, electrical conductivity, and opening up new windows of opportunity for a huge range of advanced applications. It has the most promising application in the field of detection and treatment of various forms of cancer. The Nanocarrier replaced the conventional DDS for the anticancer drugs since they had no specificity and the problems of burst release. Nanocarrier do not show any kind of side effects and are found to be safe for the normal cells. The Nanocarrier themself helps in increasing the efficacy of the anticancer drugs by selecting and accumulating at the desired site. Few Nanocarrier are approved for the clinical use in humans for certain activities. Nano-formulations having the properties of PLA, PEG, poly (vinyl pirrolidone-co-vinyl acetate) copolymer, PAA and PVA-co-albumin were used to nano-deliver Sorafenib [8]. They can substitute biodegradable polyesters in Nanocarrier. These form quite promising targeted delivery routes due to the ease of production to modulate the hydrophilic/hydrophobic balance and carry molecules for specific activities.

A dual-responsive amphiphilic random copolymer of tri (ethylene glycol)-methyl ether methacrylate and [1′-(2-acryloxy)-3, 3′-dimethyl-6-nitrospiro-(2H-1-benzopyran-2, 2′-indoline)] with DOX showed an active agent for the anticancer activity [9]. The amphiphilic PU forms polyurethane PU-DOX nanoparticles through electrostatic interactions of carboxyl-containing groups of PU-COOH and DOX·HCl in the aqueous media.

The new growth in medical technology has developed the nanoparticles which are termed Nan composites, and does not have any after effect or die off the healthy cells and they are responsive to the internal and the external stimulants. They are therefore able to substitute the traditional drug carriers and even the polymer drug carriers. The nanoparticles used in the polymer composites can generally be classified into a few based on their composition and nature of properties. Among them include the following: Inorganic nanoparticles and Organic nanoparticles.

Inorganic Nanoparticles

In particular, CNTs demonstrate very high mechanical durability and electrical conductance. Because dispersion is good in a polymer matrix, it will enhance the tensile strength, elasticity, and electric properties of the composite derived from the material. Therefore, their area of applicability is pretty wide—from the aerospace to the electronic industries, passing through the automotive industry. Graphene is a carbon nanoparticle with exceptionally high mechanical, thermal, and electrical properties. Graphene-polymer composites have improved mechanical strength and electrical conductivity, holding immense potential in flexible electronic applications, sensors, and energy storage devices [10].

Silica Nanoparticles: The next very important inorganic nanoparticle used to enhance the mechanical properties and thermal stability of the polymers is silica nanoparticles. Silica nanoparticles are employed in coatings, adhesives, and sealants for improved durability and performance under very severe conditions [17].

Metallic Nanoparticles: Metallic nanoparticles of gold, silver, and iron oxide are in use for their extraordinary optical, catalytic, and magnetic characteristics [8]. Applications in which such nanoparticles are integrated with polymers include medical diagnostics, drug delivery, and magnetic storage media.

Dendrimers: These are tree-shaped structures which bear many highly branched functional end groups. These have been designed for drug delivery and biomedical applications, having a view to increase the polymer in terms of solubility, reactivity, and compatibility [11].

Polyhedral Oligomer Silsesquioxane: POSS nanoparticles combine the features of organic as well as inorganic materials, hence providing improvements both in thermal as well as mechanical improvement to the polymer matrix [14]. They find their applications in high performance coating and Nan composites in a broad range of industrial applications.

Biomedical Applications

It is the gold or silver or iron oxide and polymer Nan composites nanoparticles that open new opportunities toward drug delivery systems. The nanoparticles are able to target cells or tissues for their accumulation and then deliver the active principles in a controlled and sustained delivery way. These are iron oxide-coated polymeric nanoparticles that deliver drugs at targeted places for the treatment of cancer or tumor [12]. These particles selectively deliver the drug at the tumor cells without having much side effect on the health tissue. Table 1 discuss some of the recently used synthetic polymers with their biomedical applications.

Table 1: Synthetic polymers with their biomedical applications

Synthetic polymer	Nan fillers	Applications	Reference
Poly(ε-caprolactone) (PCL)	Cerium oxide nanoparticles	Antioxidant and wound healing	26
Poly(N-vinylcaprolactam) (PVCL)	Temperature-responsive nanogels	Topical drug delivery systems	27
Polyetheretherketone (PEEK)	Ag NPs	Bactericidal coatings for medical devices	28
Poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS)	Conjugated polymer nanoparticles	Photo thermal therapy for cancer treatment	29
Poly(acrylic acid) (PAA)	Chitosan-based nanoparticles	Gene delivery and protein delivery systems	30

Tissue Engineering: Polymers, with the aid of nanocomposites of biocompatible nanoparticles like hydroxyapatite, help in the preparation of tissue engineering scaffolds [3]. The materials derived thereby could imitate the matrix extracellular to the cells and provide a very near-ideal environment wherein they can grow, survive, and differentiate.

Water Purification: Nan composites of Ag and TiO2 have applications in the field of water purification [10]. At this point, it would be highly intuitive that, since the materials obtained in this work from their antibacterial behaviour through degradation of organic pollutants by photo catalytic reactions, this might be an efficient and green way toward clean water.

Air Filtration: In air filtration, polymer Nan composites are designed with nanoparticles of activated carbon and metal-organic frameworks that capture the pollutants/toxins in the air. It was manifested that these materials have large surface areas, and therefore, due to the increased reactivity, the removal of airborne pollutants is enhanced. One of the major advantages of nanoparticles in synthetic polymers is that it develops a polymer Nan composite with enhanced properties in very large fields of applications. Aided by such advanced materials, it is that innovation plays the main role in fields such as biomedical, electronic, and environmental technologies in solving big problems [6]. Further research and development will also comb out new potentials to bring the impact the PNCs are having on modern technology and society to much higher levels.

Biopolymers in Nanotechnology (Nano biopolymers)

Most interest is remarked on biopolymers prepared from renewable plant, animal, and microbial sources, since most of the studied nanoparticles showed problems with biocompatibility and biodegradability. Applications of nanoparticles prepared using biomaterials range across several fields. The aim of this review paper is to present ways of preparation, properties, and applicability of biopolymer-based nanoparticles, outlining their specific advantages and potentials in different fields related to medicine, environmental science, and food technology.

Biopolymers used in Designing Nanoparticles Chitosan: Chitosan is the biopolymer cationic in nature. It is extracted from chitin, a non-toxic and well biocompatibilities biopolymer showing good biodegradability. It possesses antimicrobial activity; therefore, it has wide applications in designing the nanoparticles for the delivery of various drugs and is also exploited in gene therapy. It has amino groups, and thus the positive charge on chitosan easily undergoes functionalization or complex formation with the negatively charged groups of the drug and thereby encapsulates it for controlled release of the drug [13]. Alginate is a polysaccharide extracted from brown algae and is very popular as a gelling agent in the presence of divalent cations, for example, calcium. Alginate nanoparticles have been used in a wide range of biomedical fields, ranging from drug delivery to wound healing, because they are considered biocompatible and hydrogel-forming.

Collagen denaturation to gelatin involves degradation at variable rates, followed by release of encapsulated therapeutics. Such prepared gelatin nanoparticles can be used for drug delivery and delivery of therapeutics as part of the scaffolds made for tissue engineering. PHAs represent a class of thermoplastic, microbial polyesters. Of all kinds of biopolymers, they are biocompatible and biodegradable with high potential for exploitation in wanted medicinal and environmental applications. In this context, the PHA-such composition—based NPs are fabricated for applications in drug delivery, tissue engineering, and environmental remediation. On the other hand, the insoluble derivatives of biopolymers like collagen, elastin, chitosan, keratin, and silk are converted into their soluble counterparts through chemical and enzymatic hydrolysis for various applications. While Curcumin acts as an anticancer drug, chitosan acts as the carrier of the drugs used for chemotherapy against cancer. Because of Mucoadhesion, biocompatibility, high charge density and nontoxicity, CS finds use in medicine and pharmacy [14].

CS is a special kind of polysaccharide bearing cations. It was extracted from chitin, derived from crab and other crustacean shells. Quite importantly, the configuration of the polysaccharide could be arranged in a manner suitable for the final application. Some major advantages include colloidal stability, a tuneable membrane, and the possibility of encapsulation or integration of a wide spectrum of medications. It has been reported that CS-based matrices were applied to control the delivery of really an enormous spectrum of such biomolecules, from the very small drug molecules to big biopolymer molecules. Probably, the combination of CS and graphene can form a carrier that would load therapeutic compounds and hence allow its release in a controlled manner. Other areas of interest include the application of silver nanoparticles in biomedical studies related to cancer the agnostic. The reduction of Ag salt was performed by biocompatible polymers such as PEG, PVP, and CS. The biopolymer was tested on cell lines of human breast cancer, human lung adenocarcinoma, and mouse embryonic fibroblasts. Cancer cell proliferation has been retarded [15].

Poly (d,l,-lactic-co-glycolic acid) is the most used biodegradable and biocompatible polymer for the preparation of nanoparticles intended for biomedical applications. Carboplatin is a PT-based chemotherapy developed to be administered with Nanocarrier. In this sense, nanoparticles have been prepared conjugated with CS for enhanced FA delivery. FA/CS/PLGA These FA/CS/PLGA nanoparticles are expected to show a greater extent of cellular uptake, and therefore, tumor accumulation as a consequence of the EPR effect. CUR thiolated starch-coated nano-iron oxide particles were combined and checked against lymphocytes for their cytotoxicity and against different types of cancer cells. The CUR Nan formulation showed up to 78% drug-encapsulation efficiency in nanoparticles having a 5% polymer covering, while the loading efficiency was above 80%. From this cytotoxicity study, it had been found that this method is highly biocompatible with lymphocyte cells, but it showed pronounced cytotoxicity activity against wide range of cancer cells [16].

Dextran/nSi biopolymer Nan composites were explored as promising the agnostic systems correlated with bio imaging and son dynamic therapy. Improved removal of the biopolymer Nan composites by water stability was achieved. It has been shown in vitro that dextran-coated nanoparticles are less toxic compared to untreated nanoparticles, which might be considered an indication that coated nanoparticles have some medical value. The count of the viable cells after therapeutic ultrasonic irradiation with the embedded nanoparticles has reduced whereas the total number of the cells has almost remained the same. The resulting data opens a way for the exploiting dextran-coated porous nanoparticles in cancer imaging and SD effect [17].

Functionalization and Surface Modification

Functionalization: Biopolymer nanoparticles can be coupled with different ligands, peptides, or antibodies that enable them to target only particular cells or tissues. This would increase specificity and result in a more efficient drug delivery system [14]. For instance, folate-conjugated chitosan nanoparticles have been prepared to selectively target only those cells overexpressing folate receptors, like cancer cells.

Surface modification: In another effort to enhance the stability and biocompatibility as well as the drug-loading capability of biopolymer nanoparticles, their surface properties are modified [15]. Conjugation with polyethylene glycol, a method most commonly referred to as PEGylation, reduces the immunogenic reactions on the surface and allows the particles to remain around for a longer period in circulation in the blood stream; thus, these particles become useful for therapeutic applications.

Properties of Biopolymer Nanoparticles

Biodegradability: Due to self-degradation in vivo or in the environment, biopolymer nanoparticles never accumulate over a long period and therefore do not exert toxicity [28]. Their targeted exposition, via the rate of degradation controlled, makes them applicable through alteration of the polymer structure for a DDS of sustained release properties.

Biocompatibility: One of the outstanding properties of biopolymers is that they are by default biocompatible, and so they tend toward reducing any form of immunogenic response [29]. By so doing, nanoparticles interact with biological tissues with regard to medical applications, in which examples can be pointed out as drug delivery or tissue engineering.

Mechanical and Thermal Features

The mechanical properties of biopolymer nanoparticles differ due to the type of polymers and processing conditions involved [17]. Nan clays in biopolymer matrices strengthen the mechanical strength and stiffness of the resultant nanoparticles; hence they turn into very useful materials for packaging applications.

General Thermal Stability: The biopolymer nanoparticles generally exhibit average thermal stability. This thermal stability could still be improved upon by cross-linking or a blending process with another polymer. Improved thermal stability is relevant in fields such as food packaging and biomedical devices, where the nanoparticles can become exposed to different temperatures [18].

Surface Charge: The biopolymer nanoparticles also bear a surface charge called the zeta potential, which determines nanoparticle stability and the interaction of the nanoparticle with the biological system [17]. On the other hand, positively charged nanoparticles prepared from chitosan offer the potential for interaction with negatively charged cellular membranes in respect to cellular uptake and drug delivery.

Hydrophilicity study: This is direct research on the hydrophilicity of biopolymer nanoparticles, dealing with their interaction with water and further on with biological fluids for different applications [19]. In this respect, alginate-made particles can form hydrogels, representing this advantageous feature in the area of wound healing and tissue engineering applications.

Biopolymer nanoparticles applications

Biomedical applications

Biopolymers find frequent applications in biomedicine and healthcare. The Nan composites have lately developed interest in the detection of diseases, tissue engineering, wound healing, cancer therapy, antimicrobials, drug transporters, and sensors. It shows excellent storage and guard and release for the bioactive pharmaceuticals like pharmaceuticals, Nutraceuticals, enzymes, and probiotics. Example: biopolymer nanoparticles make a great contribution to applications in drug delivery systems because of their potential for encapsulating a wide range of therapeutic agents that range from small molecules to proteins and nucleic acids. In such respects, dispositions at the vantage of the nanoparticulate version include controlled and sustained release or improved stability and tissue- or cell-specific targeting. For instance, chitosan nanoparticles have been formulated for oral delivery of insulin and protects it from degradation in the gastrointestinal tract [20]. Table 2 highlights several biopolymers recently utilized in various biomedical applications.

Table 2: Biopolymers with their biomedical applications

Biopolymer	Nan fillers	Applications	Reference
Chitosan	ZnO NPs	Antioxidant agent	31
Carboxymethyl TKP	Au NPs	Photo catalytically activity of NO removal	32
Guar gum / PAA	Ag NPs	Antibacterial and catalytic agent	33
Guar-gum	Ag-Cu NPs	Food packaging	34
PVA	Ag NPs	Anti-reflective coating agent	35

Gene therapy: Chitosan biopolymer nanoparticles are able to carry along nucleic acids and even survive lysosomal degradation to deliver genes, including dna and other genetic material like rna [29]. Since chitosan is positively charged, it forms a complex with negatively charged nucleic acids to protect the latter from degradation, hence helping in cellular uptake. These studies have applications in the treatment of genetic disorders and cancer.

Tissue engineering: Biopolymer nanoparticles find applications even in tissue engineering in the fabrication of scaffolds that would be facilitate cell adhesion, growth, and differentiation [35]. Most often, gelatin and alginate in their nano-dimensional formulations are utilized in the fabrication of scaffolds during tissue engineering for bone and cartilage regeneration.

Water treatment systems: Biopolymer nanoparticles are used for removing pollutants and pathogens in water treatment systems [30]. Other nanoparticles, such as chitosan, have also been shown to adsorb heavy metals and organic pollutants in water, proving efficient in the treatment of wastewaters and in the remediation of the environment.

Biodegradable packaging: Biopolymer nanoparticles serve as a sustainable alternative to traditional plastics in packaging materials. It would mean that extended shelf life of food products would be ensured by the improved mechanical and barrier properties of packaging materials using biopolymer-based Nan composites with reduced environmental impacts [31]. In the case of food additives and preservatives, biopolymer nanoparticles act as carriers of food additives and preservatives in order to make them more stable and improve their bioavailability. For example, chitosan nanoparticles loaded with essential oils have been used as natural antimicrobials for food packaging so that packaged foodstuffs acquire the same microbe-fighting properties as the essential oils, thus extending the mass life of the products.

Nutraceuticals delivery: Biopolymer nanoparticles have been applied to enhance the absorption and bioavailability of Nutraceuticals delivery [32]. Alginate and chitosan nanoparticles were applied for encapsulation of vitamins, antioxidants, and other bioactive compounds and were found to show enhanced properties with increased stability and controlled release features.

Besides biocompatibility and biodegradability, about the environment, biopolymers are an essential alternative for synthetic polymers. The energy required to produce biopolymers is meagre with reduced emission of gasoline. These are the reasons; biopolymers are a vital alternative for synthetic polymers. The landscape that synthetic and biopolymers open onto in material science is very complex. Both kinds of polymers show different advantages and problems in several applications. On the contrary, synthetic polymers have high mechanical strengths, are thermally stable, and show chemical resistance due to the well-established manufacturing process; hence, they have a place in many industries: from packaging to automotive and medical devices. However, through low biodegradability and associated pollution problems, they do extensively affect the environment [22]. Biopolymers open much more sustainable ways ahead, since they are both biodegradable and renewable. Their growing applications in both packaging materials and medical uses herald a swing to green materials. While in general biopolymers are more cost-intensive in production compared to synthetic polymers, and the mechanical properties sometimes turn out worse compared to those same synthetic polymers, progress in biopolymer technology makes them ever more applicable for a much broader range of purposes. That is to say, in the future, polymers would be synthesized through a well-balanced integration of synthetic and biopolymers since they have the forces of both but against their weaknesses. In this way, sustainability and efficient recycling with reduced impact on the environment focus on technology and regulatory landscapes that go on evolving [23]. Such a convergence would give a view of materials serving not only the functional needs of modern industries but also being far more responsive to new, emerging global imperatives for environmental stewardship. Obviously, all of these objectives will have an essential basis in further research and development in synthetic and biopolymers. It may be that pathway toward a more responsible and sustainable material science.

CONCLUSION

Very recently, polymer nanocomposites advanced and highlighted new avenues of using self-healing chemistries for overcoming drawbacks in damage restoration. Despite promising self-healing polymers and composites have shown significant strides in the fields, nanocomposite systems, however, still need to be explored. Thus, this article will review chemistries from self-healing polymer nanocomposites, showcasing examples and mechanisms together with polymerization techniques used, and much work still needs to be developed into these areas that require overcoming issues in efficient synthesis, scalability, and application integration. The repeated self-healing properties in polymer nanocomposites make optimizing their design very crucial for multifunctional applications. It can provide great opportunities for improving the sustainability and performance of demanding environments. Pioneering work in this field is opening pathways for high-strength, advanced polymer nanocomposites with good durability. Next-generation developments would depend on establishing novel chemistries and synthesis strategies that enable the rapid formation of versatile, sustainable self-healing nanocomposites that can find industrial applications in many fields.

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