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NEXT-GENERATION BIODEGRADABLE POLYMERS: INNOVATIONS FOR A GREENER PLANET

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Abstract

The global demand for sustainable materials has driven significant advancements in next-generation biodegradable polymers, offering promising solutions for reducing environmental pollution. This study explores recent innovations in biodegradable polymer development, emphasizing eco-friendly synthesis, enhanced performance, and diverse applications. Modern approaches focus on utilizing renewable resources such as plant-derived polysaccharides, proteins, and microbial biopolymers to create materials with tailored mechanical properties and controlled degradation rates. The integration of nanotechnology and bio-based additives has further enhanced polymer stability, strength, and biodegradability, making them suitable for packaging, agriculture, medicine, and textiles. Additionally, advancements in polymer processing techniques, including 3D printing and green chemistry methods, have facilitated scalable and energy-efficient production. These next-generation polymers not only minimize reliance on fossil fuels but also reduce plastic waste accumulation through accelerated degradation in natural environments. Challenges such as cost, production scalability, and end-of-life management remain, but ongoing research focuses on optimizing performance while ensuring environmental compatibility. The paper highlights emerging trends, lifecycle assessments, and future perspectives for integrating these materials into circular economies. Ultimately, next-generation biodegradable polymers represent a transformative shift towards a more sustainable and resilient planet, addressing the urgent need for eco-conscious material innovations.

INTRODUCTION

Plastic pollution in the marine and coastal environment is a challenging restoration and governance issue. Similar to many environmental problems, marine plastic pollution is transboundary and therefore the governance solutions are complex. Although the marine environment is unlikely to return to the condition it was in before the "plastic era," it is an example of an environmental restoration challenge where successful governance and environmental stewardship would likely result in a healthier global oceanic ecosystem. We argue that a holistic, integrated approach that utilizes scientific expertise, community participation, and market-based strategies is needed to significantly reduce the global plastic pollution problem. Marine litter is as much a transboundary global problem as well as a local issue with a multitude of sources. An estimated 6–12 million tonnes of plastic enters the oceans each year[1]. The pollution is significant and widespread, with plastic debris found on even the most remote coastal areas (STAP 2011) and in every marine habitat [2]. Nearly 700 marine species have been found to interact with marine debris to date[3]. with ingestion and entanglement the two main types of interaction (Secretariat of the Convention on Biological Diversity and the Scientific and Technical Advisory Panel, GEF 2012. We discuss many of the complexities of this environmental restoration challenge, focusing particularly on governance responses to the issue at local, regional, and international scales. We do, however, acknowledge that an in depth discussion of all critical aspects of marine litter governance is not possible here. Although scientific studies are revealing the causes and consequences of marine plastic pollution, governments and nonstate actors are tackling solutions in myriad disparate ways. To highlight the complexities of this environmental restoration challenge, we examine current governance arrangements addressing marine litter on international and national levels. We describe market and community strategies that offer different solutions that government and international organizations areunable to provide such as education, outreach, and corporate social responsibility (CSR). We argue that combining governance solutions with scientific expertise can offer a holistic, integrated approach to reducing litter and waste entering the oceans—the first crucial step toward environmental restoration of our waterways, coastlines, and oceans. According to Underdal (1980), "To 'integrate' means to unify, to put parts together into a whole. Integrated policy, then, means a policy where the constituent elements are brought together and made subjects to a single, unifying conception." Although policy integration is complex[4]. it is recognized by the international community as the way forward for managing activities in ocean and coastal areas (e.g. through international instruments such as United Nation Conference on the Environment and Development's (UNCED) Agenda 21 (1992); United Nation Convention on the Law of the Sea (UNCLOS) (1994); and the World Summit on Sustainable Development (2002)). Litter found in the coastal and marine environment ranges from macrodebris such as large industrial containers, plastic bags, drink containers, cigarette butts, and plastic fragments, to small microdebris including manufactured plastic pellets and microbeads from consumer items. This anthropogenic litter, comprised mostly of plastic, interacts not only with marine megafauna such as seabirds, turtles, marine mammals, and fish but also with bivalves, lugworms, oysters, and corals. Although the demonstrated impacts to wildlife are most frequently reported at the organismal and suborganismal levels[5]. experts view entanglement, ingestion, and chemical contamination as all having the potential for significant (lethal or sublethal) impacts to major marine vertebrates [6]. Microplastics are a specifically identified subset of marine pollution that is of particular concern. Defined as particles ≤5 mm in size[7]. microplastics result both from the breakdown of larger plastics and through manufacture specifically for use in consumer goods. Indeed, the prevalence of marine plastic pollution and its impacts on coastal economies, marine ecosystems, and human health demonstrates that there are no simple solutions to this environmental restoration challenge. Plastic pollution is a global issue, and when it occurs in Areas Beyond National Jurisdiction (ABNJ) the issue of responsibility is particularly problematic. For example, the well-known "Pacific Garbage Patch" is one of five accumulation regions for marine debris. It is located in the east and west parts of the Pacific [8]. Finding solutions to removing debris far from land or taking responsibility for it within ABNJ from a governance and practical perspective is complex. Market-based solutions have been suggested to clean up this “garbage patch”; however, the legal parameters on the high seas are limited to UNCLOS, demonstrating the gap in international law when it comes to the mitigation and removal of marine debris from ABNJ.

Plastic pollution is a persistent challenge worldwide with the first reports evidencing its impact on the living and nonliving components of the environment dating back more than half a century. The rising concerns regarding the immediate and long-term consequences of plastic matter entrainment into foods and water cannot be overemphasized in light of our pursuit of sustainability (in terms of food, water, environment, and our health). Hence, some schools of thought recommend the revisitation and continuous assessment of the plastic economy, while some call for the outright ban of plastic materials, demonstrating that plastic pollution requires, more than ever, renewed, innovative, and effective approaches for a holistic solution. In this paper, dozens of reports on various aspects of plastic pollution assessment are collated and reviewed, and the impact of plastic pollution on both the living and nonliving components of the environment is discussed. Current challenges and factors hindering efforts to mitigate plastic pollution are identified to inform the presented recommendations while underscoring, for policymakers, stakeholders, and the scientific community, the exigency of finding sustainable solutions to plastic pollution that not only encompass existing challenges but also future threats presented by plastic pollution. Pollution is a global phenomenon, a persistent challenge that is transnational (i.e., borderless) in nature, trans institutional in purview, and transdisciplinary in solution scope [9]. as a result of unnatural disturbances (i.e., the agitation or excitation of the state of matter or a system), causing the transformation or transmutation of substances (i.e., matter) from one form to another (which may be reversible or irreversible); accordingly, pollution has the potential to change the dynamics of matter and environments, which consequentially impacts the natural characteristics of living and nonliving components.8,10 Notwithstanding, we hold that matter or energy entering an environment cannot be considered pollution (or a pollutant) if the effect of such intrusion or disturbance on the environment or system is not negative, i.e., is (i) neutral or (ii) positive. Hence, we posit that meeting these conditions should be the basis for considering such matter or energy as “green” or “eco-friendly”. For example, sunlight is considered friendly to green vegetation but unfriendly to plastic materials; in the former, it is vital for photosynthesis, and in the latter, it is known to promote photodegradation. Pollution can arise naturally, for example, by saltwater intrusion into freshwater resources and volcanic eruptions that release dangerous gases, or it can be manmade, a result of anthropogenic activities such as the exploitation of the environment and its resources and the introduction of matter or energy into the environment that are not natural to it. Substances or energies (e.g., material entropy) that are introduced into the environment through anthropogenic activities can upset and compromise the natural balance of the earth’s intricate and inter-related systems, causing a “domino effect”[10]. Pollution can also be considered as (an) unnatural disturbance(s) arising from the intrusion of energy or matter into the environment, which may result in the interruption (i.e., modification) or degradation of the natural state of a system or environment, thereby increasing the risk of the system or environment deviating from its initial state (i.e., original conditions and functions).

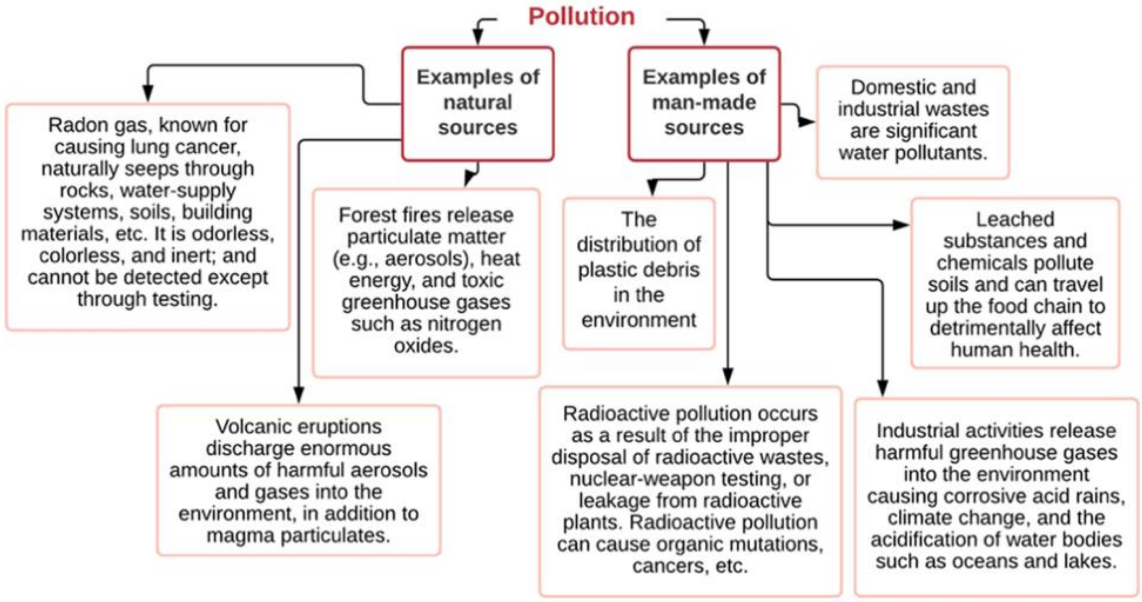


Figure 1. Common sources of pollution.

3 HEALTH AND ENVIRONMENTAL ISSUES: There is no gainsaying that plastics have contributed immensely to the rise of human civilization; however, the distribution of plastic debris (macro-, micro-, and nano plastics) in the environment and its entrainment into biological systems have become a serious issue[11]. Various health conditions such as thyroid dysfunction, obesity, diabetes, and reproductive impairment have been attributed to plastic pollution[12]. For example, it has been shown that nano plastics impact negatively the composition and diversity of microbial communities in the human gut, which, considering emerging research evidencing the strong relationship between the gut and neural networks in the brain, could negatively impact the endocrine, immune, and nervous systems[13]. As already highlighted, pollution changes the dynamics of systems and environments with consequential impacts on the natural characteristics of their living and nonliving components; thus, it is reasonable to infer that the entrainment of nano plastics into the human gut holds physiological consequences. The genotoxicity of micro- and nano plastics to DNA has been established. It has been demonstrated that if the plastic matter is small enough to cross the nuclear membrane surrounding the DNA, damage can occur, impairing the DNA structure or forming lesions, which, unrepaired or mis repaired, can cause mutagenic processes that are considered to play a role in the carcinogenesis of cells. Additionally, it was found that the type and level of damage of DNA depend on the shape, functional groups, and chemical composition of the plastic debris[14]. The human airway is a key pathway for plastic fiber entrainment into the lungs, and biopersistence of the fibers depends on their length, structure, and chemical composition. Moreover, at certain exposure limits, all plastic fibers are likely to produce inflammation, which can lead to lung challenges such as the formation of reactive oxygen species with the potential to initiate cancerous growth through secondary genotoxicity.49 9 Although there are few studies on the extent of the damage that prolonged exposure to plastic particles can cause to the human body (suggesting the need to increase research in this area), it is accepted that industry workers at textile facilities are at a high risk of contracting occupational diseases arising from high exposure to textile fibers[15]. It has long been established that constituents of plastic packaging chemically interact with or migrate into fat-containing foods; typical interactions include the migration of antioxidants from the plastic packaging into the food, sometimes bonding to the food surface.51 Such transfer of packaging additives from the packaging material to its food content is a potential health risk. Furthermore, PET, a common plastic employed in the food and beverage industry, is a source of endocrine disruptors[16]. these endocrine disruptors leach from the plastic packaging into the consumables that it contains. Even at standard room temperature, phthalates (potential endocrine disruptors) are known to leach from PET packaging into various food contents in the presence of water.Products and polymer-based articles, such as toothbrushes, shoes (materials or soles may be made from plastics), insulated electrical cables and equipment, light switches, writing pens (i.e., plastic cases), writing and printing inks (employ polymeric systems such as drag-reducing agents and stabilizers), mattresses, wigs and artificial hair (usually derived from high-performance polymers), artificial nails (e.g., acrylics), kitchen wipes (composed of microfibers), automobile paints, phone casings, computer casings, plastic wristwatches, and marine paints, are usually overlooked or underestimated as significant contributors to plastic pollution. Collectively, the “insignificant” contributions of these products or articles to plastic pollution, owing to poor disposal or through the process of wear and tear/degradation, is less insignificant. Notwithstanding, several reports focus on single-use plastic carrier bags as the primary plastic pollutant menacing our environment[17].

4 Types of biodegradable polymers:

4.1 Overview of biodegrable polymer:

Biodegradable polymers are generally divided into two groups, natural and synthetic based on their origin. Synthetic origin polymers offer advantages over natural polymers by being versatile with a wide spectrum of applications, having a capability to tailor mechanical properties and altering the rate of degradation according to the need. On the other hand, natural polymers seem to be attractive due to their excellent biocompatibility, but they have not been fully investigated due to their undesirable properties like antigenicity and batch-to-batch variation.[18]The instability of the polymers leading to biodegradation has proven to be immensely important in many medical applications.[19] Biodegradable polymers offer tremendous potential in many exciting applications like drug delivery, tissue engineering, gene therapy, regenerative medicine, temporary implantable devices, coatings on implants, etc.[20] The basic criteria for selecting a polymer for use as a degradable biomaterial are to match the mechanical properties and the degradation rate to the needs of the application, non-toxic degradation products, biocompatibility, shelf life/stability, processability and cost.[21] The mechanical properties should match the application so that sufficient strength remains until the surrounding tissue has been healed.[22] There are many polymers available for different application (Fig. 2) where the choice of the polymer is dependent on the requirements that a particular biomaterial demands. With respect to drug delivery, it is the time of release that governs the type of polymer, size and shape of the device. However, clinically approved polymers such as lactide and glycolide polymers are the polymer of choice for any application. Polymers found a multitude of uses in the medical industry, beginning with biodegradable sutures first approved in the 1960s.[19] Polyesters which are the representative class of biodegradable synthetic polymers continue to remain attractive in many clinical applications due to their unique properties. Other classes of polymers which made a significant contribution to the field of biomaterials include polyurethanes, polyanhydrides, polyaminoacids, etc.[23] Some of the natural polymers which are found to be biocompatible are extensively investigated. which lead to some breakthrough innovations like Abraxane (paclitaxel-loaded albumin particles) based on nab technology.[24] There are various successful products in clinical practice, and the number of such products is ever increasing and at a faster rate from the past few decades. Attempts have been made to develop injectable polymer compositions for use in tissue engineering applications which offer many advantages like avoiding surgery, filling cavities with complex geometries, and providing good bonding to tissue. The inability of a single biodegradable polymer to meet all the requirements for biomedical scaffolds leads to the development of biodegradable polymer matrix nanocomposites in the field of tissue engineering. These nanocomposites increase and modulate mechanical, electrical and degradation properties. Polymer matrix composites have the advantage of being very versatile, allowing fine tuning of their final properties. Biodegradable copolymers exhibiting temperature-responsive sol–gel transition have recently drawn much attention with their promising application in the fields of drug delivery, cell implantation and tissue engineering.[25] This class of copolymers exhibit amphiphilic nature due to the presence of hydrophilic (PEG)/hydrophobic segments (PLA/PLGA/PCL). These injectable hydrogels can be implanted in the human body with minimal surgical invasion. Strategies based on gene delivery or gene-activating biomaterials have a great potential in regenerative medicine, but the long-term safety of such therapies.

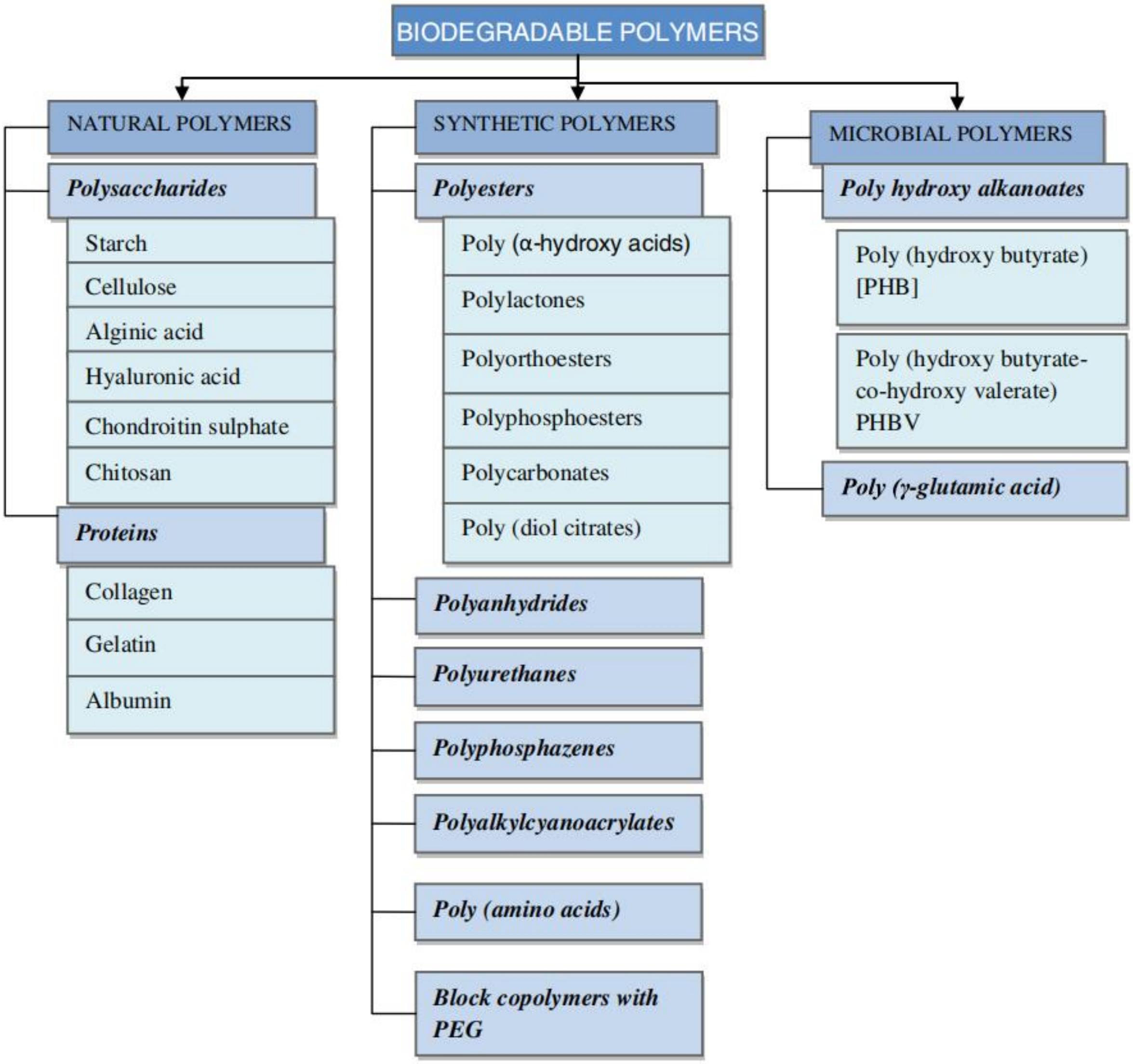


Figure 2: Classification of Biodegradable polymers.

The revelation of biodegradable polymers dates back to many years ago. From then, their emergence leads to the surge of many biomaterials applicable in various fields like controlled drug delivery, regenerative medicine, orthopedic and long-term implants which proved out to be momentous contributions of these materials. The immense effort and investigation kept on these materials are reflected by significant upsurge of the biodegradable polymer-based marketed products and ongoing clinical trials of these materials. The synthetic versatility and flexible features of these polymers to get custom designed in accordance with need make them attractive for various therapeutic strategies. Long-term biocompatibility and avoidance of surgery to remove implants are the main advantages of biodegradable materials over biostable polymers by which the former stand in for various indications over the latter. This review gives an overview on various biodegradable polymers with details on properties, mode of degradation and the potential biomedical applications associated with them.

4.2 Natural biodegradable polymer

4.2.1 Starch:

Starch is a polymer which occurs widely in plants. The principal crops used for its production include potatoes, corn and rice. In all of these plants, starch is produced in the form of granules, which vary in size and somewhat in composition from plant to plant. In general, the linear polymer, amylose, makes up about 20 wt% of the granule, and the branched polymer, amylopectin, the remainder. Amylose is crystalline and can have a number average molecular weight as high as 500 000, but it is soluble in boiling water. Amylopectin is insoluble in boiling water, but in their use in foods, both fractions are readily hydrolyzed at the acetal link by enzymes. The a-1,4-link in both components of starch is attacked by amylases (Fig. 3a) and the a-1,6-link in amylopectin is attacked by glucosidases. Starch has long been used as an additive in plastics for various purposes. It has been incorporated into resin systems to create water-impermeable yet vapor-permeable films, serving as a biodegradable filler in LDPE [26]. Starch-filled polyethylene films become porous after starch extraction, enhancing microbial invasion and oxygen saturation, which accelerates polymer degradation [27]. Otey et al. (10) developed starch–polyvinyl alcohol films coated with a water-resistant polymer for degradable agricultural mulching. Starch-based polyethylene films, containing up to 40% starch with urea, ammonia, LDPE, and EAA, demonstrated physical properties close to LDPE, with EAA acting as a compatibilizer.Three techniques incorporated starch into disposable PVC plastics: (1) coprecipitation of starch–xanthate and PVC resins, gelatinization of starch mixed with PVC latex, and (3) dry-blending starch with PVC and DOP, producing films suitable for agricultural applications [28]. Starch has also been chemically combined with commercial resins as both a filler and crosslinking agent, leveraging isocyanates' reactivity with hydroxyl groups to enhance cost-effectiveness, solvent resistance, and strength [29].

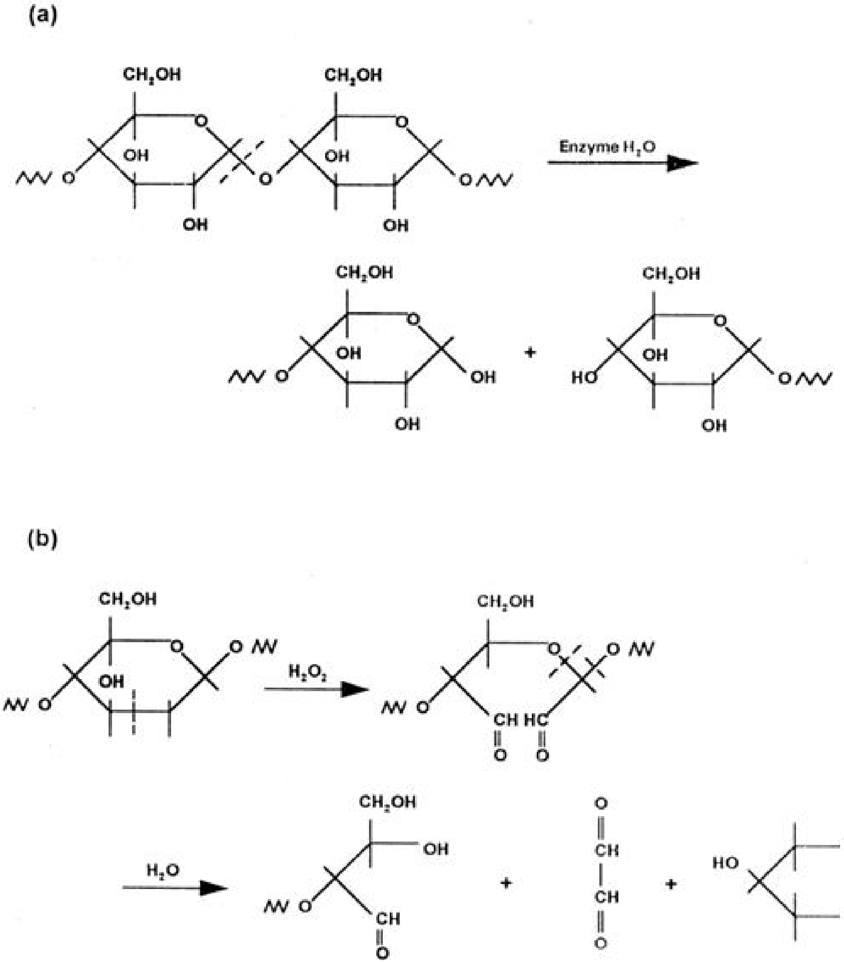


Figure 3: Enzymatic hydrolysis of (a) starch and (b) cellulose

4.2.3 Chitin and chitosan

Chitin is a macromolecule found in the shells of crabs, lobsters, shrimps and insects. It consists of 2-acetamide-2-deoxy-b-d-glucose through the b-(1-4)-glycoside linkage. Chitin can be degraded by chitinase. Chitin fibres have been utilized for making artificial skin and absorbable sutures.30 Chitin is insoluble in its native form but chitosan, the partly deacetylated form, is water soluble. The materials are biocompatible and have antimicrobial activities as well as the ability to absorb heavy metal ions. They also find applications in the cosmetic industry because of their water-retaining and moisturizing properties. Using chitin and chitosan as carriers, a water-soluble prodrug has been synthesized. [30] Modified chitosans have been prepared with various chemical and biological properties. N-Carboxymethylchitosan and N-carboxybutylchitosan have been prepared for use in cosmetics and in wound treatment. [31]

4.2.4 Cellulose:

Cellulose has garnered significant attention due to its biodegradability and widespread use in textiles without additives, simplifying result interpretation. It constitutes a large portion of sewage and refuse, decomposing readily. While cellulose fermentation for chemicals like ethanol and acetic acid has been proposed, it lacks commercial viability. Key cellulose derivatives arise from reactions with its three hydroxyl groups, including ethers (e.g., methylcellulose), esters (e.g., cellulose acetate and cellulose xanthate), and acetals. Gardener et al. [32](developed cellulose acetate films with varying degrees of substitution, comparing them to biodegradable polymers like PHBV and PCL. Films with substitution degrees below ~2.20 compost at rates similar to PHBV. NMR and GPC analyses revealed that low molecular weight fractions degrade first in more highly substituted cellulose acetates, which degrade more slowly.

4.2.5 Hyaluronic acid

Hyaluronic acid, one of the major elements in the extracellular matrix of vertebrate tissues, is also found in almost all body fluids and tissues, such as the synovial fluid, the vitreous humor of the cieye and hyaline cartilage. HA is an unbranched non-sulfated glycosaminoglycans composed of repeating disaccharides β-1,4-Dglucuronic acid and β-1,3-N-acetyl-D-glucosamide. Three types of enzymes like hyaluronidase (hyase), β-d-glucuronidase and β-N-acetyl-hexosaminidase catalyze the enzymatic degradation of HA. The degradation products of hyaluronan, oligosaccharides and very low molecular weight hyaluronan exhibit pro-angiogenic properties. It has been investigated for dermal filling (Restylane-L Injectable Gel®, Hylaform®) antiadhesive and chondroprotective effects, applied in various ophthalmic (viscosity enhancer in eye drops), orthopedic (lubricant and shock absorber) and cardiovascular (increasing compatibility of vascular grafts and stents) applications.[33]

Biodegradable polymers—an overview

4.3 Mechanism:

4.3.1 NONENZYMATIC HYDROLYSIS:

Polymer hydrolytic degradation may be defined as the scission of chemical bonds in the polymer backbone by the attack of water to form oligomers and finally monomers. In the first step, water contacts the water-labile bond, by either direct access to the polymer surface or by imbibition into the polymer matrix followed by bond hydrolysis. Hydrolysis reactions may be catalyzed by acids, bases, salts, or enzymes.[34] After implantation, the biomaterial absorbs water and swells, and degradation will progress from the exterior of the material toward its interior. The hydrophilic and hydrophobic nature of polymeric materials influences their degradation rate, and the susceptibility to hydrolysis follows this order17: (1) hydrophilic with hydrolysable bonds, (2) hydrophobic with hydrolysable bonds, (3) hydrophilic with no hydrolysable bonds, and (4) hydrophobic with no hydrolysable bonds. For instances, N-vinylpyrrolidinone (NVP) is capable of absorbing relatively large amounts of water, but it is not prone to hydrolysis.[35] All biodegradable polymers contain hydrolysable bonds, such as glycosides, esters, orthoesters, anhydrides, carbonates, amides, urethanes, ureas, etc. Polymers with strong covalent bonds in the backbone (like C-C) and with no hydrolysable groups require longer times to degrade.[36]

4.3.2 ENZYME-CATALYZED HYDROLYSIS

Enzymes are biological catalysts, i.e., they accelerate the reaction rates in living organisms without undergoing themselves any permanent change. In fact, in the absence of enzymes, most of the reactions of cellular metabolism would not occur. Hydrolysis reactions may be catalyzed by enzymes known as hydrolases, which include proteases, esterases, glycosidases, and phosphatases, among others. This class of enzymes comprises cell-derived proteins that are responsible for the catalysis of several reactions in the human body. For example, hydrolytic enzymes are present in the plasma and interstitium, in the brush border membrane and lumen of the gastrointestinal tract, and in the tubular epithelium of the kidneys, where they ensure the efficient hydrolysis of different substrates to facilitate absorption of nutrients and solutes.4 In this sense, it is expected that some of these enzymes may play an important role in the degradation of biomaterials by catalyzing their hydrolysis. It has been shown that the degree of biodegradation of polyurethanes, in the presence of cholesterol esterase enzyme, is about 10 times Understanding the Enzymatic Degradation of Biodegradable Polymers [37] higher than in the presence of buffer alone.[38] This fact may explain the higher in vivo degradation rates of some biomaterials when compared with in vitro experiments. While some enzymes catalyze only one reaction involving only certain substrates, others are not very specific.

4.3.3 MECHANISMS OF DEGRADATION In general, the first degradation event after contact with water molecules is the hydrolytic scission of the polymer chains leading to a decrease in the molecular weight. At this initial stage, the first degradation products are not small enough to become soluble, and no significant change in the material weight is detected. With increasing time, the molecular weight of degradation products is reduced by further hydrolysis, which allows them to diffuse from the bulk material to the surface and then to the solution, causing significant weight loss. Polymers can be degraded by bulk degradation[39] or surface erosion mechanisms[40]. Bulk degradation is characterized by hydrolysis of chemical bonds in the polymer chain at the center of the material, which typically results in an empty shell but maintains their size for a considerable portion of time.[41] This degradation behavior has been observed for polylactides polymeric systems, whose degradation mechanisms are well described in the literature. Degradation by surface erosion mechanism is characterized by loss of the material from the surface only, resulting in very predictable mass loss profiles. The materials get smaller but keep their original geometric shape. This feature may be beneficial for delivering molecules at constant rate and maintaining the mechanical and structural integrity of the material with degradation. Poly(anhydrides) and poly(orthoester)s are examples of surface-eroding polymers.[42] Enzyme-catalyzed degradation of polymeric biomaterials may follow a surface erosion mechanism, especially for highly crystalline and hydrophobic homopolymers. Due to their relatively large size, the enzyme molecules cannot penetrate the tightly packed structure of certain polymers, so that the enzymatic catalysis occurs at the polymer–enzyme interface. As the degrading surface becomes roughened or fragmented, enzymatic action may be enhanced as a result of increased surface area. Enzymatic degradation mechanisms of polymeric materials depend, however, on many other factors such as chemical composition, degree of homogeneity, and processing technique. Several different types of models have been applied to describe the degradation kinetics of biodegradable polymers,[43] assuming first- or second-order kinetics. Recently, computer modeling has also been used, but some of these models did not consider diffusion theory to describe transport phenomena.6 The mathematical model proposed by Duguay and coworkers [44] describes, in a very complete and comprehensive way, the in vitro enzymatic degradation of biomedical polyurethanes by a single enzyme. Despite the progress made on mathematical models to predict the degradation of biodegradable polymers, much more data and sophisticated models are needed to apply these approaches to other polymeric systems.

Understanding the Enzymatic Degradation of Biodegradable Polymers and Strategies to Control Their Degradation Rate

4.4 Synthetic polymers:

4.4.1 Polyglycolide (PGA): PGA is the simplest linear aliphatic polyester. It is prepared by ring opening polymerization of a cyclic lactone, glycolide. It is highly crystalline, with a crystallinity of 45-55% and thus is not soluble in most organic solvents. It has a high melting point (220-225 °C) and a glass transition temperature of 35-40 °C . PGA has excellent mechanical properties. Nevertheless its biomedical applications are limited by its low solubility and its high rate of degradation yielding acidic products. Consequently, copolymers of glycolide with caprolactone, lactide or trimethylene carbonate have been prepared for medical devices .

4.4.2 Polylactide (PLA): PLA is usually obtained from polycondensation of D- or L-lactic acid or from ring opening polymerization of lactide, a cyclic dimer of lactic acid. Two optical forms exist: D-lactide and L-lactide. The natural isomer is L-lactide and the synthetic blend is DL-lactide. Other different synthetic methods have been studied too. They have been reported in detail in .

PLA is a hydrophobic polymer due to the presence of $-CH_3$ side groups. It is more resistant to hydrolysis than PGA because of the steric shielding effect of the methyl side groups. The typical glass transition temperature for representative commercial PLA is 63.8 °C, the elongation at break is 30.7% and the tensile strength is 32.22 MPa. Regulation of the physical properties and biodegradability of PLA can be achieved by employing a hydroxy acids comonomer component or by racemization of D- and L- isomers . A semi-crystalline polymer (PLLA) (crystallinity about 37%) is obtained from L-lactide whereas poly(DL-lactide) (PDLLA) is an amorphous polymer. Their mechanical properties are different as are their degradation times. PLLA is a hard, transparent polymer with an elongation at break of

85%-105% and a tensile strength of 45-70 MPa. It has a melting point of 170-180 °C and a glass transition temperature of 53 °C. PDLLA has no melting point and a Tg around 55 °C. It shows much lower tensile strength. PLA has disadvantages of brittleness and poor thermal stability.

4.4.3 Composite materials:

Composite material can be defined as the assembly of two or more materials, the final assembly having properties superior to the properties of each of the constituent materials [45]. Composite materials are now commonly called reinforcement arrangements (also called fillers) which are embedded in a matrix. The matrix ensures cohesion and orientation of the load. Also, it possible to transmit to the load the stresses to which the composite is subjected. The materials thus obtained are very heterogeneous and often anisotropic. The nature of the matrix and the charge, the shape and proportion of charge, the quality of the interface and the production process used are all parameters that can influence the properties of the composite material. The matrix and the reinforcement can be metallic, ceramic or plastic, which makes it possible to envisage a multitude of combinations. The composite material is composed in the general case of one or more discontinuous phases distributed in a continuous phases. In the case of several discontinuous phases of different natures, the composite is said to be hybrid . The continuous phase is called the matrix and the discontinuous phase is called the reinforcement or reinforcing material. In composite materials components with complementary physical and mechanical properties are combined.

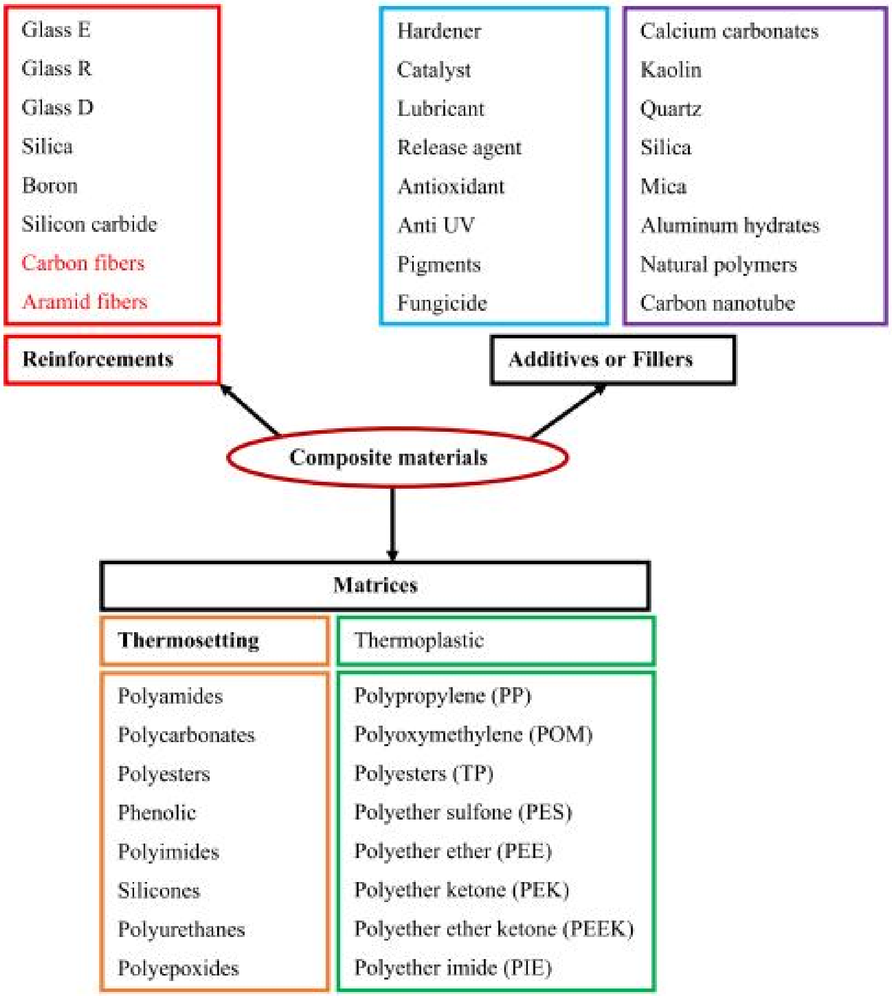


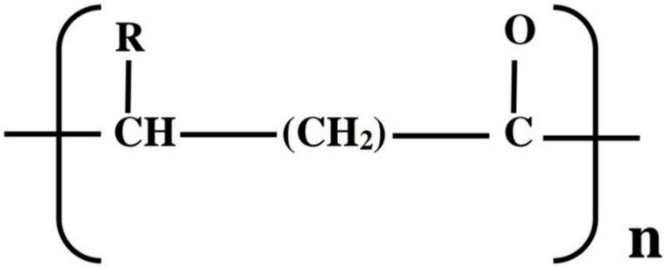
Figure 4: Composite materials formulation

4.5 Innovative Approaches in Biodegradable Polymer Design

4.5.1 Green Synthesis Techniques

4.5.1.1 Microbial Fermentation

Polylactic acid is one of the most promising biodegradable and biocompatible aliphatic thermoplastic with extensive mechanical property profile [46]. PLA is obtained from lactic acid (LA), a naturally occurring organic acid produced by microbial fermentation from renewable resources such as sugars obtained from corn, cane sugar, and sugar beets . On hydrolysis, PLA produces LA; hence, PLA can be produced and used as an environment-friendly material. PLA is highly versatile, high-strength, and high-modulus polymer that yields materials with potential use in industrial packaging or as biocompatible medical devices . PLA has good processability, and its manufacturing is amenable and can adapt the conventional plastic equipment for production of molded parts, films, and fibers. LA is a chiral molecule existing in both L and D isomers. These monomers can be polymerized into pure poly-L-LA (PLLA), pure poly-D-LA (PDLA), or poly-D-LLA, giving high-molecular-weight crystalline, or amorphous polymers.



$$-\!\!\left[\overset{R}{\overset{|}{CH}}-(CH_2)-\overset{O}{\overset{|}{C}}\right]_n\!\!-$$

Figure 5: Chemical structure of PHAs; R = methyl (C1) to tridecyl (C13).

Polylactic acid is normally synthesized in three steps: (i) LA production by microbial fermentation, (ii) LA purification followed by cyclic dimer formation (lactide), and (iii) polycondensation of LA or ring-opening polymerization (ROP) of the cyclic lactides. Polycondensation is the least expensive route for PLA synthesis; however, it does not give a solvent-free high-molecular-weight PLA. Consequently, ROP has emerged as the most common route to synthesize high-molecular-weight PLA. ROP consists of three processes: polycondensation, depolymerization, and the ring opening of the LA cyclic dimer in the presence of a catalyst. The process also involves complicated and expensive purification steps, rendering the ultimate products more expensive compared to their petroleum-based counterparts. The catalysts are mostly transition heavy metals, particularly tin, aluminum, lead, zinc, bismuth, iron, and yttrium . However, trace residues of the heavy metal catalysts are unwanted in materials for specific applications such us in medical and food contact surfaces. Therefore, replacing heavy metal catalysts with safe and environmentally acceptable alternatives has been an important concern.

Enzymatic polymerization of LA monomers has emerged as one of the most viable and environmentally benign alternative methods for PLA production . In the year 2008, Taguchi et al. (2008) established for the first time a whole-cell biosynthetic system. In that system, LA was polymerized alongside 3HB to produce P(LA-co-3HB) copolymer without the need for heavy metal catalysts, extremely pure monomers, anhydrous conditions, and high temperatures. From these pioneering studies, efforts have been made toward the synthesis of P(LA-co-3HB), PLA homopolymer, and polymerizing other monomers such as glycolate and 2HB using microbes. In addition, a system for the production of LA oligomers by microorganisms has been established. These oligomers are polymerized into P(LA-co-3HB), thereby shortening the process for PLA synthesis.

4.6 Applications:

Polyhydroxyalkanoates and PLA have found many applications in domestic, agricultural, and industrial sectors but mostly in the medical field. The polymers have been produced and improved for diverse biomedical applications such as making absorbable sutures, nerve guides, bone marrow scaffolds, repair patches, cardiovascular patches, heart valves, nerve repair devices, tendon repair devices, orthopedic pins, tissue-engineered cardiovascular devices, articular cartilage repair devices, guided tissue repair/regeneration devices, and wound dressings . The PHAs and PLA have also been used as nanoparticles for drug delivery, biocompatible porous implants and implant coatings, scaffolds, and tissue engineering applications such as antibacterial agents . PHAs also have potential use in the formation of necessities such as packaging materials, consumer and household goods, furniture, sports, health and safety automotive and transport sector, and the construction and building sector. This indicates that PHAs and PLA have high potential, and their optimum production is of interest.

4.6.1 Bio-based and biodegradable nanocomposite films

The problem of environmental waste generated by petrochemical-based non-recyclable plastic packaging materials combined with demands for high-quality food products has resulted in a growing market for biodegradable packaging made from renewable natural biopolymers such as proteins, carbohydrate polymers/polysaccharides [47]. The term “biodegradable” is generally employed to explain those materials that can be degraded enzymatically by living organisms (e.g., bacteria and fungi) to H2O, CO2, and biomass under aerobic conditions and to biomass, methane, and hydrocarbons under anaerobic conditions. Therefore, in many applications, there is significant interest in replacing synthetic plastics with biodegradable materials. Some of the natural polymers and aliphatic polyesters such as polyhydroxybutyrate, polycaprolactone, and polylactic acid, and their copolymers are biodegradable, but their commercial applications are limited due to their higher cost compared to petroleum-based plastics makes them find usage in niche sectors only. The natural polymer-based packaging materials have however some inherent shortcomings, such as low water resistance and mechanical properties. Nanocomposite technology has proven to be a promising option for overcoming these limitations. Figure 3 illustrates a modified biopolymer with improved properties.

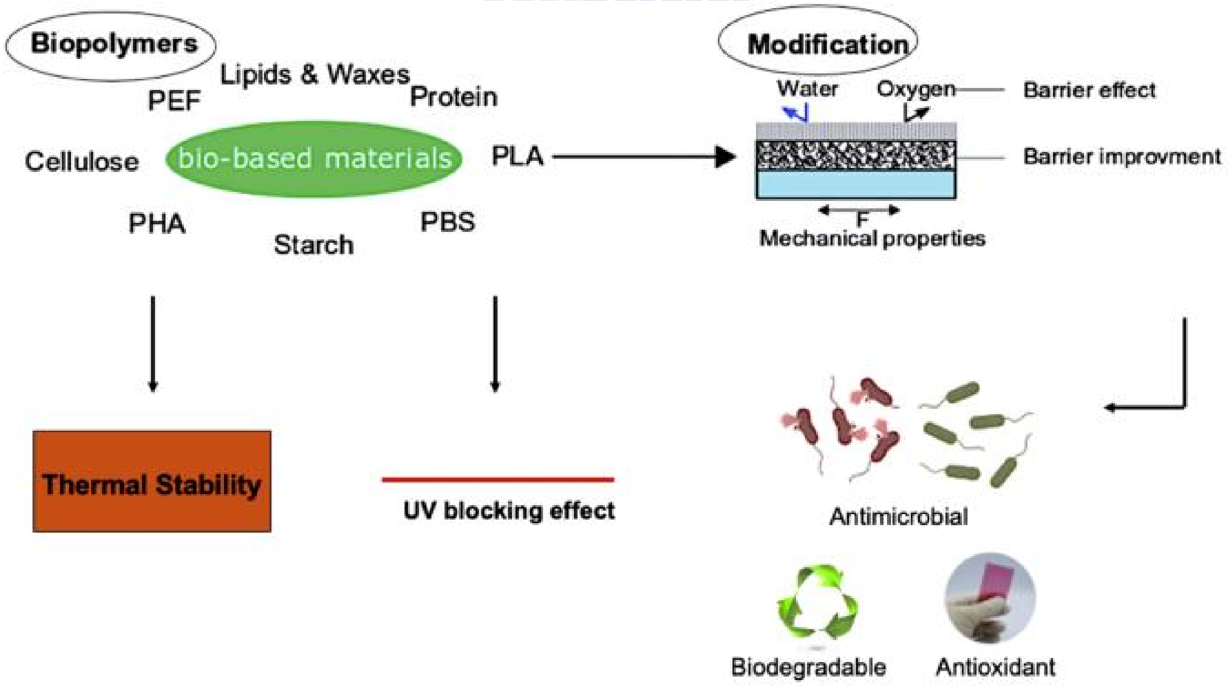


Figure6: Biodegradable nanocomposite film and its properties

(PHA Polyhydroxyalkanoate, PBS Polybutylene succinate, PEF Polyethylene furanoate, PLA Polylactic acid). Adapted from reproduced with permission form Springer and MDPI, respectively

4.6.2 Biodegradable polymer mechanism:

The biodegradation of biodegradable polymers is defined as the chemical decomposition of substances, which is accomplished through the enzymatic work of microorganisms that lead to a change in chemical composition, mechanical and structural properties and forming metabolic products, which are environmentally friendly materials such as methane, water and biomass and carbon dioxide. Figure 1 shows the biodegradation steps of polymers3. Extracellular enzymes and abiotic agents such as oxidation, photo-degradation, and hydrolysis depolymerize long-chain polymers and create shorter chains (oligomers) in the first stage . The biomineralization process, in which oligomers are bio-assimilated by microorganisms and then mineralized, is the second stage. Either aerobic or anaerobic degradation can occur. Aerobic degradation takes place in the presence of oxygen-producing CO2, H2O, biomass, and residue. Anaerobic degradation is carried out in the absence of oxygen-producing CO2, H2O, CH4, biomass, and residue.

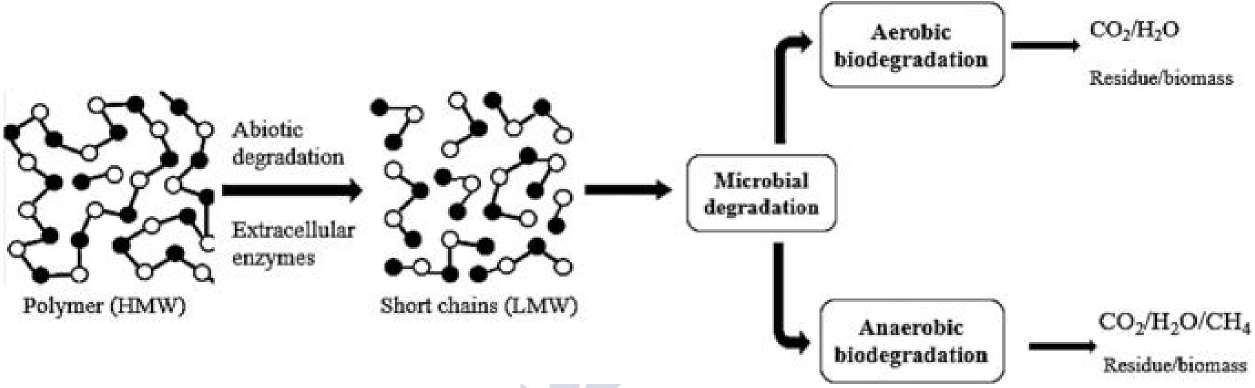


Figure 7: Biodegradation steps of polymers.

4.6.3 Thermal properties of biodegradable polymer:

Thermal analysis is used to examine chemical, physical, and structural responses as a result of a temperature change. Temperature is a basic state variable that impacts the majority of chemical processes, physical qualities, and structural changes. Thermal analysis may be defined as any scientific or technical assessment of a material in which temperature is manipulated. This term, however, has long been restricted to approaches using thermogravimetric and calorimetric effects. The basic techniques used in thermal analysis are TGA thermogravimetry analysis (TGA), differential thermal analysis (DTA), and differential scanning calorimetry (DSC). The difference in temperature between a sample and a reference is carried out by differential thermal analysis (DTA). The loss of weight measured by thermogravimetry is measured by thermogravimetry analysis (TGA). The determination of heat flow done by differential scanning calorimetry (DSC). Thermogravimetry analysis is widely used to describe the thermal stability of natural fiber and polymer composites. The thermal stability of natural fiber and polymer biocomposites has been thoroughly characterized using TG/DTG research. The lignocellulosic fibers are affected by temperature.

selected ten natural fibers including wood, bamboo, agricultural residues and bast fibers to study thermal decomposition kinetics. The complete thermogravimetric degradation process of natural fibers at a rate of 2 °C/min is shown in Fig. 11a, b. A clear DTG peak with a noticeable shoulder (arrow) is formed due to cellulose thermal breakdown, which is generally the outcome of hemicellulose thermal decomposition in an inert environment. However, since the shoulder peaks of low-temperature hemicelluloses were overlapping with the cellulose main peaks, they were no longer visible in some situations as shown in Fig. 11b. The high-temperature (tails) is usually presented by the degradation of lignin as proven in Fig. 11a, b. Because natural fibers are lignocellulosic materials, the TG and DTG curves for various are very comparable, indicating that natural fibers have similar thermal breakdown characteristics.

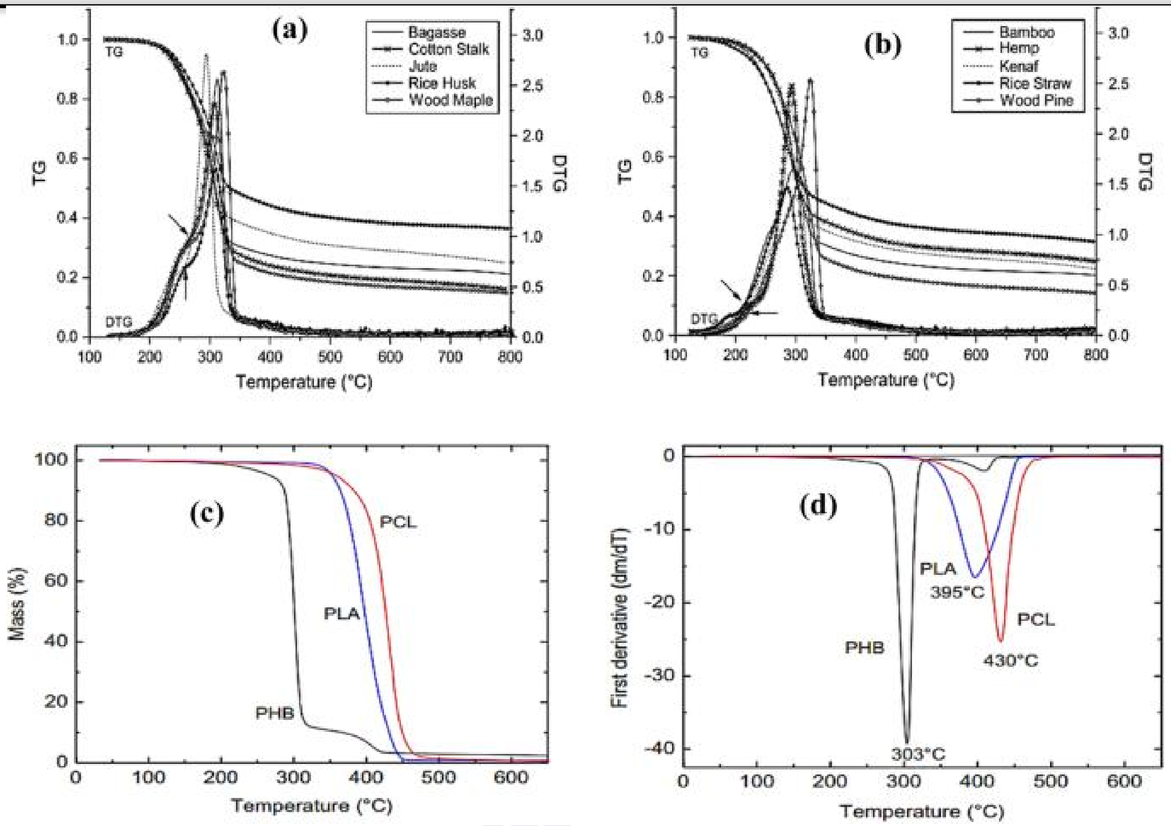


Figure 8: a Natural fibers with obvious hemicellulose shoulders and b not obvious hemicellulose shoulder c TGA for PCL, PLA, and PHB d DTGA for PCL, PLA, and PHB.

4.7 Environmental impact of biodegradable polymers:

The environment suffers from serious problems from the increasing difficulties of disposing of plastic waste that resist microbial degradation. Therefore, the researchers tried to produce biodegradable, non-polluting, and environmentally friendly materials. In recent times, the natural and synthetic origin of biodegradable polymers was produced with good compatibility and biodegradability. As the biodegradable polymers receive great attention because they degrade into non-toxic and environmentally friendly materials. Mechanical strength, thermal and electrical properties of common biodegradable polymers and their composites are shown in Fig. . Polyglycolide (polyglycolic acid, PGA) has high tensile strength (70–117 MPa). Thermoplastic starch showed low tensile strength (16–22 MPa).Chemical elements can be found in nature as components of organic molecules (such as polysaccharides, and so on) as well as in inorganic substances (such as NH3, CO2, and so on). Microorganisms transform lifeless organic materials into inorganic chemicals during biodegradation. Glucose molecules, for example, are converted back into the inorganic compounds that plants used to create glucose via aerobic biodegradation. This process is termed as mineralization as it leads in the transformation of organic material molecules into inorganic compounds and minerals. Organic molecules, like natural polymers and certain man-made polymers, are affected by the biodegradation process. Biopolymers are used in the manufacture of plastic materials that are designed to decompose in the soil or compost plants. Biodegradation of a polymeric compounds in which part of the original carbon (Cpolymer) is mineralized (CO2), part is consumed by microorganisms for their own development and reproduction (Cbiomass), and the rest remains as polymeric residue (Cresidue). Other kinds of microorganisms are engaged in the biodegradation process under anaerobic circumstances. As a result, products such as CO2 and CH4 are produced.

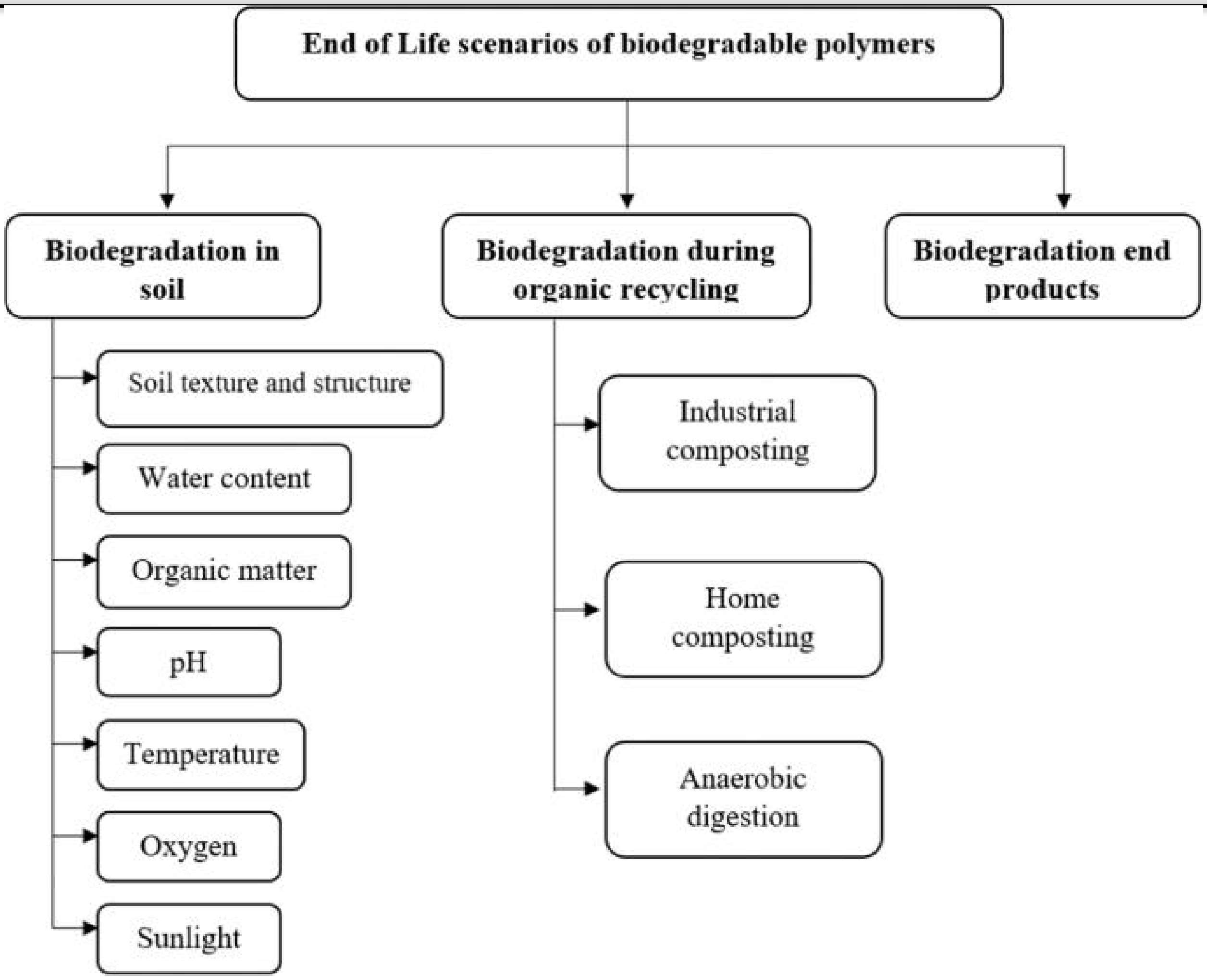


Figure 9: End-of-life scenarios of biodegradable polymers [48]

4.8 Application of bridgeable polymer: Applications are wide ranging with degradable polymers being used clinically as surgical sutures and implants. To fit functional demand, materials with desired physical, chemical, biological, biomechanical, and degradation properties must be selected. Biodegradable polymers represent a growing field. A vast number of biodegradable polymers (e.g. cellulose, chitin, starch, polyhydroxyalkanoates, polylactide, polycaprolactone, collagen and other polypeptides) have been synthesized or are formed in a natural environment during the growth cycles of organisms. Some microorganisms and enzymes capable of degrading such polymers have been identified. There are different classifications of biodegradable polymers, hereby is presented the classification according to the synthesis process, which is shown in Figure 1. Polyesters are among the most used biodegradable plastics, given their hydrolysable ester bonds; therefore, they represent a valid solution for biomedical applications. The properties of these materials strictly depend on the monomers used for their synthesis. The aliphatic polyesters are almost the only high molecular weight biodegradable compounds and thus have been extensively investigated. Their hydrolysable ester bonds make them biodegradable. Aliphatic polyesters can be classified into two types according to the bonding of the constituent monomers. The first class consists of the polyhydroxyalkanoates. These are polymers synthesized from hydroxy acids, HO-R-COOH. Examples are poly (glycolic acid) or poly(lactic acid). Poly (alkene dicarboxylate) s represents the second class. They are prepared by polycondensation of diols and dicarboxylic acids. Examples are poly (butylene succinate) and poly(ethylene succinate) . Application of biomaterials in therapy are various and some of these applications are aimed at replacing a lost function or an organ and request a therapeutic device made of biomaterials (prosthesis) for the rest of the patient's lifetime. Many other biomedical applications require a therapeutic aid for a limited period of time. Accordingly, it is desirable that the temporary therapeutic aid disappear from the body after healing in order to avoid the storage of any foreign materials. Whereas permanent aids require biostable biomaterials, temporary aids should be preferably made of degradable or biodegradable compounds that can be eliminated from the body or to be bio assimilated after use. Historically, biopolymers, i.e. polymers of natural origin such as polysaccharides and proteins, were primarily used as sources of wound dressings and suture threads either under their natural forms or after some chemical treatments. Because macromolecular compounds are usually biodegradable, i.e. degraded via biological processes, biopolymers are often regarded as suitable compounds to make bioresorbable therapeutic devices . Biodegradable polymers that are often used as biomaterials are shown in Figure 2. To be used as biomaterials, biodegradable polymers should have three important properties: biocompatibility, bioabsorbility and mechanical resistance. The use of enzymatically degradable natural polymers, as proteins or polysaccharides, in biomedical applications began thousands of years ago, whereas the application of synthetic biodegradable polymers dates back some fifty years. Current applications of biodegradable polymers include surgical implants in vascular or orthopaedic surgery and plain membranes. Biodegradable polyesters are widely employed as a porous structure in tissue engineering because they typically have good strength and an adjustable degradation speed. Biodegradable polymers are also used as implantable matrices for the controlled release of drugs inside the body or as absorbable sutures

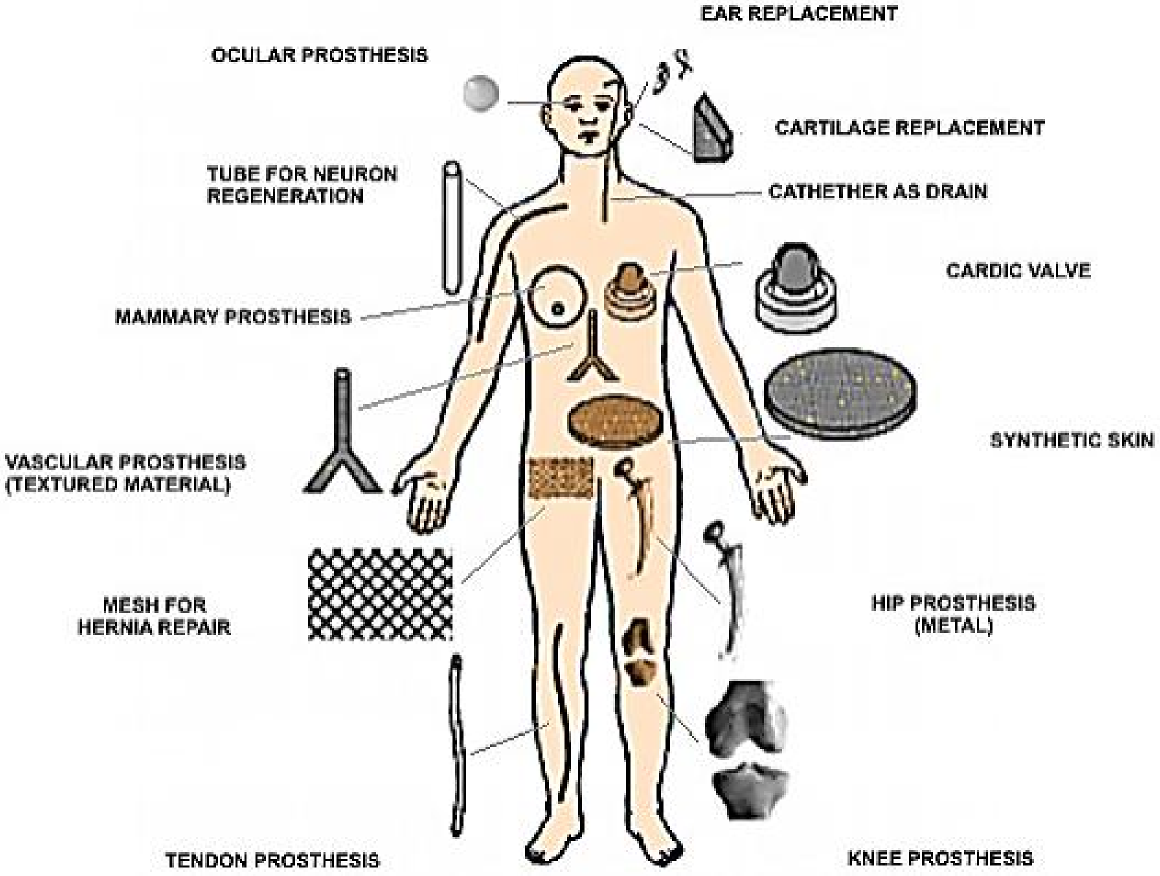


Figure 10: Biodegradable polymers used as biomaterials in human organism

4.8.1 PLA: has potential for use in a wide range of applications. It is used as a buffering agent, acidic flavoring agent, acidulant and bacterial inhibitor in many processed foods. PLA is growing alternative as a „green" food packaging polymer. Due to the larger thermal processing ability compared to other biomaterials like polyethylene-glycol, polyhydroxyalkanoates (PHA) and poly α-caprolactone; the processing of PLA can be achieved by film casting, extrusion, blow molding and fiber spinning . The major PLA application today is packaging (70%); the estimation for 2020 shows the increase of other applications especially in biomedicine. Commercialized PLA products demonstrate the fact that PLA is not being used solely because of its degradability, nor because it is made from renewable resources; it is being used because it functions very well and provides excellent properties at a competitive price . Applications of PLA are limited by several factors such as low glass transition temperature, weak thermal stability and low toughness and ductility . A large number of investigations have been performed on the blending of PLA with various polymers, such as: thermoplastic starch, poly(ethylene oxide), poly(ethylene glycol), poly(ε -caprolactone), poly(vinyl acetate), poly(butylene succinate) etc. Low molecular weight compounds have also been used as plasticizers for PLA, for example, oligomeric lactic acid, glycerol, low molecular citrates etc. . The choice of polymers or plasticizers that are to be used as modifiers of PLA is limited by the requirements of application. The final properties of these blends depend on the chemical structure of the original components, the mixing ratio of the constituent polymers, the interaction between the components and the processing steps to which they are then subjected. PLA is also used in biomedical applications, with various uses as internal body components, interference screews in ankle, knee and hand; tacks and pins for ligament attachment; rods and pins in bone, plates and screews for craniomaxillofacial bone fixation and also for surgical sutures, implants and drug delivery systems . This is based on their advantages over nondegradable biomaterials with respect to long term biocompatibility. PLA offers biodegradability, biocompatibility and thermoplastic process ability, and it is used as surgical implant material and drug delivery systems, as well as porous scaffolds for the growth of neo-tissue. Tissue engineering is a technique whose concept was introduced in 1988 by the reconstruction of the biological tissues using biomaterials. Three dimensional porous scaffolds of PLA have been created for culturing different cell types used in cell based gene therapy for cardiovascular diseases, muscle tissues, bone and cartilage regeneration. Microspheres and microcapsules have been applied in drug delivery systems (DDS). Release of drugs from these systems is based on several mechanisms that include diffusion and polymer degradation (hydrolysis or enzymatic degradation) . Erosion, diffusion and swelling are one of the ways by which polymeric drug release occurs. In the encapsulation process of many drugs, PLA and their copolymers have been utilized in nanoparticle form.[49]

Nowadays, plastics are a vital part of human society in our daily lives and are widely used in countless industries, such as packaging, building materials, textiles, transportation, healthcare, and so on. Furthermore, plastics are considered moisture-resistant, bendable, durable, and, specifically, more economical than any other material. Particularly, utilization and manufacturing have considerably upsurged for nearly half a century due to their features. After that, 8.3 billion metric tons of plastic materials have been manufactured globally, with plastic materials occupying a ubiquitous role in our daily lives. Notably, worldwide plastic production almost reached 370 million tons in 2019 and it is anticipated to substantially evolve over the coming decade . More importantly, plastic material has considerably impacted the areas of medicine, space programs, transportation, and life-saving devices such as incubators, helmets, ventilators, and carriers for safe drinking water . Excessive quantities of plastic waste are produced in both developing and developed countries. Furthermore, plastic materials' resilience and non-biodegradable features have allowed them to remain in the ecosystem over a more extended period, instigating the most stable waste product over other methods of waste. However, the continual need, mishandling, and littering of plastics became destructive. More importantly, petrochemically derived plastics damage the environment even after disposal. Polyethylene, polypropylene, polyvinyl chloride (PVC), polystyrene, polycarbonate, and polymethyl methacrylate can be cast under a thermal process and labeled as plastics. Notably, plastic materials tend to contain harmful chemicals, so land and water accretion instigate severe ecological damage. Biodegradable polymers can be applied in the medicinal arena and are mainly classified into drug delivery systems wound healing products and surgical implant devices . The advancement of biopolymeric drug delivery systems now attains remarkable interest, especially in controlled delivery. More importantly, drug delivery inside humans can be regulated through biodegradable capsules. Particularly, biodegradable polymers are used to prepare novel formulations, and the high permeability of buccal mucosa is an appropriate target for drug delivery . In this regard, drug delivery combined with biopolymers and buccal routes is shielding, safe, and rapidly functioning. Similarly, in the case of wound healing, bioresorbable non-wovens to substitute human tissue repair and simple sutures, staples, or meshes, are accessible. Comparatively, the usage of biological resorbable scaffolds for tissue engineering is worth revealing. Further, biodegradable polymers are renewable, cost-effective, and found in various varieties. Notably, biodegradable polymers are considered an exceptional candidate for wound healing due to their bioactive features, facilitating cell growth and regeneration potential, and providing antimicrobial conditions and immunomodulation. In addition, biodegradable polymers are a probable candidate for wound care because they can absorb a massive amount of water. In recent years, these polymers are capable of releasing drugs at the site of damage and making them appropriate for healing applications. Many biopolymers have good film-forming features, making them applicable for conventional commodity applications . Notably, they are used in foodstuff containers (bottles, jars), soil retention sheeting, farming film, garbage bags, and wrapping material. Additionally, biodegradable polymers in non-woven form can be used in farming, filtration, hygiene, and protecting wear.

4.8.2 Packing : A varied series of areas where uses for biodegradable polymers have been applied involve medicinal, packaging, farming, and the automotive industry. In addition, biodegradable polymers that can be applied in packaging continue to gain more consideration than those used for other applications. It is projected that 41% of plastics are used in packaging and that nearly half of that volume applies to wrap food materials . The reusable and degradable features of biopolymers are what make them tempting for inventive use in packaging. In particular, biopolymers are generally used in different industrialized applications, such as food wrapping, cosmetics, and medicine. Biodegradable polymers have a lower solubility in water and a very imperative water uptake, thereby they can be applied as absorbent candidates in biological, healthcare, horticulture, and farming applications. Particularly, biodegradable polymers have been used in certain applications in which plastics cannot be used, such as making artificial tissue. These uses might demand biomaterial features such as biocompatibility, environmental responsiveness, and biodegradable candidates with sensitivity to variations in pH and physicochemical and thermal variations . Generally, biopolymers display poor thermal and mechanical features (tensile strength and brittleness), chemical resistance, and processability than synthetic polymers. Particularly, to make them appropriate for specific uses, they can be reinforced with fillers that drastically enhance these features.

4.8.3 Drug Delivery: In recent years, drug delivery research and its advancement have been considered to be of vital significance in biomedical and healthcare uses. Nowadays, developing competent drug delivery systems is a major concern for drug delivery researchers. Drug delivery is a method of directing a pharmacologically active compound to achieve a therapeutic effect in humans. Notably, various drug delivery methods have been advanced and explored at the target site for drug delivery . For handling human-related illnesses, many paths include drug targeting systems for oral, nasal, ocular, and transdermal routes. Biopolymers have developed certain applications in drug delivery in the form of beads, solid monolithic matrix systems, films, implants, micro and nanostructured particles as well as inhalations and injectable systems, and viscous liquid formulations. Different anatomical routes are recognized as safe and reliable for administering numerous medical drugs to the human body. The selection of the drug delivery paths depends on the following disputes, (a) the effect anticipated by the kind of the disease; (b) the kind of the product; (c) the drug will be openly directed to the organ that hurts from the disease. In past decades, targeting drug delivery has amassed attention, and many approaches were established to boost the targeting of drug delivery by developing numerous nanoparticle-based systems. The invention in biomaterial fields and engineering permits the examination and utilization of numerous developed biomaterials, keeping their essential biomaterial features like biodegradability, biological compatibility, environmental alertness, etc. Biomaterials are changed or subjected to functionalization to develop these promoted candidates for enhanced drug delivery. Biodegradable polymers exist as beads, films, microparticles, and solid monolithic matrix systems; nanoparticles are applied and used via different routes targeting specific sites/cell populations in organs like the lung, kidney, and pancreas for the drug release in an established fashion, and deterioration in a limited period. In general, the greatest advantage of biopolymers is their ability to degrade under aerobic and anaerobic conditions. In particular, biopolymers in nanocarriers have fascinating considerations because they degrade within the body in physical circumstances. In addition, biopolymers can be considered for medical uses; specifically, drug-related uses. Protein-related biopolymers have been introduced as essential devices (Figure 3). Many polysaccharides, namely chitosan, chondroitin sulfate, cyclodextrin dextrin, insulin, amylase, and locust bean gum have been considered for drug delivery applications.

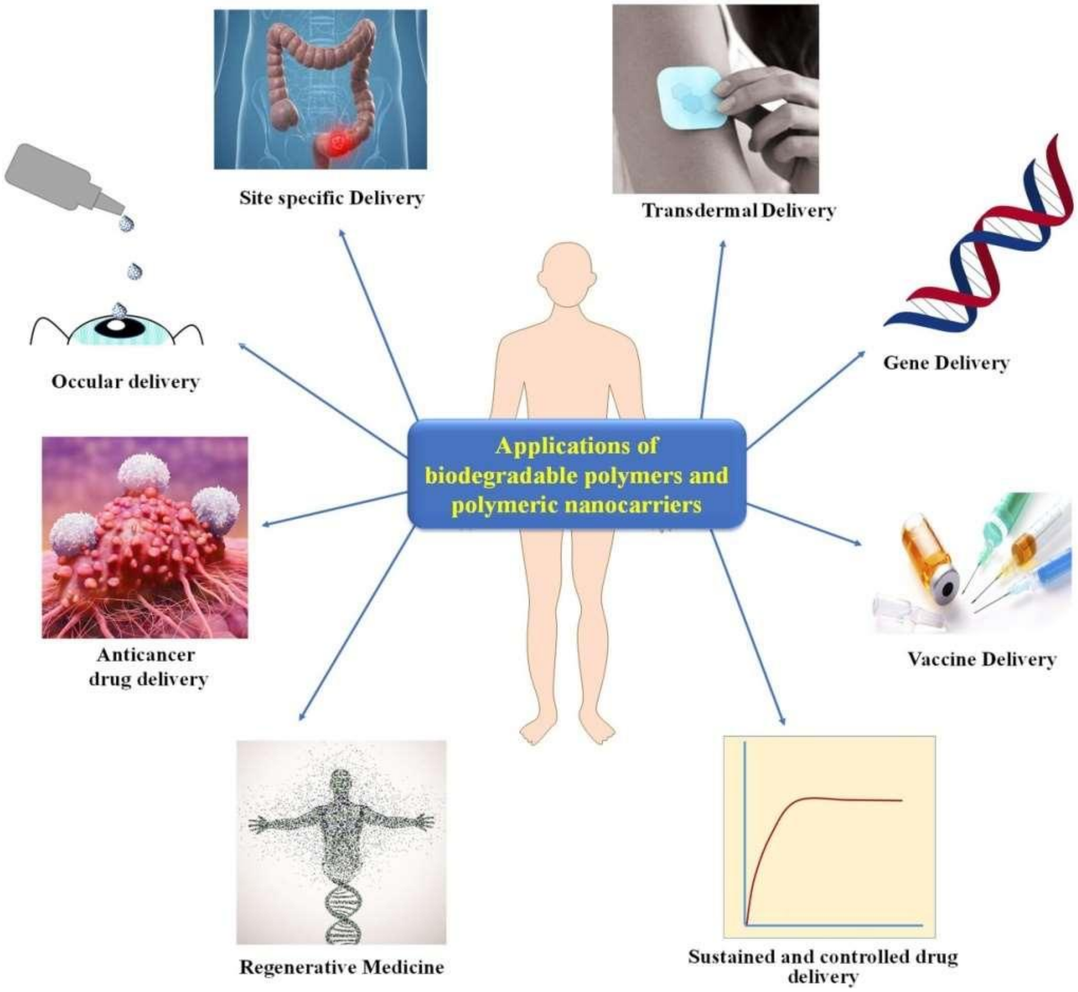


Figure 11: Different kinds of biopolymer applications and polymeric nanocarriers .

In general, biopolymer's drug delivery applications include oral, nasal, and parenteral; in addition, transdermal management of drug delivery, protein and gene delivery, and the usage of implants to are used to treat illnesses . Several aliphatic polyesters and cross-linked polyorthoesters have been explored in drug delivery use, especially in antineoplastic agents, antidiabetics, vaccine delivery, etc. More importantly, synthetic peptides are enzymatic decomposable peptides that can create cross-links in synthetic hydrogels. Similarly, new phosphazenes-based polyphosphoester must have a characteristic backbone comprising P-atoms associated with carbon/oxygen. Particularly, phosphazine biopolymers and copolymers can encapsulate hydrophilic and lipophilic drugs . Moreover, these polymers can potentially deliver the targeted site of antineoplastic agents when folic acid is introduced as a targeting ligand to the polymer . Further, this aliphatic polyester is a hydrophobic material, and PLA is demonstrated here. More importantly, PLA uses in drug delivery are mainly categorized by synthesizing new kinds of block copolymers as biocompatible hydrophobic fragments and preparing micelles or polymer microspheres for drug incorporation.

4.8.3 Chitosan-based biodegradable polymers:show good absorption, organized release, and bioadhesive features . Furthermore, these biopolymers possess mucoadhesivity, biodegradability, biocompatibility, and have remarkable biological features that make chitosan appropriate for drug delivery methods with greater biodistribution, selectivity, and minimal harmfulness. The deacetylation degree is in the range of polymer-side chains that can be manipulated for target-precise drug delivery uses . The polymer solution vaporizes to produce polymer layers, and these layers work as a protecting coating for tablets holding a sensitive drug for release . The primary concern for advancing scientific outcomes is the target-specific delivery of therapeutic drugs to the specific diseased tissue by nanomaterials when enhanced permeability and retention (EPR) is not appropriate. To overcome this, nanomaterials are surface-tuned through a ligand as a directing moiety; this ligand reveals distinctive targeting capabilities to direct selective binding of nanomaterials and reduces non-productive delivery. The essential potential of controlled drug delivery through biopolymeric nanomaterials is to advance efficacy by escalating drug concentrations at the targeting site while simultaneously curtailing harmfulness by reducing target accumulation. The current development of nanomaterials to enhance passive targets is mostly based on the improved ability of active molecular targeting. In targeted drug delivery, enriched receptor-mediated uptake is attained by engineered nanomaterials' surfaces with ligands.[50]

4.8.3 Application of biodegradable polymers in tissue engineering: Poly(tri-methylene carbonate) (PTMC) is used in the fabrication of non-commercial devices of soft tissue engineering. The biodegradable polyurethane (cPU) is produced by cross-linking with hexamethylene diisocyanate (HDI), polyethylene glycol (PGA) and prepolymer PLEG and is used as a scafolding material for hypopharyngeal tissue engineering. This has excellent hydrophilicity and relatively quick degradation. It can support the growth of human hypopharyngeal fbroblasts. Biodegradable electrospun nanofbers have the same size as biomolecules and mimic biological properties. Since electrospinning is a simple and inexpensive technique, these electrospun nanofbers are playing a very important role in biomedical applications like cardiac tissue engineering, skin tissue engineering, bone tissue engineering and nerve tissue engineering. The biodegradable thermoresponsive polymers can be used for 3D printing of hydrogel scafolds in tissue engineering. These polymers can act as sacrifcial materials for bioprinting. By using the freeform reversible embedding of suspended hydrogels (FRESH) technique, the printing of low viscosity and soft hydrogels like collagen can be obtained. Therefore, thermoresponsive biodegradable polymers are used for 3D printing of hydrogels such as collagen and gelatin and notably widening the range of printable materials for tissue regeneration.

4.8.4 Application of biodegradable polymers in food packaging: Biodegradable polymers are biocompatible, non-toxic and highly selective . In the packaging industry, they are replacing conventional petroleum-based polymers . In the plastic industry packaging field is one of the largest sectors. Nowadays these biodegradable polymers are in great demand for packaging . A commercial biodegradable polymer named Mater-Bi is based on biodegradable polyesters has numerous applications in the packaging industry because of its interesting thermal stability, processability, mechanical property and biodegradability. It is used as one of the polymers in the manufacturing of nets for fruits and vegetables . Polyvinyl alcohol (PVA) is blended with some biodegradable polymers like sodium alginate, gelatin, carboxymethyl cellulose and K-carrageenan, but particularly PVA is blended with K-carrageenan to form a strong binary blend film which exhibits high resistance and water barrier property. So, it is used as a packing material in the food industry. To improve the water vapor barrier property, biodegradable polymers like PCL are more favorable because of their flexibility. The polar groups which are present on the side chains of biodegradable polymers tend to decrease the water vapor barrier property. Biodegradable PCL/C18 blends are used in packaging materials due to their high oxygen and water vapor barrier property even at high humidity. The biodegradable polymers which are having the polar groups –OH at their molecular side chains show less water vapor barrier property. To improve the water vapor barrier property, biodegradable polymers like PCL are mixed with glycerol tris stearate (C18) which in turn increases the hydrophobicity. This is an extensively used biopolymer over polyethylene due to its better biostability and mechanical strength. The conventional thermoplastic materials used in food packaging can be replaced by biodegradable cellulose esters. Cellulose esters such as cellulose triacetate and cellulose diacetate can be prepared by the addition of additives. Montmorillonite is a biodegradable nanoclay biocomposite and it is hydrated alumina silicate layered clay. The specialty of this is to limit the penetration of gases during food packaging. Biodegradable films like whey protein isolate films are strengthened by the addition of nanoparticles like TiO_2 and SiO_2 and these films are effectively used as a packaging material that favors food quality and safety. The biodegradable polymer films like poly(3-hydroxybutyrate-co-3-ydroxyl valerate) which is developed from the Ceiba pentandra. These biocomposite films are specially designed for fruits packaging. This extends the shelf life of perishable fruits and also shows antimicrobial activity . The bionanocomposite films are prepared by blending cellulose nanocrystals with silver alginate from cellulose nanocrystal alginate (CNC/Alg). These are used in food packaging due to their UV and water barrier properties .

Biodegradable polyglycolic acid is used as a packaging material to enclose perishable foods or goods with limited shelf life. This packing film contains two layers with a reactive chemical layer that is interposed between two layers. If one layer degrades, the synthetic layer is exposed to air and it causes the change of color in the remnant layer which indicates the expiry of the shelf life of the package. PLA is used as packaging material and it is considered a “Green” food packaging polymer as it possesses good microbial activity. It is used in the retail market for packaging vegetables, fruits and salads . Natural biodegradable polymer-based silane cross-linked blended films are also used in the food packing industry because of their antioxidant activity, biodegradability, water vapor permeability, lower water vapor transmission rate has shown better shelf life. Hence, these biodegradable films have good potential for food and packaging. Active packaging is essential to extend the shelf life of the goods and to keep the product fresh. It should also maintain the quality of the product and should ensure the safety of the environment . The direct disposal of plastic bags brought many serious concerns, so this led to the use of biodegradable polymers in the food packing industry and also in other packaging materials. This resulted in a decrease in the ecological impacts due to synthetic packaging materials. The starch-based biodegradable polymer is used as thermoplastic. They are prepared by plasticization through destructuration with water or plasticizers and by heating. So thermoplastic starch blended with other biodegradable polymers or additives shows good mechanical strength and resistance to water. So, this is widely used in the food packaging field. Protein-based biodegradable polymers are also widely used in food packaging and other non-food packaging applications. The protein polymers like whey protein, milk protein, zein, wheat gluten, corn, soy protein, etc. are used in food packaging. These protein-based biodegradable polymers can be consumed along with the food. These edible films in food packaging with barrier and mechanical properties are very much useful in food packaging.

4.8.5 Applications of biodegradable polymers in textiles and hygiene products: In recent times, the usage of personal protective equipment like face masks, gloves, gowns, aprons, hoods, eye shields and shoe covers has increased across the globe due to the COVID-19 pandemic. Majorly the usage of face masks has increased to a great extent. Since most of the face masks are made up of petroleum-based non-biodegradable polymers, the amount of waste generated is high which leads to severe environmental pollution . Generally, there are three different types of masks consisting of different layers, namely N95 mask (four layers), surgical mask (three layers) and cloth mask (one layer) . These masks can be replaced by biodegradable polymers, but complete replacement of biodegradable polymers in face masks production is not possible. So any one of the layers in the mask can be replaced by biodegradable like PLA, PHA, poly(lactic-co-glycolic acid), cellulose acetate, polycaprolactone, etc. In particular, the layer which is in contact with skin is replaced by using biodegradable polymers. In addition to air filtration, these masks are antimicrobial, antifungal, UV protective and skin-friendly. The ear loops of both N95 and surgical masks are made up of biodegradable polymers called poly(isoprene) units (latex-free rubber) .

Biodegradable polymers like PLA and cellulose are used in the manufacturing of face masks. These polymers are lightweight, low cost, safely disposable and comfortable to use. In addition to this, it provides adequate filtering performance and readily degrades after discarding. Melt-blown PLA (MBPLA) electret membranes are used as interesting material for the production of face masks due to their excellent air filter capacity. These PLA melt-blown nonwoven fabrics can form electrets by corona charging technology. The biodegradable cellulose acetate polymer nanofibers provide high-efficiency filtration for aerosol nanoparticles and also provide antibacterial properties, so it majorly used in the production of masks . The biodegradable mask filters manufactured by using CsW (chitosan nanowhiskers) and PBS (polybutylene succinate) are highly efficient sustainable and fully biodegradable within a month in the soil. The gluten-based biodegradable face masks are also being manufactured and it has good viral filtration capacity. Its antiviral properties can be enhanced by using natural products like turmeric, basil, neem oil, moringa seeds, etc. The nanofiber membrane in this mask can be produced by the electrospinning method and gluten sheets are produced by the hot-press method.

The disposable baby diapers are made up of multiple layers consisting of different materials. The top layer consists of polypropylene sheets which are hydrophilic nonwoven and allow the urine to pass through it. The middle layer is made up of superabsorbent polymer which helps in holding the urine. The bottom layer is made up of hydrophobic nonwoven films which consist of polypropylene fibers. Since polypropylene is toxic and non-degradable, it can be replaced by biodegradable viscous nonwoven which is made up of cellulose. The advantages of using this cellulose provide physiological safety, skin tolerance, better moisture absorbance, easily degradable and being eco-friendly.

4.9 Challenges and future perspective of biodegradable polymer

Next-generation biodegradable polymers hold immense promise for sustainable development, but several challenges hinder their widespread adoption. One major obstacle is the high production cost, as processes like microbial fermentation and enzymatic polymerization remain expensive, and raw materials derived from renewable sources can still cost more than petroleum-based alternatives. Additionally, these polymers often exhibit limited mechanical strength and thermal stability, restricting their use in high-performance applications unless reinforced with additives or nanomaterials. Another concern is their slow degradation rates in natural environments, which depend heavily on external factors such as temperature, humidity, and microbial activity. Inconsistent degradation rates lead to uncertainty about their environmental impact, especially when they accumulate in landfills or marine environments. Scalability poses another challenge — while many green synthesis techniques show promise at the lab scale, translating these methods into large-scale production is complex and costly. Moreover, the absence of universal standards and regulations for biodegradability complicates product labeling and market acceptance. The limited availability of industrial composting facilities further restricts proper disposal options, increasing the risk of these materials being mixed with traditional plastics during waste management. Lastly, public awareness and market acceptance remain low, as consumers and industries are still adapting to these new materials, particularly when they come at a premium price.Despite these challenges, the future of biodegradable polymers is promising, with several exciting prospects on the horizon. Cost reduction strategies are being explored, such as utilizing agricultural and food waste as feedstocks and optimizing green synthesis techniques like microwave-assisted and enzymatic polymerization to lower energy consumption. Researchers are also focused on enhancing polymer properties by developing blends and nanocomposites that improve mechanical strength, thermal stability, and barrier performance. Accelerated biodegradation is another key focus, with innovations such as engineered enzymes and microbial consortia designed to break down polymers more efficiently across diverse environments. To overcome scalability hurdles, process intensification techniques like continuous flow reactors and 3D printing offer potential pathways for cost-effective mass production. The push for standardization is gaining momentum, with efforts to establish global benchmarks for biodegradability and life-cycle assessment, alongside policy incentives encouraging industries to shift towards sustainable alternatives. Integrating biodegradable polymers into circular economy models is also a growing priority, promoting the design of materials that are recyclable, reusable, or compostable, thereby creating closed-loop systems. Furthermore, raising public awareness through education campaigns and fostering industry collaboration will play a vital role in accelerating market adoption. As innovation continues to bridge these gaps, next-generation biodegradable polymers are poised to revolutionize industries and contribute significantly to a greener planet.

4.10 Conclusion:

In conclusion, next-generation biodegradable polymers represent a promising solution to the growing plastic pollution crisis, offering eco-friendly alternatives to traditional plastics. However, several challenges hinder their widespread adoption. High production costs remain a major barrier, as green synthesis techniques often require expensive raw materials and complex processes. Additionally, these polymers sometimes lack the mechanical strength and thermal stability needed for high-performance applications, limiting their use in various industries. Their degradation rates can also be inconsistent, heavily influenced by environmental conditions like temperature and microbial activity. Scalability is another concern, as translating lab-scale methods into large-scale production demands technological advancements and infrastructure. Furthermore, the absence of universal standards for biodegradability and limited access to industrial composting facilities complicate proper disposal, while public awareness and market acceptance are still developing.Despite these obstacles, ongoing research and innovation offer promising solutions. Cost reduction strategies, such as utilizing agricultural waste, are making production more sustainable. Enhancements in polymer properties through nanocomposites and functionalization are improving performance, while novel approaches like engineered enzymes are accelerating degradation rates. Efforts toward global standardization, policy support, and integration into circular economy models are also gaining momentum. As these advancements continue, biodegradable polymers have the potential to revolutionize industries, reduce environmental pollution, and support a greener future. Embracing these innovations is crucial for mitigating plastic waste and building a more sustainable planet, where materials work in harmony with nature rather than contributing to its burden.

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