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REVIEW

Advances in Biodegradable Polymers: Synthesis, Properties and Environmental Applications

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Increased apprehension about the environment due to the extensive use of plastics originating from petroleum has led to the development of biodegradable polymers as prospective replacements for several industrial and environmental applications. Biodegradable polymers are important materials for the circular economy and sustainable resource management due to their degradation into environmentally benign products in a controlled manner. This review presents the current state of research on biodegradable polymers, covering their classification, sources, synthesis methods, structural characteristics, physicochemical properties and environmental applications. Biodegradable polymers derived from natural, synthetic and microbial sources are discussed with emphasis on their structural features and their influence on thermal stability, mechanical properties, degradation behaviour and processability. Recent developments in material design and processing include advances in chemical polymerization, microbial fermentation and green synthesis approaches. Their applications in sustainable food packaging, agriculture, wastewater treatment, environmental remediation and eco-friendly consumer products are also examined in relation to the growing need for alternatives to conventional plastics. Biodegradable polymers represent a promising class of sustainable materials with the potential to reduce plastic pollution, improve resource efficiency and support environmental sustainability. Continued research in polymer design, processing technologies, multidisciplinary material development and supportive regulatory frameworks is needed to facilitate their wider industrial application and realize their long-term environmental benefits.

Keywords: Biodegradable, Sustainable materials, Polymer synthesis, Circular economy.

INTRODUCTION

Conventional petroleum-based plastics are extensively used across domestic, industrial and commercial sectors, yet their durability and resistance to microbial degradation contribute to their long-term persistence in terrestrial and aquatic environments. Recycling, reuse and efficient waste management systems remain important for improving plastic sustainability, although diverse waste streams, contamination, inefficient sorting, inadequate collection and limited end-of-life infrastructure continue to restrict their effectiveness. Biodegradable polymers have gained considerable attention as materials

capable of undergoing biological or environmentally mediated degradation under defined conditions [1]. Their biodegradability should not, though, be regarded as an inherent or universal environmental advantage, since degradation is governed by polymer chemistry, molecular architecture, processing method and the conditions of the existing environment.

Biodegradable polymers comprise natural, microbial derived and chemically synthesized materials such as poly(lactic acid) (PLA), poly(butylene succinate) (PBS), polyhydroxyalkanoates (PHAs), poly(butylene adipate-*co*-terephthalate) (PBAT), polycaprolactone (PCL), starch-based polymers and chitosan-based materials [2]. Their molecular structures and physico-chemical characteristics determine mechanical strength, thermal behaviour, barrier properties, processability and susceptibility to hydrolytic, enzymatic and microbial degradation. Degradation is influenced by chain mobility, water penetration, accessibility of degradable bonds, crystallinity, chain architecture, chemical functionality and stereochemistry. The nature and rate of degradation products can vary substantially with temperature, moisture, oxygen availability, microbial activity and the characteristics of the receiving environment. The term "biodegradable" should, therefore, not be interpreted as rapid degradation under every environmental condition [3,4].

The rapid expansion of research on the biodegradable polymers has resulted in several broad reviews addressing different aspects of the field. Kim *et al.* [5] critically examined the chemistry, characteristics, applications and future research requirements of biodegradable plastics, while Jha *et al*. [6] reviewed the current state of biodegradable biobased polymers, their challenges, techno-commercial aspects and future prospects [5,6]. Afshar *et al*. [3] examined the dependence of polymer degradation on waste-management practices and open environmental conditions, while Shi *et al*. [7] discussed recyclable and (bio)degradable polyesters within the context of a circular plastics economy [3,7]. Dallaev *et al*. [4] compiled information on polymer characteristics, applications and environmental impacts. Recent investigations have broadened the scope to life-cycle performance, chemical leaching, environmental degradation pathways and the potential role of biodegradable plastics within future plastic-management systems [8,9]. Despite this expanding body of literature, information remains dispersed across polymer chemistry, material properties, degradation mechanisms, applications, circularity and life-cycle assessment.

A clear gap remains in the integrated understanding of the structure–property degradation relationship across the major groups of biodegradable polymers [10]. Environmental performance cannot be assessed solely from biodegradability; the sustainability of a polymer system is influenced by feedstock source, energy and resource consumption, processing requirements, emissions, chemical release, recycling, composting and other end-of-life pathways [7-9]. These factors need to be considered when assessing the environmental suitability of biodegradable materials. The present review adopts a structure–property degradation environmental performance framework to critically assess biodegradable polymers. Rather than providing a general description of individual polymer classes, the review compares their material properties and degradation behaviour in relation to environmental applications. Particular emphasis is placed on quantitative property data and degradation performance under defined conditions. The review distinguishes among bio-based, biodegradable, compostable and eco-degradable materials and examines their sustainability from life-cycle and circular-economy perspectives. The feasibility, limitations and current research gaps associated with emerging technologies such as artificial intelligence, nanotechnology, synthetic biology and advanced manufacturing are discussed in the context of future development. This integrated approach provides a science-based framework for understanding the relationships among polymer structure, material design, performance, degradation and environmental fate, supporting the rational development and responsible application of next-generation biodegradable polymers.

Sources and types of biodegradable polymers: Biodegradable polymers are a wide variety of materials that can be decomposed into environmentally friendly molecules by the action of bacteria, enzymes, moisture and other natural processes [11]. The key difference between biodegradable polymers and traditional petroleum-based plastics lies in their capability to be biologically degraded under certain environmental or biological conditions, although the rate and degree of degradation can vary significantly depending on the polymer chemistry and the surrounding environment [3,4]. Their chemical composition, molecular architecture, molecular weight, crystallinity and functional groups have a significant impact on their physico-chemical properties, degradation behaviour and end-use applications. These factors influence water penetration, enzymatic accessibility, and polymer chain scission [11,12]. Biodegradable polymers are generally grouped based on their origin and synthetic route as natural, synthetic and microbially derived polymers. However, the classification based on bio-based origin and biodegradability should be distinguished, as bio-based materials are not always biodegradable [4,13]. Natural polymers, such as cellulose, starch and other polysaccharide- or protein-derived systems and manufactured biodegradable polymers, such as aliphatic polyesters and other chemically generated materials containing degradable links [14]. Polyhydroxyalkanoates (PHAs) [15] and other microbially generated polymers are biosynthesized intracellularly by microorganisms and represent an important class of bio-based biodegradable thermoplastics with tunable chemical structures and material properties [13,16]. These different classes have significant differences in molecular form, processing properties, degradation mechanisms and industrial applicability, making classification a significant basis for comprehending their structure-property function relationships [17]. Starch, a readily biodegradable natural polymer, consists mainly of amylose and amylopectin and has considerable potential for compostable packaging, agricultural films and disposable products. Cellulose, the most abundant natural polymer, offers a complementary combination of high mechanical strength and chemical stability, making it suitable for paper-based composites, packaging materials, biomedical scaffolds and textile applications. Other natural polymers, such as chitosan, alginate, collagen, gelatin [18] and protein-based polymers, possess distinct biological properties, particularly antimicrobial activity, biocompatibility and bioactivity. These characteristics make them

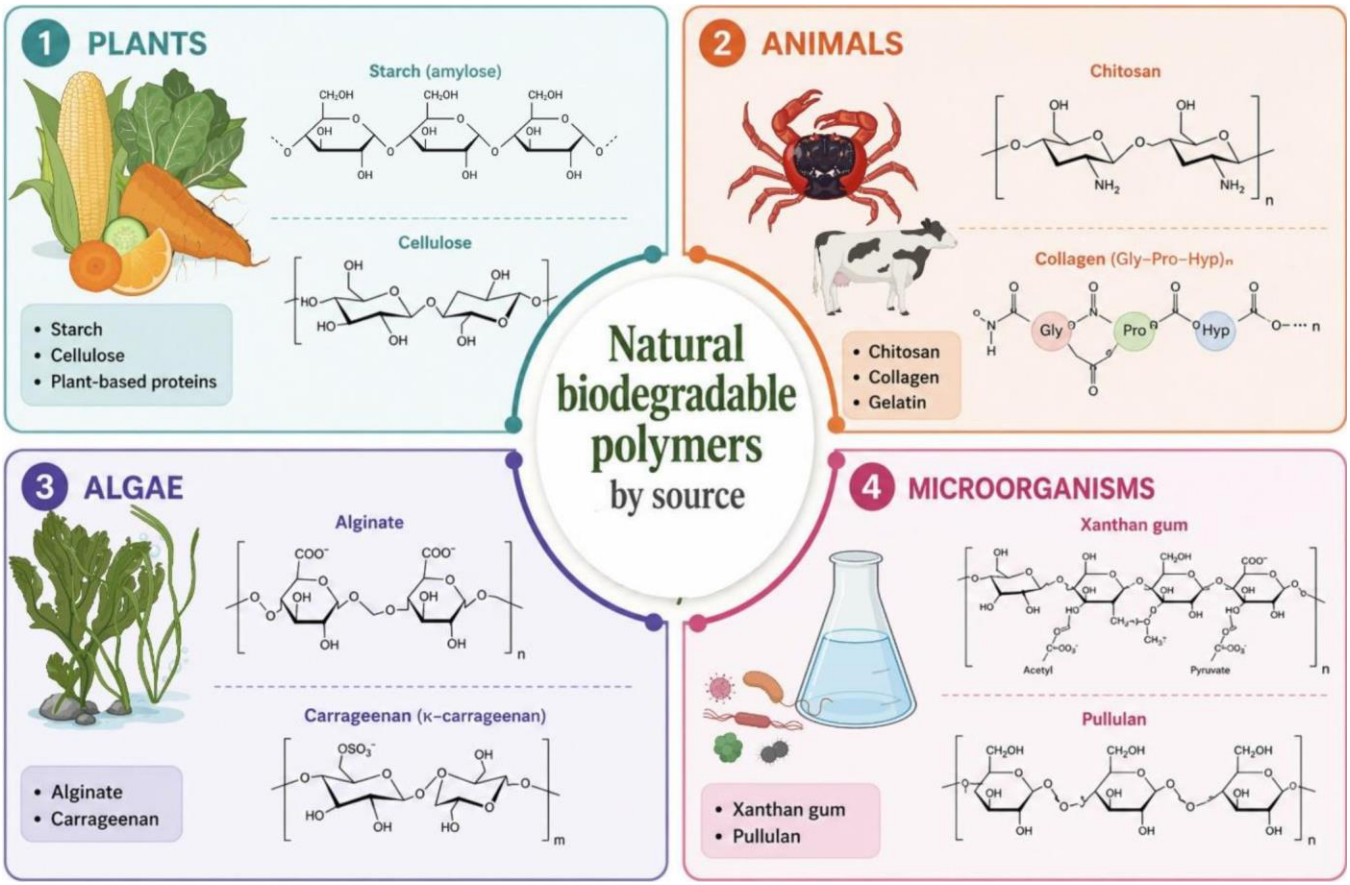

Fig. 1. Major biological sources and typical chemical structures of natural biodegradable polymers

especially valuable for pharmaceutical, biomedical and tissue-engineering applications [19,20] (Fig. 1).

Another prominent group is the synthetic biodegradable polymers, which have been specifically engineered to overcome several of the drawbacks of natural polymers such as low mechanical strength, high moisture sensitivity and limited heat stability. These polymers are commonly synthesized by controlled polymerization techniques such as ring-opening polymerization and polycondensation, which enable exact control over molecular weight, crystallinity, degradation rate and mechanical properties [21]. Among these, poly(lactic acid) (PLA) has emerged as one of the most commercially successful biodegradable polymers, owing to its production from the renewable carbohydrate sources through fermentation of carbohydrates to lactic acid, followed by polymerization [22]. Its transparency, processability, biocompatibility and relatively high mechanical strength support its widespread use in food packaging, biomedical implants, pharmaceutical delivery systems and three-dimensional printing. Its inherent brittleness, slow crystallization and limited thermal resistance remain key limitations, driving research into polymer modification, copolymerization and composite development to improve its complete performance [23,24].

The terms bio-based, biodegradable, compostable and environmentally degradable represent different attributes of polymeric materials and should be clearly distinguished. Bio-based polymers are derived from biological or renewable feedstocks, although their origin does not determine their biodegradability. Biodegradable polymers are capable of biological degradation under specified conditions [25]. Compostable polymers represent a more specific category, requiring degradation and disintegration under established composting conditions. Environmental degradability refers to degradation demonstrated within a defined environmental compartment, such as soil, freshwater or marine systems. Consequently, bio-based polymers are not inherently biodegradable, and biodegradability does not necessarily confer compostability or rapid degradation under natural environmental conditions [3,4,6].

In recent years, synthetic biodegradable polymers have been widely employed owing to their versatility, especially in the healthcare industry, sustainable packaging, agriculture and controlled release technologies [21]. Other important synthetic biodegradable polymers include poly(glycolic acid) (PGA), polycaprolactone (PCL), poly(butylene succinate) (PBS) and copolymers of these polymers (Table-1). These materials exhibit varied degradation rates, flexibility, crystallinity and processing behaviour and can be adjusted to fit the requirements of several industrial and biological applications [28].

Biodegradable polymers of microbial origin are a particular group of biopolymers which are formed spontaneously by bacteria as intracellular carbon and energy storage molecules [29]. One of the most promising categories among them is the polyhydroxyalkanoates (PHAs) owing to their complete biodegradability, good biocompatibility and renewable

TABLE-1
COMPARISON OF THE MAIN BIODEGRADABLE POLYMERS

Polymer	Origin	Main synthesis/ production	Key characteristic	Major application	Ref.
PLA	Bio-based	ROP/polycondensation	High strength and stiffness; relatively brittle	Packaging, 3D printing, biomedical	[5,6]
PHA/PHBV	Microbial/bio-based	Microbial fermentation	Tunable properties; highly biodegradable	Packaging, agriculture, biomedical	[6,26]
PBS	Bio-/fossil-based	Polycondensation	Flexible, tough and processable	Packaging, agricultural films	[27]
PBAT	Mainly fossil-derived	Polycondensation	Highly flexible and ductile	Compostable films, packaging	[4,27]
PCL	Synthetic	ROP	Highly flexible, low melting temperature	Drug delivery, tissue engineering	[5,27]

manufacture. Different microbial strains, carbon substrates and fermentation conditions can be employed to modify the physico-chemical characteristics of the generated polymers, which can have different flexibility, strength and degradation rates. PHAs have thus gained more attention for applications such as biodegradable packages, medical gadgets, tissue engineering and environmentally sustainable consumer products. However, the high manufacturing costs, low productivity and problems in downstream processing still restrict their large-scale commercialization. Thus, there is an urgent need to develop fermentation technology and metabolic engineering methodologies [30].

Biodegradable polymers are also classified based on the source of raw materials. Bio-based polymers are defined by the renewable biological origin of their feedstocks, whereas biodegradability refers to a material's ability to undergo biological degradation under specific conditions; thus, bio-based origin does not necessarily imply biodegradability [31]. Bio-based polymers are polymers that are made entirely or partially from renewable resources such as corn, sugar cane, cassava, potato starch, cellulose, vegetable oils and microbial biomass. Conversely, some biodegradable polymers are built on monomers from the petrochemical industry. But under the right environmental conditions, microbes can break them down depending on their chemical structure. Therefore, bio-based and biodegradable cannot be used interchangeably, since a polymer can be made from renewable resources and not be biodegradable and some fossil-based polymers can be totally biodegradable. Therefore, a precise classification based on origin and degrading properties is needed for the selection of appropriate materials for various environmental and industrial uses [32].

The growing variety of biodegradable polymers is a result of ongoing advancements in polymer chemistry, biotechnology and sustainable materials engineering [27]. However, no single biodegradable polymer is able to fulfill all performance, economic and environmental requirements at the same time. Typically, polymer classes exhibit trade-offs between mechanical strength, thermal stability, processability, biodegradability and production cost [33]. Natural polymers tend to provide good biodegradability, renewability and biocompatibility but might suffer from disadvantages regarding mechanical stability, moisture resistance and processing. Synthetic biodegradable polymers provide more control over mechanical and structural properties but demand more sophisticated synthesis and processing [27]. Microbial production of polymers such as PHAs is attractive due to their biodegradability and the potential to use renewable resources for their production. Nevertheless, high production costs, downstream processing and difficulties in scaling up to the industrial level are important barriers to commercialization [34,35]. Consequently, recent research has focused more on polymer blends, copolymers and bio-based composites that synergistically combine features and address the deficiencies of separate polymer systems [26,27]. Such techniques can enhance mechanical strength, toughness, thermal stability, processability and degradation properties and so broaden the possible uses for biodegradable materials. Such an integrated material design is projected to contribute significantly to the future development of sustainable polymer technologies and the transition to environmentally responsible manufacturing systems [32,36]. Biodegradability should not be understood as an intrinsic quality of the environment but as a condition-dependent property. The rate and extent of polymer breakdown rely on the polymer chemical structure and shape, environmental conditions including temperature, moisture, pH, oxygen, microbial community and exposure period, *etc*. Therefore, the results of biodegradation achieved in a conventional industrial composting environment should not be anticipated to generalize to the soil, river, marine and landfill ecosystems. Here, degradation claim means the deterioration under the environmental conditions and the analytical endpoint indicated in the relevant study [37].

Comparative analysis: The primary biodegradable polymers vary widely in their origins, synthesis processes and material properties. PLA is generally hard, rigid and inflexible, whereas PBAT and PCL are more flexible. PBS shows intermediate toughness and flexibility, while the properties of PHA/PHBV can be tailored by microbial strain, substrate and monomer composition. Their manufacturing routes also differ as PLA and PCL are produced by ring-opening polymerization, PBS and PBAT by polycondensation and PHA/PHBV by microbial biosynthesis [26,27]. These differences determine their applications, including rigid packaging and additive manufacturing for PLA, flexible films for PBAT, packaging and agricultural applications for PBS, biodegradable materials for PHA/PHBV, and biomedical and drug-delivery applications for PCL.

Synthesis strategies

Synthetic chemical routes: Chemical synthesis is an important route for obtaining biopolymers with controlled molecular weight, architecture, crystallinity and degradation behav-

iour. Ring-opening polymerization (ROP) and polycondensation are the principal chemical methods used for the synthesis of biodegradable polyesters such as poly(lactic acid) (PLA), poly(glycolic acid) (PGA), poly(caprolactone) (PCL) and poly(butylene succinate) (PBS). Their biocompatibility, biodegradability and tunable properties have supported applications in drug delivery, tissue engineering, regenerative medicine, food packaging and sustainable materials. Advances in catalyst design, polymerization technology and process optimization have improved polymer quality while supporting more sustainable manufacturing practices [38,39].

Ring-opening polymerization (ROP) is a chain-growth process in which cyclic monomers undergo ring opening to form polymer chains. The thermodynamic driving force associated with ring strain facilitates polymerization, while the choice of catalytic system governs polymerization rate, molecular weight, dispersity and other polymer characteristics [40, 41]. Metal-based catalysts containing tin, zinc, aluminium and other main-group or transition metals remain widely used for biodegradable polyester synthesis. Current catalyst development focuses on higher activity, improved stereochemical control and reduced metal residues [42]. Metal-free organocatalysts provide an alternative route, particularly for biomedical applications where residual metal contamination is a concern [43]. Polymer chain growth is initiated through activation of the cyclic monomer, followed by successive monomer insertion and propagation. Molecular weight and dispersity can be regulated through the catalyst, initiator, monomer-to-initiator ratio and reaction conditions [40]. Photoinduced ROP has extended this control by allowing polymerization to be regulated through external light stimuli, providing temporal and spatial control over polymer formation [44]. Lactide, glycolide and ε-caprolactone are commonly used for the synthesis of PLA, PGA and PCL, respectively, while cyclic carbonates such as trimethylene carbonate serve as monomers for degradable polycarbonates [41]. The precise control achievable through ROP makes it particularly suitable for high performance biodegradable polymers used in biomedical implants, absorbable sutures, controlled drug-delivery systems and tissue-engineering scaffolds [38,39,45].

Polycondensation is a step-growth process involving bifunctional or multifunctional monomers containing hydroxyl, carboxyl or amino groups. The reaction is generally accompanied by the elimination of small molecules such as water, methanol or hydrogen chloride [46]. Efficient removal of these byproducts, commonly under vacuum or reduced pressure, is required to drive the reaction towards high molecular weight. Unlike ROP, where cyclic monomers undergo ring opening and chain propagation, polycondensation proceeds through successive reactions between functional groups of monomers and oligomers. This approach is applicable to renewable feed-stocks such as lactic acid, succinic acid, sebacic acid, glycerol and amino acids and is used for the synthesis of polymers such as PBS, poly(glycerol sebacate) and PLA. Direct poly-condensation offers a relatively simple, economical and scalable route, although obtaining high molecular weights comparable to those achieved by ROP remains challenging due to equilibrium limitations and extended reaction times [38,45].

The two polymerization routes differ in their reaction mechanisms and their ability to control polymer characteristics. ROP generally provides better control over molecular weight and dispersity and is well suited to applications requiring defined polymer architectures and consistent performance, particularly in biomedical and pharmaceutical fields. Polycondensation offers greater flexibility in the use of renewable multifunctional feedstocks and remains attractive for economical, large-scale production of bio-based polymers [47]. Selection of the appropriate route depends on monomer structure, target molecular weight, catalyst or reaction conditions, production cost and the intended application. Continued developments in catalyst design, green chemistry and polymer processing are expected to improve the efficiency, environmental performance and scalability of both synthetic methods.

Mechanical, physical and structural characteristics: The physico-chemical performance and degrading behaviour of biodegradable polymers is not dictated by biodegradability but by the interplay of molecular, morphological and environmental variables. Molecular weight, chemical functionality, stereochemistry, chain architecture, branching and crystallinity determine chain mobility, intermolecular interactions and hydrolyzable or enzymatically sensitive bonds. Such structural features greatly influence the mechanical properties, thermal stability, hydrophilicity and water transport, which determine the availability of water, enzymes and microbes to the polymer matrix [48]. Thus, the degradation of a biodegradable polymer can be regarded as a structure–property degradation sequence in which the molecular architecture determines the properties of the polymer and the morphology and the accessibility of the environment influence the rate and extent of chain scission and subsequent biodegradation. These connections are also influenced by environmental factors *viz*. temperature, pH, moisture, oxygen and microbial activity [3-5]. Crystallinity is therefore an important compromise between durability and degradability of the material: higher crystallinity would lead to higher stiffness and thermal resistance but to lower water uptake and therefore to lower enzymatic access and slower chain cleavage; a higher amorphous portion would lead to higher water uptake and therefore to higher enzymatic access and to higher chain cleavage rate. This link also leads to a conclusion that the degradation rate may be different in the future deterioration and the mechanical characteristics of the polymer due to changes in crystallinity during degradation [49].

Morphology and molecular organization: The structural characteristics of biodegradable polymers strongly influence their physico-chemical behaviour, degradation profile and application potential. These materials are composed of repeating monomeric units connected through hydrolysable linkages, primarily ester bonds, which facilitate degradation under biological or environmental conditions. Molecular architecture including chain length, molecular weight, stereochemistry, branching and cross-linking, governs crystallinity, chain mobility and intermolecular interactions. The relationship between molecular architecture and polymer morphology is consequently important for designing biodegradable materials with specific mechanical, thermal and degradation characteristics [50,51].

Most biodegradable polymers contain both crystalline and amorphous phases. Polymer chains within crystalline domains are closely packed and ordered, contributing to stiffness, tensile strength, thermal resistance and dimensional stability. Amorphous domains contain less ordered chains with greater mobility, allowing easier water diffusion and increasing accessibility to hydrolytic and enzymatic degradation. The relative proportion and distribution of these phases influence both mechanical properties and degradation kinetics. Amorphous regions generally degrade more readily than crystalline domains, as the dense chain packing within crystalline regions restricts the penetration of water and enzymes into the polymer matrix [52,53].

PLA provides an important example of the relationship between molecular structure, morphology and degradation. Its degradation behaviour depends on temperature, moisture, molecular weight, crystallinity and microbial activity. Significant degradation generally occurs under controlled high-temperature composting conditions, whereas degradation is considerably slower under many natural environmental conditions [54]. The proportion of L- and D-lactic acid units affects chain packing, crystallization and thermal behaviour. Poly(L-lactic acid) and poly(D-lactic acid) can form stereocomplexes with highly ordered crystalline structures, resulting in greater thermal resistance and mechanical stability than conventional PLA [24,53]. Stereochemical composition can further modify crystallinity and consequently, degradation behaviour by altering water accessibility and chain mobility. Highly ordered structures tend to restrict water penetration and molecular movement, whereas less ordered regions provide higher accessibility for hydrolytic and enzymatic processes. Control of stereochemistry can therefore be used to tailor the thermal, mechanical and degradation properties of PLA [55].

Morphological features such as surface roughness, pore structure and spherulite formation further influence polymer performance. Porous structures are particularly useful in biomedical applications, where increased surface area and interconnected pores can facilitate nutrient transport, cell adhesion and tissue integration. In food packaging, smooth and compact morphologies are preferred for improved barrier performance. Incorporation of nanofillers such as layered silicates and nanoclays can modify polymer morphology and improve stress distribution, crystallinity, thermal stability and mechanical strength. Such nanostructured composites can provide enhanced structural integrity and durability compared with unmodified biodegradable polymers [56,57].

Physical and heat properties: The physical and thermal properties of biodegradable polymers are crucial for their use in numerous industrial, medicinal, agricultural and packaging applications. These properties are strongly affected by the molecular weight, crystallinity, stereoregularity, processing conditions and chemical composition. The properties of polymers in the manufacture, storage and service life are regulated by characteristics such as density, transparency, moisture sensitivity, thermal stability, glass transition temperature (T_g) and melting temperature (T_m) [50,52].

PLA has attracted considerable attention among biodegradable polymers owing to its high transparency, low density and good barrier properties against aroma compounds and oils, making it a promising material for sustainable food packaging. Its resistance to moisture and oxygen, however, remains lower than that of conventional petroleum-based polymers [58]. Polymer blending, copolymerization and nanocomposite formation have been explored to address these limitations and improve functional performance while retaining biodegradability [59,60].

Thermal behaviour is another important consideration in polymer processing and end-use applications. The glass transition temperature (T_g) represents the transition from a rigid glassy state to a softer and more flexible rubbery state, whereas the melting temperature (T_m) corresponds to the transition of crystalline domains into the molten state. Crystalline biodegradable polymers generally exhibit higher melting temperatures, higher thermal stability and improved dimensional stability, making them suitable for applications involving elevated temperatures. Amorphous polymers generally have lower softening temperatures and higher flexibility but offer limited heat resistance [52,53]. The balance between crystallinity, thermal stability and flexibility is consequently an important consideration when selecting or modifying biodegradable polymers for specific applications.

Processing methods such as extrusion, injection molding, thermoforming and additive manufacturing substantially influence molecular orientation and the growth of crystal structures and hence the thermal characteristics. Optimization of processing conditions can increase crystallinity, reduce internal defects and improve thermal resistance without any effect on biodegradability. Moreover, the use of nanoscale fillers in biodegradable polymers improves the thermal conductivity, heat distortion resistance and dimensional stability of the composites due to the enhanced interactions between the polymer matrix and the reinforcing particles [61]. Such developments have resulted in the development of applications of biodegradable polymers in packaging, biomedical engineering and high technology composite materials with improved thermal performance [56,57,60]. The glass transition behaviour is of special importance for the correlation of thermal properties with degradation. Restricted chain mobility below the glass transition temperature may reduce the ability to rearrange molecules and/or access water to susceptible bonds, while increased motility above T_g may boost the potential for diffusion and hydrolytic processes in amorphous regions. Thus, the crystallinity and the ambient temperature should also be considered in addition to T_g when evaluating the degradation behaviour. Degradation rates and chain mobility of a polymer at temperatures close to or beyond T_g could be completely different from those at temperatures considerably below T_g [62].

Physical characteristics: The mechanical properties of biodegradable polymers are important for their functional and commercial applications in packaging, biomedical engineering, agriculture and structural materials. These properties depend on intrinsic parameters such as molecular weight, crystallinity, chain orientation and intermolecular interactions, as well as extrinsic factors including processing conditions, environmental exposure and degradation. Tensile strength, Young's modulus, elongation at break, impact resistance, toughness and flexural strength are the principal parameters used to assess their mechanical performance [51,52]. Together,

these characteristics determine the ability of a polymer to withstand mechanical stresses during processing and service.

PLA is widely used in food packaging and biomedical applications due to its relatively high tensile strength and stiffness [63]. Its inherent brittleness and limited elongation at break restrict its use in applications requiring high flexibility and impact resistance. Copolymerization, plasticization, polymer blending and reinforcement with fibres or nanoparticles have been investigated to improve these limitations. Blending PLA with more flexible polymers such as PCL can enhance ductility and toughness while retaining adequate mechanical strength and biodegradability [24,51].

Mechanical behaviour is closely associated with polymer crystallinity and molecular architecture. Crystalline domains provide structural rigidity and resistance to deformation, whereas amorphous regions generally provide higher chain mobility, flexibility and impact resistance. High crystallinity can restrict the penetration of water and enzymes into the polymer matrix and may slow hydrolytic or enzymatic degradation when diffusion limits the degradation process. The magnitude of this effect varies with temperature, moisture and microbial activity [3]. Control of crystallinity during synthesis and processing is consequently important for achieving an appropriate balance between stiffness, strength and flexibility [50,53].

Molecular weight, chain length, chain entanglement, stereoregularity and intermolecular interactions further influence mechanical performance. Longer polymer chains, higher chain entanglement and stronger intermolecular interactions generally increase resistance to deformation, whereas higher chain mobility and amorphous content favour flexibility and elasticity. These structural parameters simultaneously influence degradation by affecting water and enzyme accessibility to hydrolysable bonds. Increased molecular weight or crystallinity can improve mechanical resistance while reducing the accessibility of susceptible bonds, potentially extending the time required for substantial degradation. This structure-property relationship is particularly relevant when biodegradable materials must maintain mechanical performance during their service life while undergoing predictable degradation after disposal [3,64].

Mechanical properties change progressively during biodegradation. Hydrolytic cleavage of polymer chains reduces molecular weight and can lead to declines in tensile strength, stiffness and structural integrity. Vieira *et al*. [65] reported reduced mechanical performance of PLA–PCL fibres during *in vitro* degradation, associated with chain scission and morphological changes. Reinforcement with nanofillers such as layered silicates and nanoclays can improve stress transfer, delay crack initiation and enhance mechanical stability [56,57]. Such modifications have expanded the potential of biodegradable polymers for engineering applications where mechanical reliability and controlled degradation are required.

Surface properties and processing behaviour: The surface characteristics and processing behaviour of biodegradable polymers are of vital importance for their functional performance. Surface properties such as roughness, wettability, surface energy, hydrophilicity and porosity are important factors in moisture absorption, microbial adhesion, protein adsorption, cell attachment and degradation behaviour [66]. These traits are important in biomedical applications where cell proliferation and tissue integration depend on surface morphology and in food packaging where surface smoothness affects barrier capabilities and product durability [51].

Hydrophilicity mainly affects water uptake and transport in the polymer matrix and is therefore responsible for degradation. Higher water affinity can improve moisture penetration and facilitate hydrolytic cleavage of sensitive bonds, while hydrophobic surfaces can prevent water penetration and slow hydrolysis [67]. However, hydrophilicity alone is not a determining factor for biodegradation, as water accessibility must be evaluated combined with crystallinity, molecular weight, chemical functionality, temperature and microbial activity. Surface roughness and porosity can further modify degradation by increasing the effective area available for water, enzymes and microorganisms. Thus, surface properties may be seen as an additional interface between polymer structure and environmental degradation [4,68]. Porous materials are suitable for tissue engineering since they can transfer nutrients and allow cell penetration, while dense and smooth surfaces are desirable for packaging applications with high barrier properties for gases and moisture [53,59].

The melt viscosity, thermal stability, crystallization rate and rheological properties are the primary factors affecting the processing behaviour of biodegradable polymers [69]. Modern manufacturing techniques consist of extrusion, blow molding, injection molding, thermoforming, fiber spinning and additive printing, allow for the manufacture of complicated geometries and application-specific characteristics of biodegradable materials. However, processing conditions must be carefully regulated since excessive temperatures or residence periods can lead to thermal degradation, loss of molecular weight and deterioration of mechanical properties [70]. Therefore, precise control of the processing parameters is necessary to preserve the integrity of the polymer and simultaneously acquire the desirable morphology and performance [50,60].

Recent discoveries in polymer engineering have brought considerable advances in processability by integration of nanofillers, plasticizers and reinforcing agents. The nanocomposite method enhances melt strength, dimensional stability, heat resistance and surface properties without affecting biodegradability. The polymer blending also shows good performance in improving the flow characteristics and extending the processing window of biodegradable polymers. These developments have resulted in the competitiveness of biodegradable materials with traditional plastics in diverse fields including sustainable packaging, biomedical devices, agriculture and advanced manufacturing, resulting in their commercialization and industrial uptake at a faster pace [53,57,60].

Structure–property degradation relationships: The relationship between molecular architecture, chain mobility and chain organization provide an important basis for understanding polymer morphology and crystallinity, which in turn influence physico-chemical properties, environmental accessibility and degradation behaviour (Table-2). These structural factors govern the progression from water and microbial accessibility to chain scission, molecular weight reduction, fragmentation and, ultimately, microbial assimilation [71]. The extent

TABLE-2
QUANTITATIVE COMPARISON OF MAIN BIODEGRADABLE POLYMERS' PHYSICO-CHEMICAL AND PERFORMANCE FEATURES

Polymer	Tensile strength (MPa)	Young's modulus (GPa)	Elongation at break (%)	T_g (ºC)	T_m (ºC)	Crystallinity (%)	Representative degradation
PLA	28-79	1.20-3.64	2-6	~54-60	~150-180	~10-40	Strongly condition-dependent; substantially faster under industrial composting than ambient environments
PHA/PHBV	21-40	1.02-3.50	1.9-20	~-5 to 40	~150-176	~40-70	Generally susceptible to microbial degradation; rate strongly dependent on composition and environment
PBS	~27-50	~0.3-1.0	~100-300	~-30	~110-115	~30-60	Condition-dependent; accelerated under elevated temperature, moisture and microbial activity
PBAT	15-34	~0.07	200-670	~-30	~123-130	~10-30	Relatively rapid under suitable composting conditions; slower under ambient conditions
PCL	~14-21	0.10-0.33	~300-897	~-60	~55-65	~40-60	Slow-to-moderate; enzymatic/microbial degradation depends strongly on temperature, crystallinity and morphology.

and rate of these processes depend strongly on environmental conditions, particularly temperature, moisture, pH, oxygen availability and microbial population. A given polymer can consequently exhibit markedly different degradation behaviour under industrial composting, soil, freshwater, seawater or laboratory conditions. Polymer degradation should, therefore, be evaluated with careful consideration of both the environmental conditions applied during testing and the intrinsic characteristics of the polymer [72].

This relationship highlights an important trade-off in biodegradable polymer design. High molecular weight, dense chain packing and high crystallinity can improve mechanical strength and thermal stability by restricting chain movement and reducing water penetration and biological accessibility, which may extend the degradation period. Higher chain mobility, higher amorphous content and increased water affinity can facilitate water and microbial access and accelerate degradation, although these characteristics may be associated with reduced mechanical strength and dimensional stability [73]. The design of a biodegradable polymer consequently requires a balance between functional performance during its intended service life and controlled degradation under defined end-of-life conditions. Biodegradability alone is insufficient; the material should retain adequate performance during use and undergo degradation within the environmental or waste-management conditions for which it is designed.

Environmental applications

Eco-friendly applications of biodegradable polymers: Increasing environmental concerns about the conventional petroleum-based plastics have led to the development and commercialization of biodegradable polymers for sustainable environmental applications. Conventional plastics, however, are not biodegradable. Biodegradable polymers are designed to perform their purpose while in use and to be biodegradable after disposal, reducing long-term environmental persistence. Due to their renewable nature, lower carbon footprint and suitability to circular economy concepts, these materials have emerged as potential alternatives to conventional materials in many different industries, especially in sustainable packaging, agriculture, environmental remediation and eco-friendly consumer products. However, the successful application of biodegradable materials requires more than inherent biodegradability; it depends on appropriate product design, suitable waste management infrastructure and life-cycle considerations to ensure meaningful environmental benefits [74,75].

Sustainable food packaging represents one of the major application areas for biodegradable polymers and a rapidly expanding commercial sector. Conventional plastic packaging often has a short service life and limited recycling efficiency, contributing substantially to municipal solid waste. Biodegradable polymers such as PLA, starch-based polymers, cellulose derivatives, PHAs and PBS have gained attention as potential alternatives due to their biodegradability, mechanical performance and suitability for food-contact applications [76]. These materials can provide protection against mechanical damage and contamination while reducing dependence on fossil-based plastics. Growing environmental concerns, stricter regulations and increasing consumer demand for sustainable packaging have further supported their development and adoption [75,77].

Recent advances have expanded biodegradable packaging beyond passive food protection towards multifunctional systems. Active packaging can incorporate antibacterial agents, antioxidants, oxygen scavengers and moisture regulators that interact with the packaged food or its surrounding environment to delay spoilage and maintain quality. Smart packaging incorporates sensors, colourimetric indicators and freshness-monitoring components capable of detecting changes in pH, temperature, microbial activity or gas composition during storage [78]. Such technologies can improve food safety and extend shelf life, with the potential to reduce food waste and its associated environmental burden. Agricultural residues and food-processing byproducts are receiving increasing attention as renewable feedstocks for biodegradable packaging films. Their use supports biomass valorization while providing alternative raw materials for sustainable packaging production [38,79].

Besides food packaging, biodegradable polymers have been widely explored within agriculture for their ability to

reduce plastic pollution without affecting crop productivity. Appropriately designed biodegradable mulch films have been shown to improve soil moisture and temperature conditions and even sustain or boost crop production in comparison to standard polyethylene films in field trials [12,80]. Such films are thus researched to replace standard polyethylene films that tend to persist in agricultural soils after the harvest. Unlike non-degradable polymers, biodegradable mulch films are designed to decompose and biodegrade in the soil, decreasing labor costs associated with film removal and limiting the buildup of persistent plastic residues [34]. However, the pace of their breakdown is highly impacted by the content of the polymer, the environmental conditions and characteristics of the soil, indicating the need to match degradation kinetics with the crop production cycle [80]. Biodegradable polymer matrices are also being examined as carriers for controlled-release fertilizers and other agrochemicals. Slow- and controlled-release fertilizer systems based on biopolymers can govern the diffusion of nutrients by biodegradable matrices or coatings, enhancing the efficiency of nutrient utilization and lowering nutrient losses to the surrounding environment [81,82]. Biodegradable microcapsules have also been recently explored for the precision delivery of micronutrients to plants, with prospects to improve the delivery efficiency of micronutrients while lowering the losses of fertilizer and pesticides [83]. These controlled-delivery systems can improve the efficiency of utilizing resources and reduce the negative ecological consequences caused by over-application of agrochemicals and promote sustainable agricultural methods [77].

Biodegradable polymers are also being used more in the environmental remediation technology. Biopolymer-based membranes, hydrogels, composite adsorbents and functionalized polymeric materials have shown great promise for the removal of heavy metals, dyes, medicines and other emerging pollutants from wastewater [84]. They offer higher surface functionality and biocompatibility and are easy to chemically alter, which allows for efficient adsorption with little secondary contamination. In particular, graft copolymers made from biodegradable biopolymers are of interest, since they combine the benefits of environmental friendliness of natural polymers with enhanced adsorption capacity and structural durability. These new materials offer an environmentally acceptable alternative to conventional synthetic adsorbents used in water filtration and wastewater treatment [85].

However, the environmental performance of biodegradable polymers should be assessed through a whole life-cycle perspective rather than biodegradability alone. Their environmental impact is influenced by feedstock availability and sourcing, production processes, energy requirements, transportation, recycling potential, composting infrastructure and end-of-life management [86]. Life-cycle assessment studies indicate that the environmental benefits of biodegradable materials vary with feedstock selection, manufacturing technology, waste-management practices and regional infrastructure. Their effective use requires integration within a broader sustainability framework that combines responsible material design, efficient waste collection, appropriate industrial composting and resource recovery. Such an approach can maximize environmental benefits while limiting unintended ecological impacts [74,75].

The development of biodegradable polymers has progressed from single-purpose alternatives to conventional plastics towards multifunctional materials capable of addressing multiple environmental challenges. Their expanding use in sustainable packaging, food preservation, agriculture and environmental remediation highlights their potential to reduce plastic pollution and improve resource efficiency. Wider commercialization and integration into sustainable manufacturing systems will require continued advances in material performance, industrial scalability, economic competitiveness and waste-management infrastructure [77,79,85].

Environmental sustainability and circular economy: Replacing conventional petroleum-based plastics with biodegradable polymers represents a potential pathway towards environmental sustainability and a circular economy. Their environmental value extends beyond their ability to degrade after use and depends on several interconnected factors, including renewable feedstock utilization, production methods, product performance, waste collection, composting facilities, recycling strategies and end-of-life management. Biodegradable polymers should not be regarded as a universal solution to plastic pollution, but as one component of an integrated materials-management system focused on resource efficiency, waste reduction and resource recovery [74,87].

A major environmental advantage of biodegradable polymers is their potential to reduce the persistence of plastic waste in terrestrial and aquatic environments. Under suitable biological or industrial composting conditions, microbial activity can convert biodegradable polymers into carbon dioxide, water, biomass and, under anaerobic conditions, methane. The conventional plastics can persist in the environment for much longer periods and may contribute to long-term plastic and microplastic accumulation. The environmental fate of biodegradable polymers is strongly influenced by polymer chemistry, microbial diversity, temperature, moisture, pH and oxygen availability. Biodegradation rates observed under controlled laboratory conditions may differ substantially from those in soil, freshwater, marine environments or industrial composting systems [88,87]. Assessment of degradation should consequently consider the conditions encountered during actual disposal.

Appropriate waste management is essential for realizing the environmental benefits of biodegradable polymers. The products labelled as biodegradable or compostable may not degrade effectively in landfills, unmanaged environments or conventional recycling streams. Proper waste segregation, efficient collection and access to suitable composting or treatment facilities are required to direct these materials towards appropriate end-of-life pathways. The presence of biodegradable polymers in conventional plastic recycling streams can interfere with sorting and recycling processes and may affect the quality of recycled materials. Clear labelling, consumer awareness and dedicated waste-management infrastructure are important for ensuring appropriate end-of-life treatment [74,75].

Life-cycle assessment (LCA) provides a comprehensive framework for evaluating the environmental performance of

biodegradable polymers from raw-material production and polymer synthesis through product use, disposal and resource recovery [89]. Unlike assessments based solely on biodegradability, LCA considers parameters such as greenhouse-gas emissions, energy and water consumption, transportation, feedstock production, manufacturing efficiency and waste management practices. Bioplastics derived from renewable biomass can have a lower carbon footprint than fossil-based alternatives, although the magnitude of this benefit depends on agricultural practices, processing technology, transportation distances, energy sources and end-of-life treatment. LCA is consequently valuable for identifying environmentally preferable production pathways and supporting evidence-based decisions concerning the use of biodegradable plastics [74].

The environmental role of biodegradable polymers is closely linked to circular-economy principles, which emphasize resource conservation, waste minimization and recovery of materials and biological resources. Circular approaches replace the conventional linear model of production, use and disposal with strategies such as recycling, composting, biomass valorization, resource recovery and sustainable product design. Biodegradable polymers derived from agricultural residues, food-processing byproducts, algae and other renewable biomass can contribute to circular bioeconomy systems by converting biological resources and waste streams into value-added materials while reducing dependence on fossil resources [90]. Integration of agriculture, biotechnology, materials science and environmental engineering can support resource-efficient value chains and more sustainable production systems [75,87].

Large-scale adoption of biodegradable polymers still faces economic, infrastructural and environmental challenges. Production costs remain higher than those of many conventional plastics, while industrial composting and other appropriate end-of-life facilities are unavailable in many regions. A common misconception is that all biodegradable polymers rapidly decompose under natural environmental conditions. Many materials require specific combinations of temperature, humidity, oxygen availability and microbial activity to achieve efficient degradation. When these conditions are absent, degradation can be substantially slower and the anticipated environmental benefits may not be fully realized. Standardized biodegradability testing, harmonized regulations, appropriate product labelling and evidence-based public education are needed to reduce improper disposal and improve end-of-life management [87,88].

Future development of biodegradable polymers should integrate advances in green chemistry, renewable feedstocks, biotechnology, waste valorization and waste-management technologies. Polymer design needs to address mechanical performance, degradation behaviour, economic feasibility, recyclability and environmental impacts across the complete product life cycle. Policy measures such as extended producer responsibility, investment in composting infrastructure, appropriate product certification and life-cycle-based environmental assessment can support responsible adoption. Effective collaboration among researchers, industry, policymakers and consumers will be essential for integrating biodegradable polymers into resource-efficient and circular production systems [74,75,87].

Perspectives on life cycle assessment (LCA) and circular economy: The environmental benefits of biodegradable and bio-based polymers should be evaluated through a holistic life-cycle approach rather than inferred solely from their renewable origin or biodegradability. LCA provides a structured framework for examining environmental impacts across the complete value chain, encompassing feedstock production, material processing, polymer synthesis, product manufacturing, transportation, use and end-of-life management. Recent studies across different application sectors emphasize the need to interpret the environmental performance of bio-based and biodegradable polymers in relation to the technological characteristics and the specific socioeconomic, agricultural and waste-management systems in which they are produced and used [91,92]. Classification as bio-based or biodegradable alone is insufficient to establish an environmental advantage.

LCA of biodegradable polymers: The environmental impact categories commonly assessed in the LCA of biodegradable polymers cover raw-material production, polymer synthesis, processing, transportation, product use and end-of-life treatment. For bio-based polymers, raw-material production requires particular attention, as biomass cultivation can involve land use, irrigation, fertilizers, pesticides, energy consumption and greenhouse-gas emissions. Replacing fossil derived carbon with renewable biological carbon does not eliminate these environmental burdens. The environmental performance depends on the biomass source, agricultural practices, geographic location, resource requirements and management of co-products. Islam *et al.* [91] reported that the environmental impacts of bioplastics vary with feedstock source, synthesis route and disposal method, a finding consistent with the observations of Yadav & Nikalje [93]. Energy and heat requirements, chemical reagents, solvent use, catalysts and process efficiency can further influence the environmental profile during polymer synthesis and processing [93].

The biorefinery concept can improve resource utilization by converting biomass into multiple products and reducing material losses. Its environmental performance remains dependent on feedstock availability, energy demand, conversion efficiency and the effective utilization of residual biomass and co-products [94]. The environmental value of renewable or waste-derived feedstocks should consequently be assessed in relation to the material and energy requirements associated with their conversion into polymeric materials. The use phase can influence LCA outcomes through the relationship between polymer properties and product performance. Material durability, required material quantity, service life and replacement frequency can alter the environmental burden associated with a product. Molina-Besch [95] observed that the use and end-of-life stages of bio-based biodegradable plastics can be particularly complex, as differences in product performance may influence material consumption, service life and the conditions under which the product enters its end-of-life pathway.

Critical comparison of life cycle pathways: Many LCA studies have reported environmental advantages for specific bioplastics under defined production and end-of-life condi-

tions. These findings require careful interpretation, as LCA outcomes are highly sensitive to the assumptions and methodological choices used in the assessment. Parameters such as the functional unit, system boundaries, allocation method, electricity mix, agricultural practices, transportation distance and end-of-life scenario can substantially influence the calculated environmental impacts [91,95].

The importance of end-of-life assumptions is evident in comparative assessments of biodegradable polymers. Park *et al*. [96] conducted a cradle-to-grave LCA of PLA and polyhydroxybutyrate (PHB) and identified end-of-life treatment as an important determinant of the environmental results. The environmental performance cannot be assessed from the production stage alone; recycling, composting, biological treatment and other disposal pathways need to be considered. Conventional LCA approaches may not fully capture certain environmental effects associated with bio-based and biodegradable plastics. Keyes *et al*. [97] emphasized the relevance of carbon sequestration and potential microplastic impacts when evaluating end-of-life pathways for bio-based compostable plastics. Such methodological considerations can influence the interpretation of environmental benefits, making clear definitions of system boundaries and impact categories essential for meaningful LCA comparisons.

Biodegradable polymers cannot be considered inherently more sustainable than conventional plastics. Their environmental performance depends on the feedstock, manufacturing route, product application, resource requirements and end-of-life pathway. This dependence is particularly relevant when comparing polymers derived from purpose-grown agricultural biomass with those obtained from biological wastes or residues, where differences in feedstock production and resource requirements can substantially influence the life-cycle impacts.

End-of-life management and circular economy integration: End-of-life management is a major determinant of the environmental performance of biodegradable polymers. The eecomposition, composting, recycling, anaerobic digestion, incineration and landfilling can have markedly different environmental outcomes. Compostability should not be regarded as an inherent environmental benefit, since its value depends on the availability of suitable collection, sorting and treatment infrastructure [98]. A polymer designed for industrial composting may provide limited environmental benefit when the required conditions, such as appropriate temperature, moisture, oxygen availability and microbial activity, are not maintained. Molina-Besch [95] emphasized that end-of-life assessment of bio-based biodegradable polymers is particularly complex due to its strong dependence on the selected treatment pathway.

Biodegradation represents one possible end-of-life pathway within a circular-economy framework rather than a universal endpoint for sustainable polymer management. Recycling can retain polymeric materials and their embedded resources within production cycles, while biological treatment may be appropriate for products with short service lives or those that are difficult to recycle due to food residues and other forms of contamination. Mechanical, chemical and biological recycling approaches can support resource recovery and circular material flows for biodegradable polymers [99]. Senosha *et al*. [100] similarly emphasized the integration of sustainability and circular-economy principles into bioplastics development.

Circular management depends on the interaction between material characteristics and the surrounding waste management system. The recovery potential of biodegradable polymers is influenced by product design, feedstock selection, processing technology, labelling, collection and separation systems, and available treatment infrastructure. Parveen *et al*. [101] highlighted the need for coordinated feedstock supply, efficient processing, appropriate product labelling and effective end-of-life management for bioplastic packaging. Technological advances in polymer development consequently need to be supported by compatible collection, sorting, recycling and biological-treatment systems.

Biorefinery-based production offers another route towards improved resource utilization and circularity by converting renewable or residual biomass into multiple value-added products. Rather than directing biomass exclusively towards polymer production, integrated biorefineries can generate polymers alongside fuels, chemicals and other co-products, potentially improving resource utilization and reducing waste [102]. The environmental and economic performance of such systems remains dependent on feedstock availability, conversion efficiency, energy requirements and the effective utilization of co-products and residual biomass.

Sustainability trade-offs and future LCA focus: The Biodegradable polymers involve several trade-offs in their environmental performance. Bio-based feedstocks can reduce dependence on petroleum resources, while intensive biomass cultivation may increase land and water requirements and contribute to fertilizer use and associated emissions [103]. Similarly, biological production routes can reduce reliance on petrochemical resources but may require substantial energy, agricultural inputs and downstream processing. At the end-of-life stage, biodegradation and composting can reduce the persistence of plastic waste when suitable conditions are available [104]. Incomplete degradation may result in smaller polymer fragments, while inappropriate disposal can prevent the material from entering its intended degradation pathway. These factors indicate that biodegradability alone cannot serve as an independent measure of sustainability [93].

Future LCA studies should improve the comparability of results through clear definitions of functional units, system boundaries, feedstock sources, energy inputs, agricultural practices, processing requirements and end-of-life scenarios. Higher emphasis should be placed on realistic waste management conditions rather than assuming universal access to effective composting or recycling systems. Molina-Besch [95] identified the challenges associated with modelling the use and end-of-life stages of bio-based biodegradable plastics, while Keyes *et al*. [97] demonstrated that the inclusion of specific environmental factors can influence LCA outcomes.

The sustainability of biodegradable polymers is determined by the complete process pathway rather than by bio-based origin or biodegradability alone. It depends on the interaction among feedstock procurement, resource consumption, manufacturing and processing, product performance and end-

of-life management. Circular-economy strategies should prioritize reduction, reuse and recycling where technically and environmentally appropriate, while biodegradable or compostable materials should be designed for biological treatment pathways where these systems are available and suitable [92,99,101].

Market trends, future outlook and challenges: Although biodegradable polymers have advanced considerably, several scientific, technological, economic and regulatory challenges continue to limit their large-scale commercialization and environmental contribution. They offer an alternative to conventional petroleum-based plastics, but their wider adoption requires a balance among material performance, production efficiency, environmental sustainability and economic viability [105]. Biodegradability alone cannot address the global plastic pollution problem; these materials need to be incorporated into sustainable production systems, appropriate waste management infrastructure and circular-economy frameworks. Addressing the remaining limitations will require advances in polymer design, manufacturing technologies, environmental assessment and end-of-life management [5,88].

Production cost remains one of the major barriers to the commercial adoption of biodegradable polymers. Their manufacture may involve renewable feedstocks, microbial fermentation, specialized catalysts or controlled polymerization processes, all of which can increase production costs relative to conventional plastics. Limited production capacity can further restrict economies of scale and market competitiveness. Several biodegradable polymers still exhibit lower mechanical strength, thermal stability, moisture resistance or barrier performance than petroleum-based plastics, limiting their suitability for demanding applications. Polymer blending, copolymerization, nanocomposite development and advanced processing technologies are being investigated to improve these properties while retaining biodegradability and economic feasibility [5,106].

A further challenge is the misconception that all bioplastics readily biodegrade under natural environmental conditions. The degradation behaviour depends on polymer chemistry, microbial activity, temperature, moisture, oxygen availability and the surrounding environment. Many commercially available biodegradable plastics require controlled industrial composting conditions to achieve efficient decomposition. Disposal in landfills, soil, freshwater or marine environments can result in substantially slower degradation and may reduce the anticipated environmental benefits. The standardized biodegradability testing, scientifically robust environmental assessments and appropriate end-of-life infrastructure are required to establish realistic degradation expectations and support responsible use [87,88].

Waste management infrastructure represents another major limitation. Inadequate sorting systems and limited public awareness can result in biodegradable polymers being mixed with conventional plastic waste, reducing recycling efficiency and complicating waste treatment. Many regions lack industrial composting facilities capable of processing compostable polymers under controlled conditions. Effective waste-management strategies require clear product labelling, consumer education, improved collection and sorting systems, suitable composting facilities and life-cycle assessment to guide end-of-life decisions [8,87].

Regulatory inconsistency remains a significant barrier to the wider adoption of biodegradable polymers. Differences in the definitions and classification of bioplastics, bio-based content, biodegradability and compostability develop uncertainty for manufacturers, regulators and consumers and complicate comparisons of environmental claims across jurisdictions [107,108]. Variations in biodegradation testing methods and certification criteria can further complicate the interpretation of results obtained under laboratory or industrial composting conditions in relation to natural environments [109]. Consistent testing methods, transparent certification systems and scientifically supported biodegradability claims are needed [107,109]. Regulatory requirements also differ across regions in areas such as labelling, compostability, waste management responsibilities and restrictions on plastic products, develop challenges for international commercialization [110]. The European Union policies on plastics increasingly emphasize waste prevention, circularity, environmental performance and sustainable resource management, illustrating the importance of policy integration across the plastics value chain [111]. The wider adoption will require higher compatibility among international definitions, certification and testing procedures, environmental labelling, economic incentives and waste-management policies, supported by cooperation among policy makers, scientists, standards organizations and industry [107,110]. Such measures can support responsible market development and strengthen the contribution of biodegradable polymers to climate mitigation and sustainable development [112].

The global biodegradable polymer market has expanded substantially in response to increasing environmental awareness, restrictions on single-use plastics and consumer demand for sustainable products. Packaging represents the principal application sector, followed by agriculture, biomedical engineering, textiles, consumer products and environmental remediation [92,113]. Investment in renewable feedstocks, microbial biotechnology and advanced polymer-processing technologies is expanding their commercial potential. High-performance biodegradable composites containing natural fibres, nanocellulose, graphene derivatives and other bio-derived fillers have improved mechanical properties and broadened potential applications [5,106]. Continued advances in material performance and manufacturing efficiency could improve the competitiveness of biodegradable polymers relative to conventional plastics.

Future research should focus on multifunctional biodegradable polymers that combine suitable mechanical and thermal performance, controlled degradation, economical production and reduced life-cycle impacts. Metabolic engineering and synthetic biology can be integrated with microbial fermentation to develop engineered microbial cell factories capable of converting inexpensive or waste-derived feedstocks into biodegradable polyesters, with the potential to increase productivity and reduce production costs [11,114]. Enzyme-assisted polymer synthesis provides another research pathway, as biocatalytic polymerization can operate under relatively mild conditions and reduce dependence on conventional metal-based catalysts and harsh reaction

environments [115,116]. High-throughput polymer synthesis and automated biodegradation screening can accelerate the investigation of structure–property biodegradability relationships across large polymer libraries [117]. Artificial intelligence and machine-learning approaches in polymer informatics can support materials discovery through prediction of physico-chemical properties, exploration of large chemical spaces and identification of candidate polymers with application specific characteristics [118]. Integration of computational modelling, high-throughput experimentation, synthetic biology and automated materials development may accelerate the design of biodegradable polymers with tailored properties and improved sustainability [117,118]. Renewable feedstocks, waste valorization, low-carbon production and closed-loop recycling should be incorporated into circular bioeconomy models to improve resource efficiency and reduce environmental burdens [5,106].

The environmental evaluation under realistic conditions represents another important research priority. Alongside laboratory studies, long-term field investigations are needed to assess polymer degradation in soil, freshwater, marine environments and composting systems [119]. Such studies can provide information on degradation kinetics, ecotoxicological effects, potential microplastic formation and environmental safety, supporting evidence-based regulation and responsible commercialization. Polymer development should be accompanied by standardized life-cycle assessment methods capable of evaluating environmental performance across feedstock production, manufacturing, use and end-of-life stages [87,120].

The biodegradable polymers have progressed from specialized research materials to an important area of sustainable materials science. Their successful large-scale application will depend on reducing production costs, improving material performance, developing appropriate waste-management infrastructure, strengthening regulatory consistency and promoting interdisciplinary collaboration. Continued advances in biotechnology, polymer chemistry, nanotechnology, materials engineering and environmental science, supported by appropriate policies and public awareness, can strengthen the role of biodegradable polymers in circular-economy systems and environmentally responsible industrial development.

Conclusions

Biodegradable polymers offer promising alternatives to conventional petroleum-based plastics, with potential to reduce persistent plastic waste and support the development of sustainable materials. This review has discussed their classification, sources, synthesis routes, structural and physicochemical characteristics, environmental applications and future prospects. Differences among natural, synthetic and microbially derived polymers influence their degradation behaviour, mechanical performance, thermal stability and industrial applicability. Advances in chemical polymerization, microbial fermentation and green processing have expanded the range of achievable polymer properties and improved their potential for commercial application. Emerging technologies provide new opportunities for the development of biodegradable polymers while introducing challenges that require systematic evaluation. Artificial intelligence can facilitate prediction of structure–property degradation relationships and guide polymer optimization, although the limited availability of standardized and environmentally relevant datasets restricts model reliability. Nanotechnology can enhance mechanical, thermal and barrier properties, but the influence of nanofillers on degradation kinetics, ecotoxicity and environmental fate requires further investigation. Synthetic biology offers opportunities to engineer microbial platforms for PHA production from renewable and waste-derived feedstocks, with strain stability, substrate variability and scale-up remaining important challenges. Advanced manufacturing techniques such as additive manufacturing and electrospinning provide control over polymer architecture and product design, yet processing conditions can alter crystallinity, molecular orientation and degradation behaviour. Integration of these technologies with standardized degradation testing, scalable processing and life-cycle assessment is needed to improve material performance without compromising environmental safety or predictable end-of-life behaviour. The expanding use of biodegradable polymers in sustainable food packaging, agriculture, wastewater treatment, biomedical engineering and environmental remediation reflects their broad functional potential. Their large-scale adoption remains constrained by production costs, limited manufacturing capacity, variable degradation under natural environmental conditions, inadequate waste treatment infrastructure and differences in international standards. Addressing these limitations requires coordinated efforts across polymer chemistry, biotechnology, materials science, environmental engineering, waste management and policy development.

Future research should prioritize biodegradable polymers that combine high mechanical and thermal performance, controlled degradation, economic feasibility and reduced environmental impacts across their life cycle. Nanotechnology, synthetic biology, AI-assisted materials design, renewable and waste-derived feedstocks, and circular bioeconomy strategies can support the development of next-generation materials. Their environmental benefits should be validated through comprehensive life-cycle assessment, standardized biodegradability testing and long-term field studies under environmentally relevant conditions. Scientific innovation needs to be accompanied by appropriate regulatory frameworks, compatible waste management infrastructure and responsible industrial implementation. Such integration can strengthen the contribution of biodegradable polymers to resource-efficient manufacturing, plastic pollution reduction and the transition towards a sustainable circular economy.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this article.

DECLARATION OF AI-ASSISTED TECHNOLOGIES

During the preparation of this manuscript, the authors used an AI-assisted tool(s) to improve the language and no data, results or scientific conclusions were generated by AI. All analyses, interpretations and conclusions are the authors'

own. The authors reviewed and edited the content and take full responsibility for the published work.

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