Advancements, applications, and challenges of polyhydroxyalkanoates (PHAs) in packaging as biodegradable bioplastics

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Contents

1. Introduction to polyhydroxyalkanoates (PHA) 2
   1.1 Structure and type of PHA 2
   1.2 General properties of PHA 4
   1.3 Production of PHA: synthesis, additives, and processing 8
   1.4 PHA market overview 11
2. Environmental impacts of polyhydroxyalkanoates (PHA) 14
   2.1 Overview of biodegradability of polymers 14
   2.2 Biodegradability of PHAs 16
   2.3 Comparison of the biodegradability of PHA with other biopolymers 17
   2.4 Biodegradation of PHA in different environmental conditions 20
3. Perspectives on polyhydroxyalkanoates (PHA) in packaging applications 22
   3.1 Packaging applications: statistics and regulatory standards 22
   3.2 Status of PHAs in food packaging applications 25
4. Conclusion 35
References 36

Abstract

The rising environmental concerns associated with petroleum-based plastics have driven the search for biodegradable alternatives, particularly for short-term and disposable applications. Polyhydroxyalkanoates (PHAs), a class of biopolymers and bioplastics, derived from renewable resources, offer promising features for sustainable packaging. However, PHAs often face technical challenges limiting their practical applications in packaging. Recent advancements in biomanufacturing processes have aimed to address the limitations, such as thermal stability, selective biodegradability, barrier properties, and mechanical and physical properties, through diverse approaches including new

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production processes, diversified feedstocks, and fermentation technologies. This chapter explores the structural diversity and types of PHAs, their environmental degradation behaviors, and the perspectives on their application within the packaging industry, particularly in alignment with regulatory standards and sustainability goals.

Keywords: Polyhydroxyalkanoate (PHA), Biodegradability, Sustainability, Packaging

1. Introduction to polyhydroxyalkanoates (PHA)

1.1 Structure and type of PHA

Polyhydroxyalkanoates (PHAs), commonly recognized as biodegradable bioplastics in the market, are a diverse class of macromolecules that can produce many combinations of polymers of highly varied structures and properties. The general structure of PHA is shown in Fig. 1., where R represents a side chain. PHA monomers can have aliphatic saturated, unsaturated, straight, or branched side chains, and some microorganisms can synthesize PHA with aromatic, halogenic, pseudohalogenic, or alkoxy groups (Koller et al., 2013). Like other polymers (Mangaraj et al., 2019) which are commonly used in packaging and other industries, PHAs have been characterized using numerous analytical techniques, including a series of thermal analyzers, mechanical and physical property testers, rheological behavior testers, scanning electron microscopy (SEM), ultraviolet-visible (UV-vis) spectroscopy, Fourier transform infrared (FTIR) spectroscopy, gas chromatography-mass spectrometry (GC/LC-MS), and gel permeation chromatography (GPC) (Torri et al., 2014).

The PHA family is commonly classified into three groups based on chain length. Short chain length (scl) PHAs have three to five carbon atoms in a monomer, medium chain length (mcl) PHAs have six to 14 carbon atoms in a monomer, and long chain length (lcl) PHAs have 15+ carbon atoms in a monomer. The level of crystallinity of PHAs is largely contributed by chain length. The material properties, and thus suitable applications, of PHAs are highly dependent on which of the aforementioned classes and levels of crystallinity they fall into.

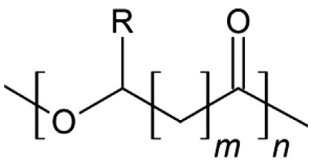

Fig. 1 General structure of PHA.

The short chain lengths of scl-PHAs result in highly crystalline polymers, with an average degree of crystallinity ($\%X_C$) values of 40 precent–80 precent. This crystalline structure causes the physiochemical properties of scl-PHAs to closely resemble that of polypropylene (PP) (Muiruri et al., 2023). Scl-PHAs are stiff and brittle, with high glass transition temperatures (T_g) and melting temperatures (T_m) of 3–8 °C and 160–180 °C, respectively (Mozejko-Ciesielska et al., 2019). The longer chain lengths of mcl-PHAs result in much less crystalline polymers, with $\%X_C$ values of 20 precent–40 precent and consequently lower T_g (around −43 °C) and T_m (30–80 °C) values (Hahn et al., 2024). This gives mcl-PHAs flexible and elastic properties that result in polymers with high elongation at break (up to 300 precent–450 precent) but low tensile strength, more closely resembling the properties of low-density polyethylene (LDPE) (Chen, 2013). As the irregularity of their chemical composition and structure increases, they become more amorphous and adopt characteristics similar to those of elastomers, latexes, and resins, making mcl-PHAs potentially suitable for applications as rubbers, adhesives, and/or glues (Rebocho et al., 2020).

PHAs with a single type of repeating monomeric unit linked together with covalent bonds, such as polyhydroxybutyrate (PHB), are termed homopolymers or monopolymers and have simple, homogenous chemical structures. PHB can refer to poly(3-hydroxybutyrate) (P3HB), a polyester of 3-(*R*)-hydroxybutanoic acid, or poly(4-hydroxybutyrate) (P4HB), a polyester of 4-(*R*)-hydroxybutanoic acid. PHB is a semi-crystalline isotactic stereoregular polymer with large crystals in the form of spherulites which contribute to the material's high brittleness, Young's modulus, and tensile strength (Woo et al., 2020). The large spherulites exhibit inter-spherulitic cracks due to the low nucleation density of PHB (Kushwah et al., 2016). The whole rigid amorphous fraction (RAF) of PHB is formed during crystallization; the RAF of low molar mass PHB is only 5 precent–10 precent, which is less than half that of high molar mass PHB, despite identical crystallinity (Bugnicourt et al., 2014). This is a result of the enhanced covalent coupling of crystals and amorphous structure in high molar mass PHB, which also experiences a higher degree of reversible melting and crystallization due to the de-coupling of segments of macromolecules that traverse between phases (Di Lorenzo and Androsch, 2019).

PHAs with two or more different monomeric units, called copolymers, are highly commercialized in the bioplastic market. Copolymers are often modified by adding other monomers into their chemical structure. Examples of copolymers include poly(3-hydroxybutyrate-co-4-hydroxybutyrate) (P3HB4HB), a polyester of 3-hydroxybutanoic acid and

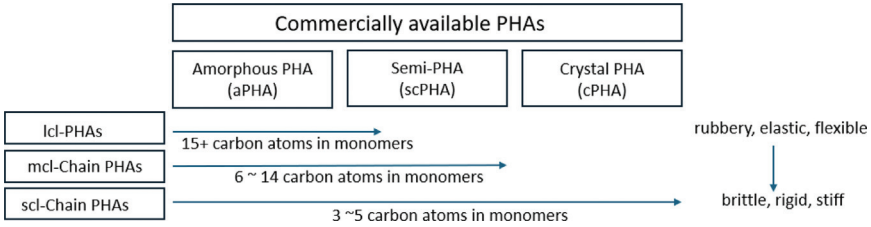

Fig. 2 Relationship between chain length and crystallinity of commercially available PHAs.

4-hydroxybutanoic acid, and poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV), a polyester of 3-hydroxybutanoic acid and 3-hydroxypentanoic acid. Increasing the 3-hydroxyvalerate (3HV) content of PHBV results in improved impact strength and other mechanical properties by modification of crystallinity, along with decreased T_g and T_m values (Abbasi et al., 2022). Copolymers of 3HB with mcl-PHA can also exhibit improved properties, such as a lower T_g, since mcl-PHA forms a separate crystalline lattice or does not form one at all (Eesaee et al., 2022). Tailoring the ratio of monomers in PHA copolymers provides an opportunity for specialized polymer synthesis where specific properties are needed for certain applications in packaging.

PHAs can also be classified by the broader definitions of crystalline (cPHA), semi-crystalline (scPHA), and amorphous (aPHA), as shown in Fig. 2. These classifications are based on the level of crystallinity of the polymer. cPHAs such as P3HB are brittle and exhibit high thermal resistance, while scPHAs such as P3HB4HB with 4HB 5 precent–15 precent have moderate properties, and aPHAs such as P3HB4HB with 4HB >30 precent are flexible and exhibit low thermal resistance (Zhang et al., 2023). Another method of classifying PHAs focuses on their origin, categorizing them as natural or semisynthetic. Natural PHAs are produced naturally by microorganisms from general substrates, while semisynthetic PHAs require the addition of unusual precursors—for example, the addition of 3-mercaptopropionic acid to promote the biosynthesis of poly(3-hydroxybutyrate-co-3-mercaptopropionic) (P [3HB-co-3MP]) (Loo and Sudesh, 2007).

1.2 General properties of PHA

The properties of polyhydroxyalkanoates (PHAs) vary greatly depending on their molecular weight, side chain length, kind of monomer, distance between ester bonds in the backbone, and functional group

(Acharjee et al., 2023). Crystalline and semicrystalline PHAs are further influenced by the crystals' organization, morphology, and interconnection to amorphous regions (Ghassemi et al., 2024). These factors result in more diverse thermal and mechanical properties than those observed in other biodegradable or bio-based bioplastics like polylactic acid (PLA), polybutylene succinate (PBS), and polybutylene adipate-co-terephthalate (PBAT) (Rafiqah et al., 2021). The properties of short chain length (scl) PHAs are similar to those of conventional petroleum-derived plastics, while medium chain length (mcl) PHAs are highly amorphous thermoplastics with elastomeric, adhesive properties and varying degrees of crystallinity (Azizi et al., 2024). A summary of the properties of PHAs compared to polylactic acid (PLA), polypropylene (PP), low-density polyethylene (LDPE), and polyethylene terephthalate (PET) is shown in Table 1.

PHAs are insoluble in water but are soluble in halogenated solvents such as chloroform, dichloromethane, or dichloroethane (Tarrahi et al., 2020). Some commercially available scl-PHAs are soluble in other organic solvents such as ethyl acetate (Bio). PHAs are nontoxic and biocompatible, meaning they can be implanted in living tissues without triggering any immunological responses, and exhibit antioxidant characteristics by neutralizing free radicals (Song et al., 2018). Other functional activities, such as antimicrobial activity, can be achieved by integrating antibacterial agents, such as silver nanoparticles, into the polymer matrix. PHAs have good water resistance and superior light resistance (including ultraviolet) compared to conventional plastics (Naser et al., 2021). This high UV stability is a unique advantage compared to PLA. However, PHAs demonstrate poor resistance to acids and bases (Martin and Avérous, 2001). PHAs are relatively resistant to hydrolytic degradation but they sink in water, encouraging anaerobic biodegradation in aquatic environments (Quecholac-Piña et al., 2020). Crystalline scl-PHAs like polyhydroxybutyrate (PHB) are highly hydrophobic and are slow to degrade due to its high structural stability that lowers accessibility by microorganisms (Wang et al., 2016).

PHAs have a density of 1.23 g/cm^3, a small pore size, and a high volume to surface ratio (Sharma et al., 2021). Their structure depends heavily on the type of PHA. For example, PHB has large crystals in the form of spherulites, and its crystalline structure can crystallize in two different forms: a helical (α-form) and a planar zigzag (β-form) conformation (Yeo et al., 2018). PHB with crystals in the β-form conformation results in plastic films with superior mechanical properties (Al et al., 2024). PHA molecules are chiral and take the R-conformation due to the stereospecificity of PHA

Table 1 Properties of PHAs compared to other commercial polymers (Fetters et al., 1994).

	scl-PHA	mcl-PHA	PLA	PP	LDPE	PET
Density (g/cm^3)	1.23	1.23	1.25	0.91	0.92	1.38
Glass transition temperature (°C)	4 to 15	≈ -40	50 to 65	- 5 to -20	−100 to -120	67 to 80
Melting temperature (°C)	160 to 180	30 to 80	140 to 180	163	110	240 to 260
Crystallinity (%)	40 to 80	20 to 40	0 to 40	30 to 70	40 to 60	0 to 60
Tensile strength (MPa)	20 to 40	10 to 20	50 to 70	30 to 40	10 to 20	50 to 100
Young's modulus (MPa)	500 to 1500	50 to 300	2000 to 3000	1000 to 2000	100 to 300	2000 to 4000
Elongation at break (%)	3 to 10	200 to 600	2 to 10	200 to 700	400 to 900	50 to 300

polymerase, and therefore PHAs exhibit optical activity (Kelley, 2001). The chiral carbon of PHAs combined with the polar oxygen group results in piezoelectric properties that are not commonly observed in plastics, which broadens the potential applications of PHA, especially in the biomedical field—for example, nerve repair, bone-filling augmentation, or ligament and tendon grafts (Fukada and Ando, 1986).

It is well known that the physical properties of PHAs are diverse. PHB, which has the simplest chemical composition of PHAs, has excellent mechanical strength, with tensile strength and Young's modulus comparable to polypropylene due to high crystallinity, but almost no elasticity as evidenced by its elongation at break of 5 precent (Tordjeman et al., 2001). Despite being quite ductile after molding, PHB is rigid and brittle because it undergoes secondary crystallization at room temperature (Turco et al., 2021). The higher density of crystalline phases compared to the amorphous phase induces cracks between crystals, and when placed under stress, large spherulites experience radial and circumferential cracks from which fractures can form (Crist and Schultz, 2016). PHB is difficult to process by conventional methods and its brittle behavior and low deformability significantly limits its potential applications (Gao and Drozdov, 2024). Copolymers are less brittle and stiff than PHB and are easier to process but have lower Young's modulus (Mai et al., 2024). Aside from other PHA monomers, PHB is miscible with other polymers, such as polyethylene oxide, polyepichlorohydrin, polyvinyl acetate, and polyepsiol caprolactone. Mcl-PHAs are elastic and flexible with much higher elongation at break points but much lower tensile strength and Young's modulus than scl-PHAs like PHB. The mechanical properties of mcl-PHAs are generally considered to be weak, but copolymerization can significantly improve impact strength, flexibility, and processability due to their lower crystallinity (Alfano, 2024).

Films made with PHA have high strength, elastic modulus, and water resistance (Rakkan et al., 2024). The water vapor permeability of PHA is similar to that of PLA, PET and ethylene vinyl alcohol (EVOH), but higher than that of PE and PP due to the presence of polar groups in PHAs. The oxygen permeability of PHA is much lower than PP and PE, similar to that of PET and PLA, and much higher than that of EVOH (Macnamara Jr, 2024). This indicates that PHA films provide a good barrier against oxygen and therefore PHA-based food packaging would effectively prevent microbial growth and food spoilage. PHA films also have good tensile strength, printability, flavor and odor barrier properties, grease and oil resistance, heat sealability, temperature stability, and are easily dyed (Mangaraj et al., 2019).

However, it has been reported that PHA films experience rapid aging and poor melt strength, low elongation at break, poor ductility, and poor heat resistance depending on the type of PHA and level of crystallinity (Emaimo et al., 2022).

PHAs are thermoplastic materials, but their weak thermal characteristics limit their potential applications (Elmowafy et al., 2019). The poor temperature stability of PHAs in their molten state may result in degradation occurring during processing (Kervran et al., 2022). PHB has a low heat distortion (deflection) temperature and a high susceptibility to rapid thermal degradation, with decomposition occurring just above its melting temperature (T_m) (Vanovčanová et al., 2016). Thermal decomposition of PHB results in a rapid decrease in molecular weight, a reduction in melt viscosity, a decrease in crystallization temperature, and an increase in crystallization time (El-Hadi et al., 2002). The T_m of PHB is high, but the T_m and glass transition temperature (T_g) of PHAs decrease as chain length increases (El-Taweel et al., 2004). Therefore, mcl-PHAs show significantly lower T_m and T_g values than scl-PHAs and have significantly poor thermal characteristics. However, the low T_g of mcl-PHAs prohibits brittle behavior at temperatures as low as below freezing and suggests a potential for the use of mcl-PHAs as rubber-like materials or flexible packaging applications (Dartiailh, 2022).

1.3 Production of PHA: synthesis, additives, and processing

Bacteria perform fermentation of sugars or lipids into linear polyesters (PHAs) as storage granules of carbon and energy (Lenz and Marchessault, 2005). The biosynthesis of PHA within bacterial cells can occur via multiple pathways. One pathway involves two molecules of acetyl-CoA (from Tricarboxylic Acid Cycle) being condensed into a molecule of acetoacetyl-CoA by β-ketothiolase. This molecule is then converted into 3-hydroxybutyryl-CoA by acetoacetyl-CoA reductase and then an ester bond formation is catalyzed by PHA synthase to generate poly(3HB). Another pathway involves substrates originating from the β-oxidation pathway of fatty acids, in which (*R*)-enoyl-CoA hydratase, acyl-CoA oxidase, and 3-ketoacyl-CoA reductase generate hydroxyalkanoate monomers. In addition, simple sugars from the environmental sources are used to convert (*R*)-hydroxy acyl intermediates from their acyl carrier protein (ACP) form to Co-A form by [ACP]acetyltransferase, before being polymerized by PHA synthase (Bhola et al., 2021). An overview of these biosynthetic routes is illustrated in Fig. 3.

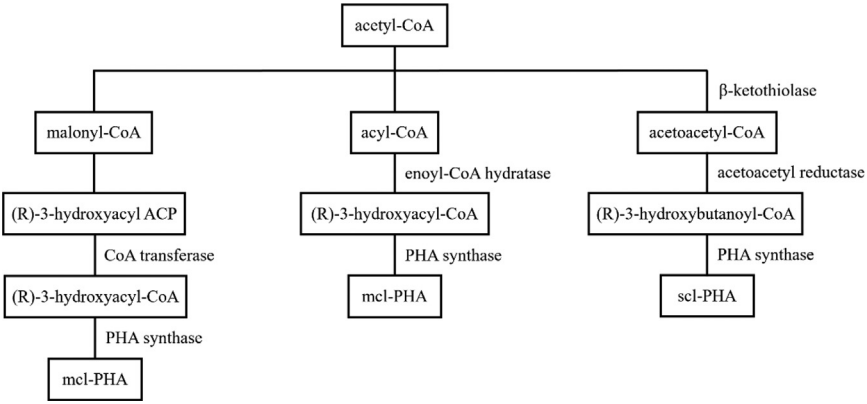

Fig. 3 Summary of biosynthesis pathways of PHA (Samrot et al., 2021).

Substrate accounts for 30 precent–40 precent of the total production cost for PHA (Favaro et al., 2019). Substrates can range from organic components like sucrose, starch, and cellulose; chemicals such as propionic acid or 4-hydroxybutyric acid; food by-products like molasses, whey, and glycerol; and even fossil resources like methane or mineral oil (Bhattacharyya et al., 2019). Food and agricultural wastes and their by-products can also be used as feedstock, offering an opportunity for the circular economy. Fruit and vegetable waste including potato waste, onion peels, apple pulp waste, pineapple waste, and date seeds have successfully been used as substrates (Guleria et al., 2022). Using a modern arrested anaerobic digestion process, the utilization of diverse agricultural biomass has increased for PHA production. Optimized bacterial growth conditions are a challenge to maintain in PHA production and most fermentation processes do not facilitate maximum yield of PHA granules after cultivation (Koller, 2018). Mixed cultures are less expensive but result in poor yields and productivity, whereas pure culturing requires sterility and filtered substrates that can be a barrier to commercialization (Perez-Garcia and Bashan, 2015). Co-productions of PHA with other products—amino acids, proteins, protein hydrolysates, alcohols, biosurfactants, etc.—can improve financial viability and can be used to produce animal feed, nutraceuticals, wood adhesives, flocculants, and biostimulants (Pesante and Frison, 2023). About 60 precent of production costs are accounted for by extraction and purification of the PHA (Leong et al., 2017). PHA-rich biomass must first be separated from supernatant using techniques such as flocculation, decantation, centrifugation, lyophilization, or filtration, which can be expensive and time-consuming, then pretreated to damage the cell

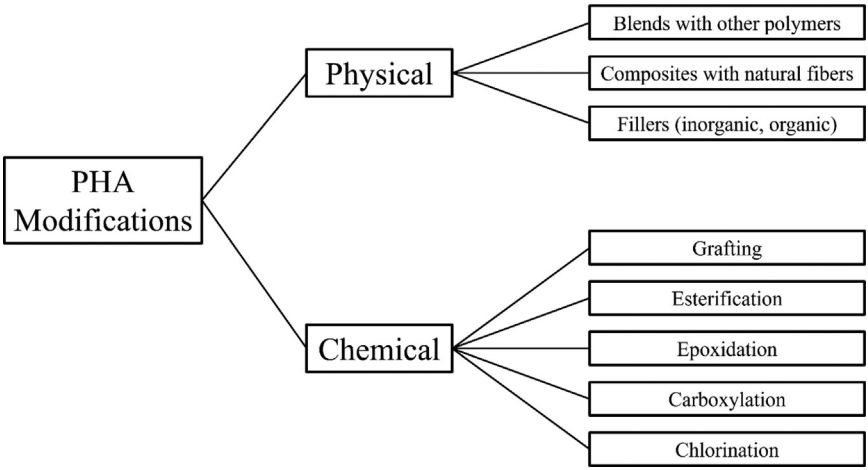

Fig. 4 Summary of PHA modification methods (Greene, 2013).

wall by mechanical, heat, alkali, or enzymatic means (Mondal et al., 2023). PHA extraction can occur by (1) digestion of non-PHA cell mass (NPCM) with chemicals, enzymatic, biological, or mechanical methods, or (2) using a solvent (usually chlorinated e.g. chloroform or dichloromethane) to modify cell permeability then release and solubilize PHA (Pérez-Rivero et al., 2019). Extraction causes the PHA granules to crystallize. Biological recovery of PHAs with living organisms like rats or mealworms is a cost-effective and environmentally friendly alternative method of extraction (Singh et al., 2024).

PHA can be modified in many different ways to change its properties, amphiphilic character, surface structure, rate of degradation, and more (Bhat et al., 2024). A summary of possible modifications to PHA is shown in Fig. 4. Note that this is not an exhaustive list, and many novel approaches are being developed. Plasticizers enhance molecular motion, lower crystallinity, lower glass transition temperature, and increase flexibility, ductility, toughness, permeability, and processability (Mannina et al., 2020). Plasticizers usually have low molecular weight and low steric hindrance: common plasticizers include polyethylene glycol (PEG), glycerol, citrate esters, oligomeric lactic acid, triacetin, di-glycidyl ether, soybean oil, and salicylic ester (Godwin, 2024). However, the effect of plasticizers on PHA is limited and generally insufficient for large-scale application (Râpă et al., 2015). Blends with other polymers can cause many of the same effects, but the phase separation in PHA blends causes them to degrade at lower

temperatures (Na et al., 2003). Compatibilizers or crosslinkers are often required to improve miscibility between the polymers by embedding in polymer interfaces and lowering interfacial tension, or inducing covalent bonds between the polymers, respectively (Ajji and Utracki, 1996). Fillers, or composites with natural fibers, can lead to drastically different mechanical properties and reduce the volume of PHA needed, thus lowering material costs. Common inorganic fillers include minerals, clay, and titanium dioxide, while common organic fillers include bacterial cellulose, cellulose nanocrystals, and lignin-based or hemicellulose-based materials (Barhoum et al., 2020). Fillers often act as a nucleating agent and have varying or little effect on mechanical and thermal properties of PHA, but generally reduce crystallinity (Majerczak et al., 2022). Nucleating agents such as orotic acid, α-cyclodextrin, boron nitride, talc, terbium oxide, and lanthanum oxide increase nucleation density and reduce spherulite size to speed up crystallization after processing (Yu et al., 2011). Stabilizers prevent UV degradation or oxygenation from decreasing mechanical properties (Pospíšil et al., 2003). Direct biosynthesis of functionalized PHA—for example, grafting hydrophilic groups to enhance hydrophilicity—is an alternative approach to the modification of PHA properties that reduces the need for subsequent modification after extraction (Gumel et al., 2015).

PHA is commonly manufactured using injection molding, extrusion and extrusion blow molding (Lee et al., 2020). PHA can be thermoformed with conventional equipment and optimum processing temperature is usually around 180 °C to avoid degradation (Naser et al., 2021). Advanced processing techniques, including electrospinning, laser micro perforation, and additive manufacturing used for the production of medical devices with PHA (Koller, 2018).

1.4 PHA market overview

The biodegradable bio-based bioplastic market is led by polylactic acid (PLA) and polyhydroxyalkanoates (PHAs) (Prieto, 2016). While China dominates global bioplastic production, Europe is the largest producer of PHAs, followed by North America (Degli Esposti et al., 2021). PHAs have been under research and development since the 1990s and have only recently seen industrial manufacturing (Chen, 2009). Despite the wide range of possible PHA polymers, commercial production of PHAs is largely limited to five types: poly(3-hydroxybutyrate) (P3HB), poly(3-hydroxybutyrate-co-4-hydroxybutyrate) (P3HB4HB), poly(3-hydroxybutyrate-co-3-hydro-

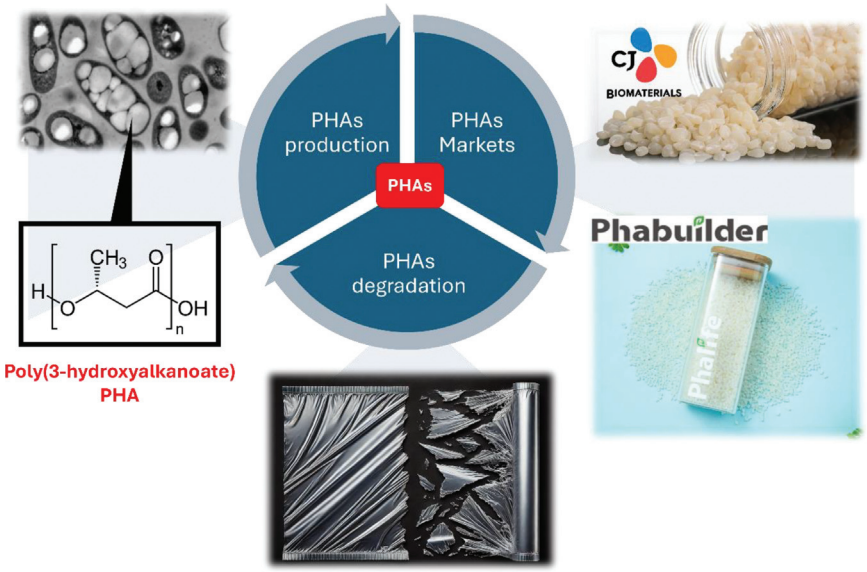

Fig. 5 Overview of polyhydroxyalkanoates (PHA): production, markets, and degradation.

xyhexanoate) (PHBHHx), poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV), and poly(4-hydroxybutyrate) (P4HB) (Koller and Mukherjee, 2022). Cost of production is the primary limitation to expanding the PHA market, especially for low-value products such as packaging, where the cost of production is not balanced with high product costs as in the biomedical industry. Medium chain length (mcl) PHAs have a higher production cost than short chain length (scl) PHAs and therefore are not as widely commercially available yet (Thomas et al., 2022).

Current major producers of different PHAs with capacity exceeding 1000 tons/year are outlined in Table 2 below (Product, 2024; Biomaterials, 2025; Biomaterials et al., 2024; Miyako Kagaku Co., Ltd, 2024; Miyako Kagaku, 2025; PhaBuilder, 2025; PhaBuilder, 2025; PhaBuilder, 2025; TianAn Biologic Materials et al., 2024). Note that more recent data is unavailable for some manufacturers. Other major companies not listed include Newlight Technologies (USA), Natureplast (France), ColorFabb (Netherlands), and EarthBi (Germany) (Sabapathy et al., 2020). A consolidated overview of PHA production pathways, market distribution, and environmental degradation characteristics is illustrated in Fig. 5.

Table 2 Current major producers of PHAs worldwide.

Type of PHA	Manufacturer	Country	Substrates	Brand/Trade name	References
P3HB	Bio-On	Italy	Beet sucrose, byproducts of the sugar beet industry, the agricultural surplus	Minerv-PHA	Miyako Kagaku Co., Ltd. (2024)
P3HB4HB	PhaBuilder (2025)	China	–	PB3000G	PhaBuilder (2025)
	Biomaterials (2025)	Korea	Sugars	PHACT	(Biomaterials)
	PhaBuilder (2025)	China	Glucose, corn steep liquor, GBL	PB3430G	PhaBuilder (2025)
PHBHHx	CJ Biomaterials	Korea	Bacterial fermentatation of sugar	PHACT PHA	Product (2024)
	RWDC Industries Ltd	USA	Waste cooking oil	Solon®	et al. (2024)
	Miyako Kagaku (2025)	Japan	Vegetable oil	Bluepha® PHA	Miyako Kagaku (2025)
PHBV	TianAn Biologic Materials et al. (2024)	China	–	ENMAT®	TianAn Biologic Materials et al. (2024)
	PhaBuilder (2025)	China	–	PHALife™, PHAmily®, PHA Keychain	PhaBuilder (2025)

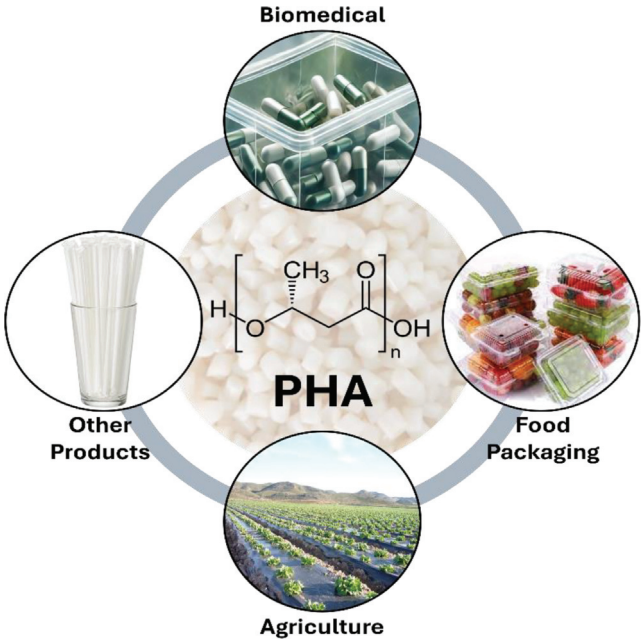

Fig. 6 Various applications of PHA.

2. Environmental impacts of polyhydroxyalkanoates (PHA)

2.1 Overview of biodegradability of polymers

With the growing global population and rapid advances in technology, plastics have become essential across nearly every aspect of modern life and industry (Panda et al., 2010). Plastics are versatile and durable materials, making them essential in numerous applications. However, their widespread use has led to serious environmental concerns due to their persistent nature in ecosystems (Kumar et al., 2021). Especially, conventional packaging materials available in the market, such as polypropylene, polyethylene terephthalate, and polyethylene, are nonbiodegradable and mostly derived from petroleum (Sid et al., 2021). The growing accumulation of these materials in the environment has become a serious ecological concern, threatening both terrestrial and aquatic ecosystems and contributing to lasting environmental impacts (Bashir et al., 2020; Ahn et al., 2024).

Plastic waste accumulates extensively in both terrestrial and aquatic ecosystems, with the marine environment being particularly affected. In

these habitats, plastics break down into microplastics due to mechanical and physical interactions with atmospheric agents (Duan et al., 2021). Growing evidence shows that plastics have the capacity to absorb environmental pollutants, potentially transferring these contaminants up the food chain and impacting both animal and human food sources (Huang et al., 2021). Consequently, interest has grown in developing highly biodegradable plastics to mitigate these impacts. Derived from renewable feedstocks, these materials provide an environmentally friendly alternative, reducing fossil fuel dependency and emissions from greenhouse gas.

For instance, PLA and PHA, biodegradable polymers, are produced through biotechnological processes (e.g., PHA synthesized from microbial fermentation of agricultural byproducts) and chemical synthesis (e.g., PLA from lactic acid) (Taib et al., 2023; Dalton et al., 2022). These polymers are becoming essential in reducing plastic waste, especially in sectors like packaging, due to their potential to degrade in natural environments under specific conditions. Biodegradability describes the process by which organic substances break down into simpler chemical components through the action of microorganisms. In this process, microorganisms metabolize the materials, producing substances such as water, methane and carbon dioxide in aerobic conditions, and eventually microbial biomass (Reineke, 2001). This complex process occurs in several stages, beginning with non-biological (abiotic) factors like oxidation or hydrolysis, which fragment the material to make it accessible for microbial assimilation (Iram et al., 2019). Understanding this initial abiotic breakdown is crucial, as it enables microorganisms to further convert these fragments into basic inorganic compounds through metabolic processes. The biodegradation of polymers follows a multi-stage process involving both abiotic and biotic mechanisms (Silva et al., 2023). Initially, abiotic degradation occurs, where environmental factors such as sunlight, temperature, oxygen, and water cause oxidative or hydrolytic breakdown of the polymer structure. These conditions contribute to physical fragmentation, reducing the polymer's molecular weight and creating micro-scale fragments with increased surface area, which facilitates subsequent biological degradation. This stage may involve processes such as photodegradation, thermal degradation, and mechanical wear, all of which enhance the material's vulnerability to microbial action. Following abiotic breakdown, biotic degradation begins as microorganisms, including bacteria and fungi, colonize the polymer surface, forming a biofilm that supports microbial activities like depolymerization. During this process, extracellular enzymes cleave the polymer chains into smaller molecules, such as monomers and oligomers,

which are then metabolized by microbial cells. This metabolism provides a carbon source that is ultimately converted into inorganic end products such as CO_2 and water in aerobic environments or CH_4 in anaerobic conditions along with microbial biomass. This complete degradation pathway, known as mineralization, varies depending on environmental conditions and polymer type, with some materials requiring controlled composting environments while others can degrade naturally in soil or marine settings. Biodegradability in polymers also depends on the polymer's chemical structure, which affects how it interacts with environmental conditions and its susceptibility to breakdown (Lucas et al., 2008). The polymer's chemical and physical properties, along with its structure, determine how well it interacts with environmental factors that initiate biodegradation. However, biodegradability is influenced not only by the chemical composition but also by the specific conditions of the environment, as these factors govern the rate and extent of degradation. Decomposition can occur in two main environmental types: aerobic (with oxygen) and anaerobic (without oxygen) (Fotopoulou and Karapanagioti, 2017). Each type affects the rate and completion of the biodegradation process, as the surrounding conditions play a crucial role in determining how and to what degree polymeric materials degrade.

2.2 Biodegradability of PHAs

Among various biodegradable polymers, polyhydroxyalkanoates (PHAs) are particularly promising due to their versatility in structure and function. There are over 90 types of PHAs, which vary in their monomer compositions, leading to a broad range of properties (Anjum et al., 2016). Short-chain-length PHAs (scl-PHAs) have thermoplastic qualities similar to conventional plastics like polyethylene, while medium-chain-length PHAs (mcl-PHAs) exhibit elastomeric and rubbery properties, making them flexible and resilient. This diversity arises from variations in microbial synthesis pathways, feedstock types, and production techniques, allowing PHAs to adapt to numerous applications, from packaging to biomedical uses (Diniz et al., 2023). Notably, PHA degrades more readily in diverse environmental conditions such as marine and soil settings because it is highly susceptible to microbial action compared to PLA, which requires industrial composting environments to break down effectively.

Biodegradation typically involves abiotic processes, such as exposure to UV light, oxygen, and hydrolysis, followed by microbial assimilation. This

sequential breakdown produces smaller fragments that microorganisms can consume, ultimately resulting in end-products like CO_2 and water in aerobic conditions or methane in anaerobic conditions. Studies indicate that the efficiency of this process is influenced by environmental factors, such as temperature and humidity, as well as the polymer's composition (Andrady, 1994). For example, PLA degradation accelerates in warmer, more alkaline environments, making it suitable for controlled industrial composting, whereas PHA demonstrates effective natural degradation without requiring specialized conditions (Goetjes et al., 2024). Using biodegradable plastics like PHA can thus mitigate landfill accumulation, reduce greenhouse gases, and provide an alternative to conventional plastics that persist in ecosystems, harming wildlife and contaminating food chains. The implementation of bioplastics is seen as a crucial step toward sustainable waste management and reducing the environmental footprint of synthetic plastics.

2.3 Comparison of the biodegradability of PHA with other biopolymers

PHAs break down naturally in environments such as marine sediments, compost or soil. PHB can biodegrade in both aerobic and anaerobic conditions without releasing toxic by-products (Meereboer et al., 2020). The rate of biodegradation depends on several factors, including temperature, moisture, microbial activity, environmental pH, molecular weight, exposed surface area monomer type, polymer composition, and crystallinity (Kliem et al., 2020).

Among widely studied biodegradable synthetic and natural bioplastic, polyhydroxyalkanoates (PHAs) are often compared with other bioplastics, including polylactic acid (PLA), polycaprolactone (PCL), polybutylene succinate (PBS), and polybutylene adipate-co-terephthalate (PBAT), each exhibiting distinct degradation profiles and environmental compatibilities. Herein, commercially available PBS, PBAT, and PCL are synthesized using petroleum-based monomers, although bio-driven monomers are actively introduced to the market (Gironi and Piemonte, 2011). For instance, the breakdown of PHB, one of PHAs, is facilitated by enzymes such as PHB depolymerase, which converts PHB into hydroxy acids that microorganisms can use as carbon sources (Kaur and Chauhan, 2024). This enzyme is found in organisms like Alcaligenes faecalis, where it acts as an endo-type hydrolase, cleaving internal bonds within the polymer chain. Other notable PHB degraders include Rhodospirillum rubrum, Bacillus

megaterium, Azotobacter beijerinckii, and Pseudomonas lemoignei. Estimates indicate that PHB-degrading microorganisms constitute 0.5 precent to 9.6 precent of microbial colonies in natural environments, thriving primarily under mesophilic conditions (20 °C–37 °C). Only a few species, such as specific Streptomyces strains, are capable of degrading PHB at higher temperatures (50 °C), suggesting potential applications in high-temperature composting. PCL also exhibits significant biodegradability in natural environments, driven by bacteria and fungi, including Pseudomonas and Streptomyces species (Naser et al., 2021). PCL's degradation is aided by its flexible, lower-melting structure, which allows easier microbial access. In contrast, PBS, another aliphatic polyester, shows slower degradation in aquatic conditions but biodegrades effectively in soil and compost. Studies indicate that blending PHB with PBS can enhance overall degradation rates, as PBS contributes structural flexibility, enabling increased microbial activity. For example, a thermotolerant Aspergillus species was shown to degrade 90 precent of PHB film within five days at 50 °C, supporting the potential for controlled composting applications. PBAT, a flexible synthetic co-polyester, shows substantial biodegradability in soil and compost and is frequently blended with PLA to improve flexibility and biodegradability (Meereboer et al., 2020). However, PBAT exhibits slower degradation in marine conditions due to a lack of compatible microbial communities. Studies reveal that under composting conditions around 58 °C, PBAT can achieve approximately 75 precent degradation within six weeks. In aerobic environments, PHAs degrade into carbon dioxide and water, while anaerobic conditions yield carbon dioxide and methane. In compost settings, PHAs have shown significant degradation, with about 85 precent decomposing within seven weeks at temperatures up to 60 °C and moisture levels around 55 precent. Under aquatic conditions, PHAs degrade more slowly, requiring up to 254 days in water temperatures below 6 °C. Blending PHB with PLA tends to slow enzymatic erosion due to increased crystallinity from the PLA; however, PHB/PLA blends still biodegrade faster than pure PLA (Kaur and Chauhan, 2024). Ultimately, PHAs remain the most versatile among biodegradable polymers in terms of environmental compatibility and efficiency of degradation. Their adaptability across various conditions, combined with the effective microbial and enzymatic pathways involved in their breakdown, positions PHAs especially PHB as promising materials for sustainable applications in reducing plastic pollution. A comparative summary of degradation conditions and microbial activity for these bioplastics is presented in Table 3.

Table 3 Comparative biodegradability of biodegradable polymers.

Bioplastic	Key Properties	Optimal Degradation Conditions	Microbial Activity	Degradation Rate
PHA	Various crystallinity; microbial origin	Compost (60 °C, 55 precent moisture), soil, aquatic environments	Pseudomonas, Bacillus, Streptomyces, and fungi	Up to 85 precent degraded within 7 weeks in compost (60 °C); 254 days in cold water (< 6 °C).
PLA	High crystallinity; synthetic, renewable	Industrial compost (≥ 58 °C with specific microbial consortia)	Geobacillus, Thermobifida	70 precent–90 precent degraded within 6-12 weeks in industrial composting; minimal degradation in soil and marine environments.
PCL	Low melting point; flexible, synthetic	Soil, compost (ambient temperatures), limited marine suitability	Streptomyces, Pseudomonas, Aspergillus	Moderate degradation: 50 precent–60 precent in soil within 12 weeks; slower in marine, typically requiring 180+ days.
PBS	Moderate crystallinity; aliphatic polyester synthetic	Soil, compost (ambient to moderate temps)	Wide range of bacteria and fungi	Approximately 60 precent–70 precent degraded in compost within 8-10 weeks; slower in aquatic environments.
PBAT	Synthetic co-polyester	Compost (around 58 °C), soil	Mesophilic bacteria, fungi	Achieves 75 precent degradation in compost within 6 weeks; slower in marine conditions, up to 20 precent degradation in 180 days.

2.4 Biodegradation of PHA in different environmental conditions

The biodegradation of pure PHA has been investigated in diverse settings, such as aquatic environments and soil (Folino et al., 2020). A key process for biodegradation takes place under composting settings. In this context, PHA packaging often blends with natural fillers and other biodegradable and bio-based bioplastic elements demonstrates superior biodegradation rates and efficiency compared to polylactic acid (PLA). For instance, PHA (PHACT A1000P) by CJ biomaterials demonstrates excellent biodegradability in diverse environments, including industrial and home composting systems. Studies indicate that incorporating more than 30 precent PHACT A1000P into PLA increases the blend's ability to degrade under home compost conditions, achieving near-complete biodegradation under specific settings (Krishnaswamy and Lee, 2024).

In a study by Volova et al. (2017), the biodegradation of polyhydroxyalkanoates (PHAs) with different chemical compositions was examined in soil environments, focusing on poly(3-hydroxybutyrate) [P(3HB)] and its copolymers, including poly(3-hydroxybutyrate-co-3-hydroxyvalerate) [P(3HB-co-3HV)], poly(3-hydroxybutyrate-co-4-hydroxybutyrate) [P(3HB-co-4HB)], and poly(3-hydroxybutyrate-co-3-hydroxyhexanoate) [P(3HB-co-3HHx)]. Results indicated that copolymers degraded significantly faster than the homopolymer P(3HB), with decomposition times varying depending on copolymer structure. Specifically, P(3HB-co-4HB) and P(3HB-co-3HHx) exhibited more rapid biodegradation, often fully breaking down within 60 to 90 days under these conditions, attributed to their lower crystallinity and higher amorphous content. By contrast, the P(3HB) homopolymer took over 120 days to reach a comparable level of degradation. This study highlights the impact of chemical structure on the degradation rates of PHAs, with increased amorphous regions facilitating faster microbial breakdown. In a study by Burgos et al. (2014), the biodegradation properties of PLA/PHA-based films plasticized with oligomeric lactic acid and other additives were assessed under industrial composting conditions. The findings indicate that while PHA can enhance rigidity and serve as a nucleating site within the blend, reducing the rate of PLA degradation, the addition of specific plasticizers reversed this effect by accelerating overall disintegration rates. The degradability of PHA homopolymers and copolymers in these controlled composting environments reinforces their appeal for sustainable packaging applications that align with organic waste disposal systems.

However, concerns persist about the inconsistency of biodegradation outcomes, especially in settings beyond industrial composting, such as home composts or aquatic systems. In some cases, certain biodegradable films showed only partial fragmentation rather than complete biodegradation, which underscores the ongoing challenge of ensuring that bioplastics break down fully in diverse natural conditions, not just under idealized composting setups.

Under environmental conditions with a lower concentration of microorganisms than those found in composting systems or wastewater sludge, the breakdown of bio-based plastics becomes more challenging. However, PHAs have shown promising biodegradability in both soil and seawater. For instance, a study by Meereboer et al. (2020). demonstrated that PHB films could achieve full degradation within about three weeks after being buried in soil. Additionally, their work highlighted that the biodegradation rate of PHB can be modulated by exposing PHB to UV light or incorporating TiO_2 nanoparticles, providing insights into the environmental persistence of PHA-based packaging containing inorganic nanoparticles. This understanding is valuable in assessing the long-term ecological impact of PHA bioplastics in natural environments.

Similar observations were made in research by Zhao et al. (2020), a range of bio-based plastics including PLA, PHB, PBS, PCL, Polyhydroxyoctanoate (PHO), thermoplastic starch, and their blends— were evaluated for their ability to degrade in various controlled and natural settings. PLA showed high degradation efficiency within industrial composting conditions but exhibited resistance to breakdown in other environments, such as home compost, freshwater, and marine ecosystems. Notably, blending PLA with PCL was found to improve its biodegradability, making it suitable for home composting. Additionally, several biodegradable polymers and their composites showed efficiency in thermal anaerobic processing with substantial bio gas production, although the degradation periods were significantly longer than those typical of commercial anaerobic systems. PHB was particularly notable for its extensive biodegradation in both water and soil, achieving complete degradation in diverse conditions, including mesophilic anaerobic (35 °C), marine pelagic (30 °C) and freshwater aerobic (21 °C) environments. In contrast, PHO showed only limited degradation, with minor breakdown in anaerobic conditions and moderate results in freshwater over a 56-day period. PHB/PHO blends initially degraded more slowly but eventually matched PHB's biodegradation performance in marine conditions. However, despite these promising results for some materials,

most polymers evaluated did not meet the ISO and ASTM biodegradation standards.

Building on prior studies regarding the mass loss of polyhydroxyalkanoate (PHA) in natural marine environments, recent work by Read et al. (2024). investigated the biodegradation rate of PHA materials specifically in marine conditions, applying these findings to estimate the durability of PHA-based products, including applications like single use items and food packaging. This study offers clarity on the practical implications of PHA biodegradability in marine ecosystems, allowing for a transparent evaluation of the risks and benefits of PHA utilization in such environments. To achieve reliable degradation rate data, a streamlined model was applied, conceptualizing the biodegradation process through three key stages: biofilm formation, depolymerization, and mineralization. The study determined that PHA biodegrades at a rate that varies by environmental exposure: floating PHA products, such as water bottles, may persist for between 1 and 2 years, while items situated on the ocean floor could degrade more rapidly, within approximately 4 to 9 months. These results highlight the value of PHA, and specifically polyhydroxybutyrate (PHB), in managing plastic waste, as these polymers demonstrate a high degree of versatility and biodegradability across diverse environmental conditions, both natural and anthropogenic. Nevertheless, these findings also underscore the need for careful post-consumer management of PHA-based materials. As biodegradable plastic blends, even those incorporating PHA, enter different environments, ongoing research is essential to optimize formulations that enable accelerated degradation across multiple settings, thus mitigating the risk of environmental contamination due to incomplete biodegradation.

3. Perspectives on polyhydroxyalkanoates (PHA) in packaging applications

3.1 Packaging applications: statistics and regulatory standards

Packaging is recognized as the dominant industry responsible for the most of plastic consumption and waste generation, accounting for nearly half of the global total plastic waste each year (Ncube et al., 2021). In 2022, it was estimated that the total amount of plastic utilized for the production of packaging materials, along with the waste produced as a result of these activities, amounted to approximately 400.3 million tons worldwide

(Pilapitiya and Ratnayake, 2024). Among various industries, packaging exhibits the shortest average product lifespan, approximately 0.5 years from production to disposal, compared to other industries such as industrial machinery (20 years), textiles (5 years), building and construction (35 years), and transportation (13 years) (Geyer et al., 2017). This short lifespan contributes significantly to the accumulation of plastic waste, making it essential to assess waste generation by country or region and to examine how effectively these areas can manage such waste volumes.

In 2016, China generated approximately 21.6 million metric tons of plastic waste, followed by the United States, which produced a significantly higher amount of 42 million metric tons despite its smaller population, resulting in a notably higher per capita waste generation rate of 130 kg per year (Law et al., 2020). India, as the second-most populous country, contributed 26.3 million metric tons of plastic waste, with other significant contributors including Brazil at 10.7 million metric tons, Indonesia at 9.1 million metric tons, and Germany at 6.7 million metric tons (Law et al., 2020). These countries demonstrate the direct correlation between population size, industrial activity, and waste generation. The management of plastic waste in these regions, particularly in rapidly developing nations, often remains inadequate (Browning et al., 2021). This leads to substantial environmental degradation, as large portions of waste are disposed of in uncontrolled landfills, or improperly managed, which exacerbates the global plastic pollution problem (Mihai et al., 2021). Moreover, the plastic pollution has been significantly accelerated after the pandemic because of the rapid increase in use of single-use plastic in packaging, which has been designed for customers to seek for more convenience and safety in their daily lives (Das et al., 2021). This issue, along with other major challenges in plastic consumption and waste infrastructure, is outlined in Table 4. As a result, there is a critical need for the implementation of waste management systems and the adoption of circular economic principles, especially in nations that are leading contributors to global plastic waste. Therefore, modern society is confronted with a convergence of factors that significantly impact various aspects of human activities today. Specifically:

Furthermore, current consumption patterns related to packaging and plastics have garnered significant attention due to their negative environmental impact (Thøgersen, 1996). In response, the packaging industry is experiencing a transformative shift. For instance, several countries are introducing stringent regulations aimed at reducing the environmental footprint of packaging materials. A notable example is the European Union's Circular

Table 4 Key issues in plastic consumption and waste management.

Issue	Description
Rising plastic consumption	Global plastic production reached 359 million metric tons in 2018 and continues to grow.
Dominance of the packaging sector	Packaging is the largest consumer of plastic, accounting for 42 precent of global plastic consumption.
Short product lifetime	The average lifespan of packaging products is 6 months, contributing significantly to plastic waste.
Inadequate waste management in major countries	Largest plastic waste-generating countries often lack adequate infrastructure, resulting in improperly managed plastic waste.
Economic disparity in waste generation	Many high plastic-waste-generating countries are in low-to-medium income brackets, making it challenging to implement sustainable waste management systems.

Economy Action Plan, which emphasizes a hierarchy of waste management practices (Cerqueira-Streit et al., 2023). This hierarchy prioritizes prevention, followed by preparation for reuse, recycling, recovery (including energy recovery), and finally, disposal. Such frameworks are designed to promote sustainability and reduce reliance on non-renewable resources in packaging.

1) Preparation for re-use involves activities like checking, cleaning, or minor repairs, which restore waste products or components to a usable state without requiring further processing steps. This ensures that materials can be reused efficiently (Babaremu et al., 2024).

2) Recovery refers to processes like mechanical recycling, where plastic waste is used as input material for creating valuable new products through techniques that conserve resources (Schyns and Shaver, 2021).

3) *Re*-use describes the process of employing products or components that haven't reached waste status again for their original function, without significant modification (Ben Amor et al., 2023).

4) Recycling involves reprocessing waste materials into new products, materials, or substances. This process includes organic reprocessing but excludes energy recovery and reprocessing into fuel (Luu et al., 2022).

5) Disposal is any operation that does not qualify as recovery, even when the operation involves reclaiming substances or energy as a secondary outcome (Luu et al., 2022).

According to recent policies, by the year 2030, all packaging materials should be designed for reuse or recycling, including compostable options (Thapliyal et al., 2024). The European Directive 852/2018 sets ambitious

goals, aiming for 50 precent of packaging to be recycled by 2025 and 55 precent by 2030 (Foschi and Bonoli, 2019). Within this context, polyhydroxyalkanoates (PHA) present a promising solution for cost-effective packaging, particularly in low-income countries (Rekhi et al., 2022). Compliance with these legal and environmental standards requires adherence to established technical frameworks, such as the Harmonized Standards. These standards were developed between 2000 and 2005 to help businesses meet the essential criteria outlined in the European Directive 94/62/EC on Packaging and Packaging Waste (Waszczyłko-Miłkowska et al., 2024). This directive focuses on reducing packaging waste generation, promoting reuse, recycling, and recovery of packaging materials. To ensure that packaging meets these requirements, European standards provide guidelines that businesses can follow to demonstrate conformity, thus supporting the region's waste management and sustainability initiatives. Relevant technical and regulatory standards guiding sustainable packaging design are summarized in Table 5.

Building on these technical frameworks, Directive 2018/852 (Parliament and Union, 1994) retains the packaging definition established in Directive 94/62/EC, which includes materials designed for protection, containment and delivery of products from producers to consumers. Considering the Circular Economy, the discussion around PHA will focus on its market potential, particularly its mechanical and thermal properties, its biodegradability, and its applications within this sustainable context.

3.2 Status of PHAs in food packaging applications

Environmental pollution from the widespread use of plastic materials has become a critical issue, exacerbated by the fact that these materials require significant time to decompose, leading to their persistent accumulation across diverse ecosystems (Liao and Chen, 2021). The development of biodegradable plastics, especially those derived from renewable sources, has been extensively researched and is increasingly recognized for their potential to mitigate this challenge (Ahn et al., 2024). Among biodegradable options, bio-based plastics such as cellulose-based, starch-based materials, and polyhydroxyalkanoates (PHAs) are particularly noteworthy, as they offer sustainable alternatives that can significantly reduce the environmental impact of plastic waste (Stublić et al., 2024). PHAs represent a class of biobased polyesters synthesized by various bacterial and archaeal species as intracellular carbon storage materials (Knoll et al., 2009). These polyesters exhibit a broad range of thermoplastic and elastomeric properties, depending on the structure of

Table 5 Overview of application standards in packaging.

Requirement	Standard	Description
General framework for packaging requirements	EN 13427:2004	Establishes principles for compliance with EU packaging regulations, aligning with waste management and sustainability objectives.
Source reduction in packaging manufacturing	EN 13428:2004	Focuses on minimizing material usage through eco-design, ensuring reduced packaging waste without compromising functionality.
Reusable packaging requirements	EN 13429:2004	Sets criteria for reusable packaging, supporting circular economy principles by promoting durability and minimizing the need for new materials.
Packaging recoverable by recycling	EN 13430:2004	Outlines requirements for packaging design that facilitates recycling, helping businesses meet EU recycling targets effectively.
Packaging recoverable by energy recovery	EN 13431:2004	Provides specifications for packaging suited for energy recovery, ensuring compatibility with waste-to-energy systems to optimize calorific value.
Compostable and biodegradable packaging	EN 13432	Defines requirements for compostable and biodegradable packaging, ensuring it decomposes under industrial composting conditions to reduce environmental impact.

their monomeric units (Sudesh et al., 2000). PHAs are classified into short-chain-length (scl-PHA), medium-chain-length (mcl-PHA), and long-chain-length (lcl-PHA) categories, based on the number of carbon atoms in their monomers (Reddy et al., 2022). Furthermore, PHAs can be produced as homopolymers, consisting of a single type of monomer, or as copolymers when different types of monomer units are incorporated into the polymer chain (Anjum et al., 2016).

Food packaging is one of the most significant applications for plastic products, requiring materials that can provide effective protection against external factors like dust, external impact, moisture, and UV light (Akelah and Akelah, 2013). To ensure food safety and quality, these materials must also preserve the sensory attributes of food and maintain stability under a variety of storage conditions (Leistner and Gould, 2002).

Additionally, they should be resistant to degradation during the packaging's functional life, while also being designed to degrade efficiently once discarded, promoting environmental sustainability (Guillard et al., 2018). Ensuring durability during storage and enhanced biodegradability after disposal are both critical features. Mechanical strength, thermal stability, chemical resistance, permeability, flavor retention, migration prevention, and biodegradability are critical factors in assessing the suitability of PHA for food packaging applications (Koller, 2014). These properties are essential for determining whether PHAs can effectively meet the demands of food preservation while also promoting environmental sustainability.

The thermal and mechanical properties of polymers are crucial for determining their processing capabilities and suitability for end-use packaging applications (Dedieu et al., 2022). Crystallinity directly affects the brittleness and stiffness of the material, while key thermal properties, such as glass transition temperature (T_g) and melting temperature (T_m), play a significant role in defining heat resistance (Katiyar et al., 2014). On the mechanical side, important parameters include Young's modulus, which measures the stiffness of the polymer; tensile strength, which indicates the force required to break the material; and elongation at break, which shows the material's stretchability before failure (Chen et al., 2020). For food packaging, the permeability of the material to gases like water vapor, oxygen, and carbon dioxide is essential (Siracusa, 2012). These permeability characteristics are crucial for maintaining moisture balance, protecting against microbial growth, preventing food oxidation, and ensuring bacteriostatic effects (Baschetti and Minelli, 2020). Polyhydroxyalkanoates (PHAs) offer a key advantage over conventional plastics due to their biodegradability (Meereboer et al., 2020). Several bacterial strains can break down PHAs through the action of PHA depolymerase enzymes, making their disposal environmentally friendly (Muhammadi et al., 2015). However, there are challenges associated with using PHAs for food packaging, including thermal degradation, the potential leaching of polymer additives into food, interactions between packaging and contents, and relatively high production costs (Kumar et al., 2020). The major limitations and performance challenges of PHAs in food packaging applications are summarized in Table 6.

Numerous studies, including those by Kourmentza et al. (2017), have highlighted two significant drawbacks of PHA in packaging applications: odor and high production costs. These residuals, which are derived from cell walls, can create noticeable odors in the final PHA material, complicating

Table 6 Challenges and prospects of PHAs.

Aspect	Challenges and Solutions
PHA Production Cost	– High costs due to raw material expenses required to support bacterial growth. – Limited feedstocks which may be used for food sources. – Limited production efficiency and scalability. – Unknown environmental impact of use of engineered microorganisms for fermentation and its associated cost increase.
Quality of PHA	– Variability in quality and uniformity when produced in mixed cultures. – Often undesirable smells, colors, and impurities.
Biodegradability	– Various biodegradability up on environmental conditions. – Difficulty in defining the global standard for biodegradability due to geological and environmental diversity. – Difficulty in reuse in the view of the technical cycle of circular economy.
Mechanical Properties	– Challenges in achieving consistent crystallization and mechanical stability. – Difficulty in enhancing elongation at break without compromising other properties.
Barrier Properties	– Medium levels of gas and water vapor barrier properties which are crucial for a long-term shelf life of product.
Thermal Stability	– Relatively low thermal deformation temperature which is crucial for food and health care applications. – Relatively low thermal decomposition temperature during manufacturing process.
Blends and Composites	– Balancing cost reduction with maintaining barrier properties and biodegradability. – Ensuring compatibility with other biodegradable polymers in blends.
Blends with Natural Additives	– Sensitivity to moisture during processing. – Challenges in drying natural additives and achieving compatibility with PHA.

its use in packaging for odor-sensitive advanced purification processes, such as chemical treatments and high-pressure extraction, have been proposed to reduce impurities in PHA, enhancing its suitability for consumer goods packaging (Kourmentza et al., 2020).

Table 7 PHA in packaging applicationIn this context, PHA has proven effective in packaging applications, particularly when blended with other polymers to enhance mechanical and barrier properties, allowing for expanded use in items like perishable foods. In preserving the shelf life of beverages, factors such as oxidation of nutrients and flavor, microbial growth, and pigment stability are key, especially for carbonated drinks, where carbonation loss is also a concern. For acidic beverages, packaging materials must withstand acidic environments; PHB shows a medium oxygen transmission rate and good water resistance, making it ideal for such applications. Using PHB as a coating over PLA enhances these barrier properties, creating robust bio-based packaging material for beverages, and 100 precent PHB-based materials are also viable options. Paperboard coated with starch, PHB or PLA has shown potential in reinforcing moisture and oxygen barrier functions, making it suitable for beverage packaging (Stublić et al., 2024). Table 7 presents applied cases of PHA in food packaging, whereas Fig. 6 provides an overview of its broader application spectrum.

PHA Application	Material Property Changes	Improvements/Key Findings	References
PHB-PLA blend for food packaging	Increased miscibility, mechanical strength, and flexibility	Improved processability, flexibility, and composting suitability	Arrieta et al. (2017)
PHA blends for thermal properties enhancement	Enhanced thermal stability and processability	Improved mechanical strength and heat resistance	Jordá-Reolid et al. (2022)
Blending PHAs with biodegradable polymers	improvement in mechanical properties, better gas barrier performance	Higher mechanical strength and gas barrier properties for food packaging	Stublić et al. (2024)
Biodegradable food packaging using PHA produced from agrifood waste.	Enhanced thermal and chemical stability.	Suitable for long-term food storage and sustainable packaging	Atarés et al. (2024)

Continued

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PHA Application	Material Property Changes	Improvements/Key Findings	References
PHA-based films with cellulose	Improved gas barrier properties, higher crystallinity	Cellulose addition improves gas barrier and mechanical properties	Bhardwaj et al. (2014)
PHA-based films with cellulose nanofibers	Enhanced gas barrier properties and crystallinity	Improved gas permeability and mechanical properties suitable for food packaging applications	Fabra et al. (2016)
PHA-PLA composites for packaging	Enhanced thermal stability and mechanical properties	Improved flexibility, durability, and environmental suitability for packaging	Naser et al. (2021)
Multilayer films with PHA and cellulose nanocrystals	Improved gas barrier properties and mechanical strength	High oxygen barrier performance suitable for food packaging applications	Melendez-Rodriguez et al. (2021)

PHA-Starch blends and composites for bioplastics	Enhanced biodegradability and mechanical properties	Improved processability and suitability for sustainable packaging applications	Jayarathna et al. (2022)
Eugenol-loaded PHA-based multilayer antimicrobial food packaging	Enhanced antimicrobial activity and mechanical properties	Eugenol-containing PHA monolayers improve food preservation and shelf life in packaging applications	Figueroa-Lopez et al. (2020)
PHA-based biomaterials for sustainable food packaging	Enhanced biodegradability, mechanical strength, and thermal stability	Unlocking the potential of PHAs for environmentally friendly and high-performance food packaging	Yeo et al. (2024)
PHA/PLA blends for transparent and gas barrier films	Improved transparency, gas barrier properties, and biodegradability	Fully bio-based and compostable films suitable for sustainable packaging applications	Aversa et al. (2023)
PHB/PLA-based biodegradable active packaging for salmon	Enhanced mechanical strength, gas barrier properties, and biodegradability	Improved shelf life and quality of salmon through the use of bio-based active packaging	Ma et al. (2018)
PHA-based electrospun materials for food packaging	Enhanced biodegradability and mechanical performance	PHA electrospun fibers offer sustainable and effective solutions for food packaging applications	Patiño Vidal et al. (2024)

Cost is another major challenge to the wide adoption of PHA in packaging applications. High production expenses stem mainly from the cost of raw materials used to sustain microbial growth, which in turn impacts the price of the final product. Many researchers, including González-Rojo et al. (2024), emphasize that the high cost of feedstock and downstream processing, combined with the need for pure cultures, are substantial contributors to PHA's overall expense. To solve this concern, many scientists and stakeholders across the world are currently investing on production of PHAs by diversifying the type of feedstocks or utilizing food wastes or agricultural by-products for production of PHAs (Chen et al., 2020; Dietrich et al., 2017).

The biocompatibility of PHA has made it valuable for high-margin applications in the pharmaceutical industry, where such costs can be more easily offset due to higher profit margins (Koller, 2018). In pharmaceuticals, PHA's compatibility with biological systems is a key advantage, supporting its use in products where environmental and safety standards are particularly stringent (Kalia et al., 2023). In the broader packaging market, the feasibility of using PHA is influenced by manufacturers' cost-benefit analysis and the potential for a sustainable market presence (de Castro et al., 2022). In the broader packaging market, the feasibility of using PHA is influenced by manufacturers' cost-benefit analysis and the potential for a sustainable market presence. While more expensive than traditional plastics, PHA's favorable properties—including printability, resistance to oils and greases, heat sealability, and its ability to act as an effective barrier to flavors and odors—make it a compelling choice for food packaging, aligning with industry needs for functional, eco-friendly materials (Sharma et al., 2021). These characteristics support its competitiveness against conventional plastic alternatives and position it as a valuable option for high-performance, biobased packaging solutions.

Specifically, certain medium-chain-length PHAs (mcl-PHAs) offer a versatile range of applications in sustainable and biodegradable materials, particularly suitable for single-use items and food packaging due to their physical properties (Muneer et al., 2020). mcl-PHAs demonstrate favorable barrier characteristics, similar to polypropylene (PP), with low water vapor permeability, an essential property for packaging applications requiring moisture resistance. Such properties enhance the utility of mcl-PHAs in applications like disposable bags, medical devices, cheese coverings and biodegradable containers (Saravanan et al., 2022).

The mechanical properties of PHAs are adaptable, ranging from flexible to semi-rigid, influenced by the polymer's molecular composition

and structure (Tjong, 2006). For instance, while poly(3-hydroxybutyrate) (PHB) exhibits a high modulus and brittleness, its copolymerization with 3-hydroxyvalerate (3HV) reduces its glass transition temperature (T_g) and melting temperature (T_m) due to the lower crystallinity induced by the increased irregularity in their chemical composition (Abdelwahab et al., 2012), providing improved flexibility (Bossu et al., 2021). Consequently, copolymers like PHBV (with varying 3HV content) exhibit enhanced elongation at break, making them more suitable for flexible packaging applications compared to the stiffer PHB (Rivera-Brisoand Serrano-Aroca, 2018). Similar to their mechanical properties, PHAs exhibit a broad spectrum of thermal properties, which are influenced by their structural diversity. Thermal properties of mcl-PHAs also vary, with PHB typically having a T_g near 1 °C and a T_m around 170 °C, whereas PHBV copolymers can have T_g and T_m values significantly modified by their compositional makeup (Lovera et al., 2007). The degree of crystallinity in PHAs varies widely, often between 50 precent–70 precent, affecting their processing and end-use performance (Kaniuk and Stachewicz, 2021). These adaptable mechanical and thermal properties enable PHAs to serve as potential replacements for conventional polymers like polypropylene (PP), with mcl-PHAs being positioned as an eco-friendly alternative for applications demanding flexibility and durability (Jo et al., 2018).

In terms of commercial viability and market demand, Earthfirst Films (USA) produces a line of biodegradable and compostable packaging films made from biopolymers, including PHA and PLA, tailored for sectors such as food, beverage, and consumer goods. These films are developed to align with sustainability objectives, offering composability in both home and industrial settings while delivering effective barrier properties for packaging applications, especially for perishable items. By incorporating materials like fillers to improve mechanical integrity and reduce costs, plasticizers for added flexibility, and stabilizers for protection against UV and oxidation, Earthfirst's PHA-based films are designed for diverse packaging requirements. Fig. 7 illustrates Earthfirst's PHA film products and technologies.

Concerns remain regarding materials utilized in food packaging and their possible interactions with foods, especially in cases where plastics that have been in contact with food are reused (Dey et al., 2021). Additionally, the environmental impact of conventional plastics, due to their prolonged degradation times and reliance on non-renewable resources, has prompted increasing global interest in adopting biodegradable alternatives (Moshood et al., 2022). The shift to biodegradable plastics, especially in packaging, is viewed as a

Fig. 7 Earthfirst Company's films: technology and products.

viable strategy to reduce the environmental footprint of petroleum-derived plastics (Ferreira-Filipe et al., 2021). However, recycling traditional plastics for food packaging remains challenging due to contamination risks, which limits their reusability and often makes recycling economically unfeasible (Arvanitoyannis and Bosnea, 2001). Recycled materials can only be used in food packaging if they comply with strict regulatory standards, leading to high costs and extended processing times. Despite numerous recycling initiatives, unified and efficient recycling programs are still lacking in certain regions (Da Costa et al., 2020).

Food packaging involves the integration of technological innovations, scientific methodologies, and design aimed at safely enclosing products, facilitating their secure transport and distribution, and maintaining product integrity at minimal cost to the consumer (Versino et al., 2023). Recent studies have widely studied bio-based plastics and biopolymers, particularly for food packaging applications. Replacing petroleum-based packaging with bio-based containers and films offers a sustainable alternative, combining an eco-friendly approach with improved performance. A sustainable economy focuses on utilizing materials from biomass for packaging applications. It is crucial to focus on barrier properties, specifically on biobased materials used in food packaging (Wu et al., 2021). Hydrophilic polymers often exhibit insufficient moisture resistance, leading to elevated water vapor transmission through packaging materials. This can degrade food quality, reduce shelf life, elevate costs, and ultimately contribute to increased waste. PHA, PBAT, PBS and PLA are commonly and widely utilized as bio-based biodegradable bioplastics. The barrier properties of bio-based bioplastic films can be enhanced by incorporating fillers such as nanofibers (Ahn et al., 2024).

PHB provides superior light-blocking capabilities in both ultraviolet regions and visible compared to PLA. The properties of PHA can be enhanced by surface modification or by blending it with other polymers, enzymes, and inorganic compounds. PHA has been developed as a sustainable material for a wide range of packaging applications, including shopping bags, food containers, compostable bags, and more. Companies such as CJ Biomaterials and Earthfirst Films by PSI have introduced PHA-based films suitable for flexible packaging, home compostable bags, and various disposable items. These films offer unique environmental benefits, including reduced carbon footprint and biodegradability, making them ideal for single-use products and applications requiring sustainable end-of-life options.

4. Conclusion

Polyhydroxyalkanoates (PHAs) present one of the promising solutions to the environmental issues caused by conventional plastics, particularly in packaging where biodegradable alternatives are in high demand for modern lifestyle societies. PHAs produce very low greenhouse gas emissions with energy requirements. It also provides unique properties, such as natural degradation in various environments, derived from renewable resources. It aligns with sustainability goals, although it still faces challenges due to high production costs and performance limitations. While PHAs generally lack the mechanical and barrier properties of traditional plastics, the recent innovations in biomanufacturing processes, diversified feedstocks, and application processes, such as bio-nanocomposites, copolymer blending, and multilayer structural designs with other materials, have significantly improved these attributes, enhancing their mechanical strength, flexibility, and moisture resistance. Additionally, incorporating bioactive compounds into PHA films has the potential to extend the shelf life of packaged foods and reducing waste. Despite these advancements, further research is needed to optimize production efficiency and ensure consistent quality. Collaborative efforts among diverse global stakeholders, including but not limited to customers, non-profit organizations (NGOs), governments, industry, and academia, will be crucial to addressing these economic and technical barriers, and supporting PHAs' transition to mainstream applications. While PHAs may not yet be a complete substitute for conventional plastics, their eco-friendliness and adaptability position them as valuable materials for reducing plastic pollution and advancing a circular economy in packaging.

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