Current Applied Science and Technology e-ISSN: 2586-9396

Curr. Appl. Sci. Technol. 2025, Vol. 25 (No. 5), e0263545

Review article

Microbial Plastics: Structure, Engineering, Applications, Degradation, and Future Scope of Sustainable Bioplastics

Tejaswini Muralikrishnan[1], Sneha Unnikrishnan[2] and Karthikeyan Ramalingam[1]*

[1,2]B.S. Abdur Rahman Crescent Institute of Science and Technology, Chennai, India
[2]Post doctoral researcher, University College Dublin, Ireland

Received: 3 June 2024, Revised: 28 August 2024, Accepted: 17 January 2025, Published: 27 March 2025

Abstract

The rampant usage of non-biodegradable materials and in particular conventional plastics hampers the ecological balance and poses environmental hazards. Conventional plastics persist in the environment for long periods due to their resistance to degradation, contributing to pollution and health risks. There is an urgent need for sustainable and biodegradable alternatives to mitigate these issues. Polyhydroxyalkanoate (PHA) is gaining attraction as a potential replacement for non-biodegradable polymers due to rising awareness of global environmental concerns. Microbial plastics have physicochemical properties like petrochemical plastics. These biopolymers usually comprise hydroxy-acyl-CoA derivatives and are synthesized from fatty acid metabolic pathways. Microbial plastics are present as storage granules that accumulate intracellularly in microorganisms. However, the physicochemical properties of these bioplastics vary depending on the microbial origin and synthesis mechanism. Numerous multidisciplinary scientific approaches have been used to elucidate various aspects of microbial bioplastics. PHA has promising potential applications in a variety of industries as well as in the medical field. However, the high production cost of PHA has been a significant disadvantage. Therefore, scientists have recently developed transgenic plants containing microbial PHA biosynthesis genes to lower the cost of the polymer. Further effort is required in this regard to increase the production of bioplastics for the successful replacement of non-biodegradable plastics. This review seeks to address these challenges by examining microbial bioplastic synthesis and degradation mechanisms, particularly PHAs, and exploring their industrial and therapeutic applications. It aims to provide insights into current limitations and propose strategies for overcoming them to establish microbial bioplastics as a viable and sustainable alternative to conventional plastics.

Keywords: microbial bioplastics; microorganisms; biopolymers; polyhydroxyalkanoates; therapeutic applications; limitations

*Corresponding author: E-mail: karthikeyan.sls@crescent.education
https://doi.org/10.55003/cast.2025.263545
Copyright © 2025 by King Mongkut's Institute of Technology Ladkrabang, Thailand. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

1. Introduction

Biomaterials are natural materials that are synthesized and catabolized by various organisms and these bioplastics offer a broad range of biotechnological applications. These bioplastics can be assimilated by many species (biopolymer) and have no toxic effects on the host (biocompatible), providing them a significant advantage over other conventional synthetic products. Bioplastics are a type of biomaterial that was first produced in 1926 from the bacterium *Bacillus megaterium*. Bioplastics, as the name suggests, are made from organic and renewable sources of biomass like agro-wastes, plant residues, woodchips, starch, or microbes in contrast to conventional plastics which are generally made of non-renewable petrochemical products (Abe et al., 2010). Bioplastics, which are biopolymers, are used in various industries including food packaging, agriculture, medicine, textiles, automobiles, biomedical applications (Aburas, 2016).

Microorganisms can store polyhydroxyalkanoate (PHA) in their cytoplasm up to 97% of their cell dry weights (CDWs) (Muhammadi et al., 2015). The necessary circumstances to increase PHA accumulation in bacterial cytoplasm are excess amounts of carbon sources combined with nutritional limitations such as nitrogen or phosphorous, and pH alterations (Shah et al., 2008). PHA can be produced from a wide range of renewable resources by a wide range of microorganisms, including gram-positive and gram-negative bacteria, many of which have been found to collect PHAs both in the presence and absence of oxygen (Hermann-Krauss et al., 2013; Anjum et al., 2016).

Bioplastic degradation depends on various factors like biomass source, processing, additives, and the chemicals involved. Moreover, the use of bioplastics can help cut down the amount of energy being consumed during plastic production and can result in lower emissions of greenhouse gases, serving as a better alternative to conventional plastics. However, bioplastics may not be taken to be the best alternative as they also have their share of drawbacks such as lag in terms of durability, malleability, and practicality of use. The use of bioplastics instead of regular plastics makes possible the potential reduction in waste generation and pollution resulting in a sustainable and green future (Atiwesh et al., 2021).

This review describes the fundamentals of bioplastics with special emphasis on PHAs and the production from both pure and mixed microbial cultures. It also highlights the microbial accumulation and degradation of PHAs. Further, bioplastic applications have been discussed.

2. Microorganisms and Bioplastics

Microorganisms serve as cell factories in the synthesis of bioplastics. These polyesters are produced by a variety of microbes that have been cultivated under diverse nutrient and environmental conditions (Adane & Muleta, 2011). Microbial biopolymers are typically lipophilic in nature and water-insoluble. They aggregate as reserve materials in the form of mobile, amorphous, or liquid granules.

2.1 Polyhydroxyalkanoates

Polyhydroxyalkanoates (PHAs) are the most popular forms of microbial bioplastics. PHAs are polyesters that have adjustable mechanical and physical characteristics. PHAs have a

high rate of biodegradation and biocompatibility. PHAs are a promising bioplastic alternative to traditional petrochemical plastics (Ahuja et al., 2024).

As storage compounds, polyhydroxyalkanoates can accumulate up to 80% of dry bacterial biomass. Poly-3-hydroxybutyrate (PHB) and polyhydroxy valerate (PHV) are the two most important PHAs, with monomer formulas of (-OCH(CH3)-CH2-C(O)- and (-OCH (CH2CH3)-CH2-C(O)-, respectively (Adhikari et al., 2016). Depending on the microorganism involved in the synthesis of bioplastics, the physicochemical properties, structure of macromolecules, monomeric composition, size, and the number of granules vary (Amini et al., 2019). Besides, microorganisms which synthesize bioplastics, are also predominant degraders of bioplastics. Aerobes, anaerobes, photosynthetic bacteria, archaebacteria, and lower eukaryotic microorganisms are among the microorganisms involved in the biodegradation and catabolism of bioplastics (Anderson & Dawes, 1990).

2.2 PHA accumulation

Both prokaryotic and eukaryotic organisms serve as suitable sources for bioplastic synthesis. Metabolic engineering and structural studies serve as promising options in selecting the right microbial candidates for bioplastic synthesis. To achieve greater control over the quality, quantity, and economics of microbial bioplastic production, various methodologies and different sources like natural isolates and recombinant organisms have been explored (Barnard & Sanders, 1989).

PHA accumulation occurs because of growth imbalance caused by nutrient limitations. PHAs are produced by a diverse range of microorganisms. Table 1 presents the different bacteria, algae, and transgenic plants involved in the synthesis of bioplastics along with the type of bioplastics synthesized. Several bacterial strains use the polymer as a source of carbon as well as an energy source under starvation. Because of their lower solubility and higher molecular weight, PHAs are an ideal carbon-energy storage material and therefore have no impact on bacterial cell's osmotic pressure (Lu et al., 2023). It should be noted that bacteria such as *Alcaligenes latus* (Beun et al., 2002) and a mutant strain of *Azotobacter vinelandii* (Blinková & Boturová, 2017) were shown to accumulate PHA under nutrient limitations. Yet limitation in nitrogen was shown to increase PHA synthesis in *A. latus*, which suggested that the growth during PHA accumulation is inefficient (Boyandin et al., 2013).

PHAs are produced using both pure and mixed microbial cultures (MMC); however, owing to high storage capacity and cell density, the use of pure cultures led to the highest process yields and PHA productivities (Brandl et al., 2005). Mixed cultures are advantageous as they do not require aseptic conditions and are more adaptable to complex substrates such as agricultural waste than pure cultures (Lü, 2007). Mixed cultures are more economical for PHA production. However, mixed cultures must be enriched with PHA-accumulating microorganisms before PHA production, and the yield is lower (Chee et., 2010). Important parameters to be optimized for PHA production are enrichment conditions, culture stability, suitable feedstock, and supplement. Figure 1 shows bacterium-producing PHAs and general structure of PHAs.

Organic waste can be used as a feedstock in the production of PHAs. However, for organic wastes to be viable feedstocks, they must be relatively concentrated, easily degradable, and abundantly available. PHA bioplastics derived from such wastes are now being considered for commercialization (Chen & Wu 2005). The use of malt wastes from beer breweries as carbon sources for the microbial synthesis of bioplastics has been

Table 1. Overview of microorganisms utilized in the synthesis of bioplastics.

Sl. No.	Microorganisms	Synthesized Bioplastics	Source	Bioplastic content (wt%)	Reference
Bacteria					
1.	*Aeromonas hydrophila*	MCL-PHAs	Lauric acid	19.5	(Hu et al., 2005)
2.	*Bacillus megaterium*	PHB	Cheese whey	64	(El-malek et al., 2020)
3.	*Pseudomonas putida* KT2440	PHA	Stearic acid	36.4	(Ruiz et al., 2019)
4.	*Serratia* sp. ISTVKRI	PHA	Volatile fatty acid	51	(Reddy & Mohan, 2015)
5.	*Burkholderia xenovorans*	PHA	Palm oil derivative, fatty acid	22-70	(Fukui et al., 1998)
6.	*Pseudomonas aeruginosa*	MCL-PHAs	Palm oil	39	(Giosafatto et al., 2020)
7.	*Plasticicumulans acidivorans*	PHA	wastewater	70	(Gonzalez-Gutierrez et al., 2010)
8.	*Comamonas testosteroni*	PHA	Mustard oil, olive oil, castor oil, sesame oil, groundnut oil	79-88	(Grothe et al., 1999)
9.	*Cupriavidus necator, Cupriavidus necator* H16	PHB9	Olive oil, sunflower oil, crude palm oil	60-90	(Hempel et al., 2011)
10.	*Pseudomonas cepacia*	PHB	Xylose, lactose	50	(Hrabak, 1992)
11.	*Alcaligenes latus*	PHB	Sugarbeet juice	38	(Wang et al., 2013)
12.	*Bacillus megaterium*	PHB	Beet molasses, dates	50	(Ishii et al., 2008)
13.	*Halomonas halophila*	PHB	Cheese whey hydrolysate	82	(Kucera et al., 2018)
14.	*Bacillus cereus*	PHB	Dirout channel	28.799	(Hamdy et al., 2022)
15.	*Burkholderia sacchari*	PHB	Wheat straw hydrolysate	60	(Cesario et al., 2014)
16.	*Rhizobium viciae, R. meliloti, Bradyrhizobium japonicum*	PHB	Volatile fatty acid	62.43	(Jung et al., 2018)
17.	Recombinant *Escherichia coli* JM109	PHB	Soybean oil	6	(Jia et al., 2013)
Algae					
18	*Spiruline plantensis*	PHB	Kosaric medium	10	(Jau et al., 2018)
19	*Nostoc muscorum*	P(3HB)	Acetate	45-60	(Sharma et al., 2007)
20	*Synechocystis* sp. PCC6803	P(3HB)	Fructose	38	(Panda & Mallick, 2007)
21	*Synechococcus* MA19	P(3HB)	CO_2	7-50	(Miyake et al., 1997)
22	*Oscillatoria limosa*	P(3HV)	CO_2/Acetate	6	(Stal, 1992)
Transgenic plant					
23	*Arabidopsis thaliana*	PHB	Plastid	14	(Kourtz et al., 2007)
24	*Camelina sativa*	PHB	Seeds	15	(Malik et al., 2015)
25	*Saccharum officinarum*	PHB	Plastid	11.8	(McQualter et al., 2014)
26	*Populus* sp.	PHB	Plastid	3.69	(Dalton et al., 2012)

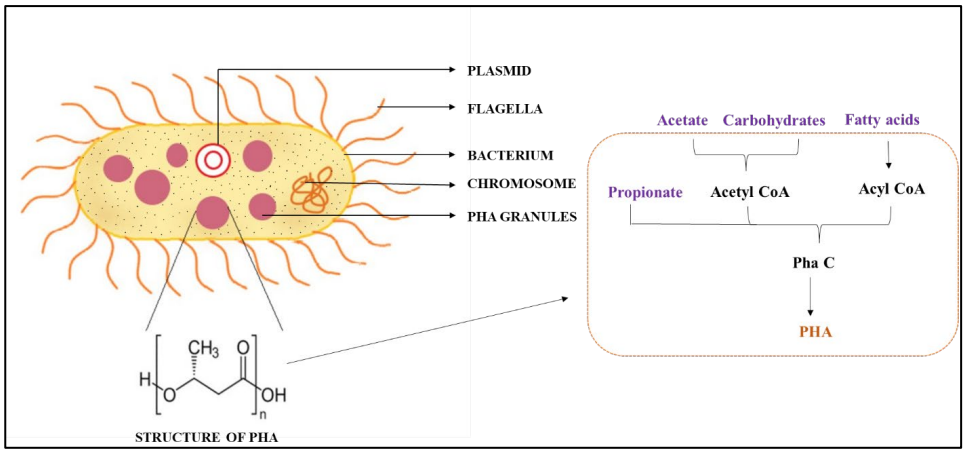

Figure 1. General structure of PHAs (polyhydroxyalkanoates), their localization in bacteria, and the corresponding biosynthesis

investigated and this has led to the eventual use of wastewater from food industries as a nutrient source for microorganisms in the synthesis of bioplastics. Using *A. latus* DSM 1124, specific polymer production yield was amplified to 70% polymer cell and 32 g/L cell dry weight (Wong et al., 2004). Besides industrial waste, cheese whey was also used as a carbon substrate for PHA synthesis. Cheese whey fermentation is important because it generates precursors of PHAs and modifies PHA composition based on the type of organic acid produced (Colombo et al., 2016). The different substrates used for PHA production alter its rate of production and yield. Polyhydroxybutyrate (PHB) is a type of PHA and is a biodegradable biopolymer synthesized by microorganisms as intracellular granules under nutrient-limited conditions with excess carbon. Ethanol leads to a higher yield of PHB when compared to glucose (McAdam et al., 2020). An experiment by Yu et al. (1999) revealed that different polyhydroxyalkanoate copolymers with distinct polymer properties could be produced using various types of food wastes as the source of carbon. The highest amount of PHB was accumulated by *Pseudodonghicola xiamenensis*, which was identified using 16S rRNA gene analyses. The use of 4 % (w/v) date syrup produced a PHA concentration of 15.54 g/L and 38.85 % PHB yield, with a productivity rate of 0.162 g/L/h. Mostafa et al. (2020) were the first to show that *P. xiamenensis* produces a bioplastic, implying that the natural habitats of the Red Sea could serve as a potential biological reservoir for novel bioplastic-producing bacteria. Some *Pseudomonas* strains can also accumulate monomers like 3HB from a variety of carbon substrates. On genetic analysis, it was found that these *Pseudomonas* strains possessed a minimum of two distinct polymerizing enzymes with distinct substrate specificities (Dawes & Senior 1973).

2.3 Metabolic engineering for PHA production

For the natural selection and isolation of bioplastic producers, recombinant technology serves as a promising approach. This promising approach involves genetically engineering microorganisms to introduce new production pathways that facilitate bioplastic synthesis (Chacón et al., 2024). However, this necessitates the expression of multiple genes as well as PHA production optimization in the host (Khatami et al., 2021). Figure 2 represents the

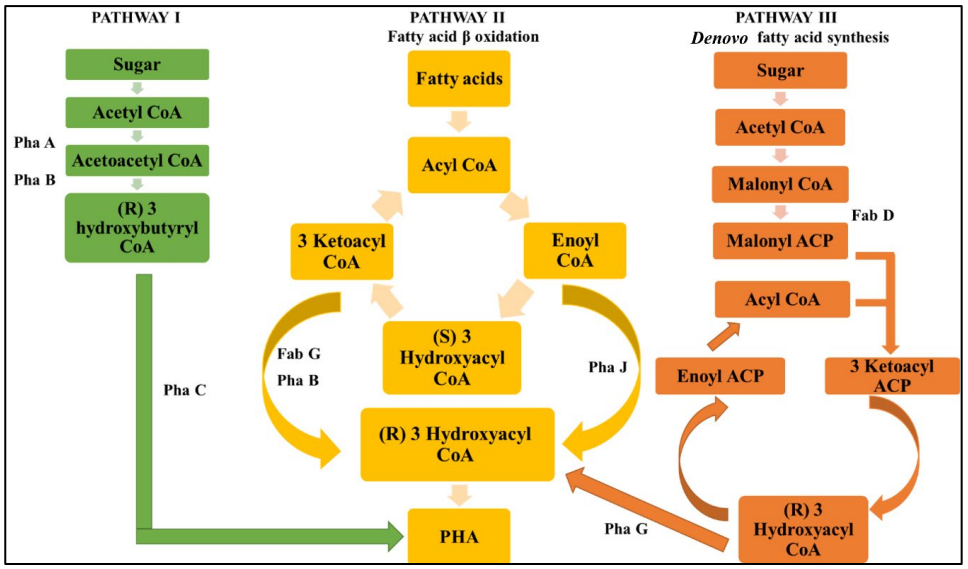

Figure 2. Metabolic pathways for PHA biosynthesis Pha A: β ketothiolase, Pha B: acetoacetyl Coenzyme A reductase, Pha C: PHA synthase, Pha G: acyl-ACP-CoA transacylase, Pha J: enoyl C, Fab G: 3ketoacyl acyl carrier protein reductase

different metabolic pathways involved in PHA biosynthesis. The temperature, pH, oxygen levels, and bioreactor conditions (agitation speed, bioreactor type, scale) need to be monitored for effective bioplastic production. Genetic engineering techniques have been used to manipulate PHA biosynthesis since the entire operon which controls the biosynthesis of P(3HB) in *R. eutropha* was cloned (Matsusaki et al., 1998), and this technique enables gene expression in various organisms. *Eschericha coli* is an ideal model organism for heterologous gene expression, since the physiology, biochemistry, and genetics of *E. coli* have all been extensively studied. As a result, *E. coli* strains are genetically modified to produce PHB. On introducing the PHA CAB operon from *R. eutropha*, recombinant *E. coli* became a PHA producer. The yeast, *Saccharomyces cerevisiae* is a prominent eukaryotic system that has been used to produce PHA. Incorporating the PHA synthase gene of *R. eutropha* itself could cause the cytoplasm to accumulate smaller amounts of PHA (Maestro & Sanz, 2017). The monomer-supplying pathway in *S. cerevisiae* needs to be improved to further elevate the P(3HB) production capacity (Dias et al., 2006). According to Hempel et al. (2011), the introduction of the bacterial PHB pathway of *R. eutropha* H16 into the diatom *Phaeodactylum tricornutum* was first reported to be possible for the PHB production in a microalgal system. PHB levels as high as 10.6% of algal dry weight were obtained after the bacterial enzymes were expressed, and this research demonstrated the tremendous potential of microalgae such as the diatom *P. tricornutum* in bioplastic synthesis. A successful method for transforming β-butyrolactone into poly(-hydroxybutyrate) (PHB), a promising biodegradable polyester, involves ring-opening polymerization (Yang et al., 2021). The synthesis of PHA-PEG from β butyrolactone mediated by metal complexes has received a lot of attention recently and has made significant progress (Adamus et al., 2012). The high degree of (stereo)control that some of these catalysts demonstrate under favorable circumstances is a key topic of interest (Ajellal et al., 2010; Brulé et al., 2011). The potential for bioplastic and

thermoplastic blend production in microalgal biomass species of *Chlorella vulgaris*, a green alga, and *Spirulina platensis*, a cyanobacterium, was investigated. This thermomechanical polymerization study of microalgae protein biomass revealed that *Chlorella* demonstrated better bioplastic behavior than *Spirulina* microalgae, while *Spirulina* demonstrated better blend performance (Ding et al., 2016). There is considerable progress in recombinant hosts. However, the barriers to obtaining large amounts of PHA at a lower cost are yet to be overcome. The relationship between microbial mechanisms and environmental conditions is crucial for effective microbial bioplastic production. Controlled fermentation helps maintain optimal conditions for microbial growth and PHA synthesis. Genetic engineering of microbial strains improves bioplastic yield. Process optimization with advanced bioreactor designs and real-time monitoring systems can ensure high-quality production of bioplastics. The use of waste materials or renewable resources as substrates decreases the production costs and increases the sustainability of bioplastic production (Ali et al., 2023).

3. Microbial Degradation of Bioplastics

Biodegradation refers to degradation mediated by microorganisms. Besides the synthesis of bioplastics, microorganisms degrade bioplastics in various ecosystems. Aerobes, anaerobes, photosynthetic bacteria, archaebacteria, and lower eukaryotic microorganisms are predominantly involved in the catabolism and biodegradation of bioplastics (Kumbar et al., 2014). It has been discovered that over 150 microbial species, including bacteria, actinomycetes, and fungi, are capable of decomposing various types of bioplastics (Swetha et al., 2024). In general, bacteria and fungi degrade bioplastics because these microorganisms are the most prevalent in every ecosystem. Sewage sludge, leachate from landfills, waste compost, soil, sand, pond, and lake sediment from water bodies are abundant with degradative microorganisms. Many studies have been conducted to identify microorganisms capable of degrading biopolymers (Laborit, 1964).

3.1 Microbes involved in bioplastic degradation

Bacteria were the most common microorganisms isolated from aquatic habitats, including marine and river water, that were capable of bioplastic degradation. Bioplastics primarily demonstrated high degradability in soil and compost environments. Hence, the biodegradability of bioplastics in soil and compost environments has been studied extensively (Lee et al., 2005). Bacterial and fungal species isolated from soil, compost, seawater, river water, and other environments and their ability to utilize bioplastics in their end products were assessed. In a laboratory test, a clear zone formation was observed encircling microbial growth in an agar plate added with bioplastic as the sole carbon source and the diameter for the zone clearance is indicative of the bioplastic degradation mediated by bacteria or fungi (Lee, 1996). High levels of PHB-degrading microbes were found in soil compost, soils, and farm hay. Soil from agricultural land was investigated as a potential source of polylactic acid (PLA) degraders, due to its high organic content (Penkhrue et al., 2015). This study revealed that 16 of 79 soil microorganisms isolated by the clear zone method from agricultural soil could degrade PLA, polycaprolactone (PCL), and polybutylene succinate (PBS) bioplastics, and *Amycolatopsis sp.* strain SCM MK2 4 exhibited the greatest enzyme action towards PLA and PCL bioplastics.

The role of fungi in degradation is also being explored. According to the study by Ishii et al. (2008), over 20 filamentous fungal strains isolated from different soil and

freshwater resulted in clear zones on agar plates containing poly(3-hydroxybutyrate) (P3HB). Table 2 presents the different microorganisms involved in the degradation of bioplastics along with the type of bioplastic degraded by the microorganisms. *Fusarium oxysporium*, for example, degrades bioplastics while also acting as a phytopathogen and the increased population of such fungal strains during biodegradation process may hamper ecological balance. It was reported that an increased prevalence of *Fusarium oxysporium* or other phytopathogens in agricultural soil infected crops and reduced yields. However, such environmental issues can be addressed by developing appropriate guidelines for bioplastic production, application, and degradation. Bioplastic biodegradation is enhanced by the co-culture of various microorganisms. In co-culturing, the bioplastic intermediates released by the primary microorganism are utilized by the other microorganisms aiding in the biodegradation. Co-inoculation of fungi and bacteria can accelerate bioplastic degradation. The combination of *Fusarium solani* WF-6 and *Stenotrophomonas maltophilia* YB-6 increased the biodegradation of polybutylene succinate, even though the YB-6 strain was incapable of degrading the PBS independently (Lizarraga-Valderrama et al., 2015). Another study found that when *Streptomyces thermonitrificans* PDS-1 was co-cultured with *Bacillus licheniformis* HA1, PCL degradation was higher (Lu et al., 2011). The co-cultivation of *Sphinogomonas paucimobilis* sp. with hydrolyzate degraders significantly enhanced polymer (p-dioxanone) degradation. However, it is to be noted that microorganisms use enzymes to catalyze the biodegradation of biopolymers. Enzymes, both intracellular and extracellular, are responsible for the enzymatic degradation of bioplastics. Researchers all over the world have been looking into the mechanisms of biodegradation of various bioplastics such as PLA, PHAs, PCL, PBS, and others. Furthermore, bioplastic-degrading enzymes are isolated from bacteria and fungi and characterized using molecular tools and techniques (Luengo et al., 2003).

Table 2. Overview of microorganisms and their corresponding bioplastic degradation

Sl. No.	Degradative microorganisms	Degraded Bioplastics	Reference
1.	*Pseudomonas aeruginosa, Bacillus subtilis*	PHA	(Nelson et al., 1981)
2.	*Candida albicans, Fusarium oxysporum*	PHA	(Nelson et al., 1981)
3.	*Leptothrix sp, Pseudomonas putida, Variovorax* sp.	PHA	(Niaounakis, 2015)
4.	*Penicillium* sp., *Trichoderma pseudokoningii, Acremonium recifei., Cogronella* sp., *Paecilomyces lilacinus*	PHB	(Nigmatullin et al., 2015)
5.	*Enterobacter* sp., *Gracilibacillus* sp., *Bacillus* sp.	PHB	(Novikova et al., 2008)
6.	*Aspergillus niger*	PHB	(Obruca et al., 2009)
7.	*Penicillium* sp., *Aspergillus* sp.	PHB	(Oppermann-Sanio & Steinbüchel, 2002)
8.	*Cephalosporium sp., Gliocladium album, Eupenicillium* sp., *Gerronema postii, Cladosporium* sp.	PHB	(Page, 1989)
9.	*Pseudomonas lemoignei*	PHB	(Panith et al., 2016)
10.	*Burkholderia capacia, Streptomyces* sp., *Cupriavidus* sp., *Bacillus* sp., *Mycobacterium* sp., *Nocardiopsis* sp.	PHB	(Peng et al., 2012)

3.2 Enzymes involved in bioplastic biodegradation

As enzymes play an important role in the biodegradation of bioplastics, enzymes involved in bioplastic biodegradation were produced and included were esterase from *Comomonas acidivorans*, lipase from *Alcaligenes faecalis*, and serine hydrolase from *Pestalotiopsis microspora* (Ma et al., 2018). PHA/ PHB depolymerases derived from bioplastic-degrading microorganisms were analyzed (Mamelak, 1989; Madison & Huisman, 1999). Numerous studies on depolymerase purification from bioplastic-degrading microorganisms have been conducted. *Streptomyces thermoviolaceus* subsp. *Thermoviolaceus* 76T-2 was used to isolate the depolymerase enzyme responsible for PCL degradation (Marang et al., 2014), *Rhodospirillum rubrum* synthesizes depolymerase intracellularly. This intracellular depolymerase was researched as a PHB-degrading enzyme (Mergaert & Swings, 1996).

The degradation of three types of bioplastics, as well as their effects on microbial biomass and diversity in the soil environment, were investigated. PBS-starch was buried in three types of soils that differed in bacterial biomass (7.5/106, 7.5/107, and 7.5/108 cells/g soil) to investigate the effect of bacterial biomass in soil on the biodegradability of bioplastics. The rate of bioplastic degradation was accelerated, accompanied by an increase in bacterial biomass in the soil. The results of 16S rDNA (ribosomal deoxyribonucleic acid) PCR-DGGE (polymerase chain reaction/denaturing gradient gel electrophoresis) analysis revealed that the bacterial diversity was unaffected by the degradation of bioplastics. This study also revealed that the bioplastic degradation rate in soil was dependent on the bioplastic composition (Müller & Seebach, 1993).

3.3 Factors influencing bioplastic degradation

Besides microorganisms, various factors influence degradation. Pressure, temperature, pH, incubation time, type of polymer and active cell concentration are some of the vital parameters that affect or regulate microbial degradation of polymers, as do other biological processes (Mostafa et al., 2020; Lu et al., 2023; Piyathilake et al., 2024). Several microbiological and ecological factors related to the location of polymers play an important role in their decomposition (Nadhman et al., 2012). The biodegradability of various bioplastics in the same local habitat was also found to vary significantly depending on the structure, composition, and inherent properties of biopolymers (Nakasaki et al., 2006).

4. Therapeutic Applications of Bioplastics

PHAs have become indispensable in a wide range of novel applications, including agricultural, industrial, medical, and therapeutic applications (Bano et al., 2024), and these applications are mentioned in Table 3. According to Chen & Wu (2005), the toxicity of various PHAs, including PHB, P4HB, PHBV, PHBHHX, and polyhydroxy octanoate (PHO), along with their degradation were analyzed. The non-toxicity and non-carcinogenicity of polymers make them an ideal candidate for nutritional or therapeutic applications. PHA, as a biomaterial, can interact with a biological system to direct a medical treatment with an appropriate host response (Ang et al., 2020). PHA has been studied for a variety of therapeutic applications, which include heart valves and nerve conduit tissue engineering (Reddy et al., 2003), vascular tissue engineering, bones, and cartilage (Reddy & Mohan 2015). PHA is also involved in drug delivery carrier materials (Sabarinathan et al., 2018) and PHAs were reported to be non-carcinogenic during long-term implantation (Sadat-Shojai et al., 2016). PHAs and their composites have been used in making bone marrow

Table 3. Different types of bioplastics involved in various industries along with their applications

Sl. No.	Industry	Used Bioplastics	Applications	Reference
1.	Agriculture	poly (4- hydroxybutyrate) [P(4HB)] and PLA/PHA-blends	Used in making agricultural nets	(Wang et al., 2010)
		PHA	Used for agricultural grow bags	(Ward et al., 2005)
		PHA, polylactic acid (PLA), polybutylene succinate, ethylene vinyl acetate	Mulch production	(Williams et al., 2013)
2.	Food packaging	PHB	film based packaging for food	(Wu, 2012)
3.	3Dimensions printing (3D)	PHA and PHB	Used as filler in 3D printing	(Yİlmaz & Beyatli, 2005)
4.	Wood plastic composite	PHB, PHBV	Incorporated in wood plastic composites	(Simó-Cabrera et al., 2021)
5.	Construction	PHA	Crude nanocomposite from bacterial biomass and PHAs are used for used for insulation walls and construction of walls and partitions	(Kucera et al., 2018)
6.	Cosmetics	PHA	Found to absorb and retain the oil and used in oil blotting films	(Sudesh et al., 2000)
7.	Personal hygiene	PHA	Used in the manufacture of diapers and other packaging materials	(Van Loosdrecht et al., 1997)
8.	Animal production	P(3HB)	Used as a biocontrol agent and antimicrobial agent	(Vaidya et al., 2019; Defoirdt et al., 2007)

scaffolds, orthopedic pins, cardiovascular patches, tendon repair devices, cartilage repair devices, and wound dressings (Sankhla et al., 2020).

4.1 Bioplastics in tissue engineering and implants

PHBHHx (poly (3-hydroxybutyrate-co-3-hydroxyhexanoate) outperformed PLA and PHB in the support of bone tissue growth by increasing bone marrow cell proliferation. Arginylglycylaspartic RGD peptide fused with PHA granule binding protein PhaP forming (PhaP-RGD) and coated on PHBHHx scaffolds, resulted in improved cell adhesion, proliferation, and chondrogenic differentiation in the scaffolds and therefore could help cartilage tissue engineering (Serafim et al., 2008).

In *in vitro* and *in vivo* conditions, PHB on blending with hydroxyapatite (HAP) improved cell growth (Shishatskaya et al., 2016; Simó-Cabrera et al., 2021). P3HB4HB has the potential to be developed into material for the synthesis of artificial blood vessels due to its strength, elasticity, and prompt elastin formation (Srubar et al., 2012).

4.2 Bioplastics in neurology

PHB offers neurological benefits. It aids axonal regeneration and promotes the survival, proliferation, and attachment of adult Schwann cells (Steinbüchel & Schlegel, 1991). According to Wang et al. (2010), to extend the differentiation of human bone marrow mesenchymal stem cells (hBMSC) into nerve cells, a terpolyester of 3-hydroxybutyrate, 3-hydroxyhexanoate, and 3-hydroxy valerate (PHBVHHx) were utilized.

4.3 Bioplastics in drug delivery

Bioplastics can also serve as suitable drug delivery systems. PHA hydrophobic nano and microparticles are ideal for transporting hydrophobic drugs (Sudesh et al., 2000). A PHA-based drug delivery system was developed by the fusion of polypeptide ligands, PHA nanoparticles, and PhaP (Sudesh et al., 2007). This ligand-PhaPPHA has been shown to effectively target cancer cells.

PHBHHx nanoparticles loaded with insulin phospholipid blends have been reported to be a successful delivery system due to their prolonged therapeutic effects, particularly in comparison to insulin solution (Suriyamongkol et al., 2007). Microparticles made of PHB and PHB–PHV copolymers facilitate low rates of drug release and enable drug deposition.

4.4 Bioplastics in gene delivery

PHA can be used as a suitable gene delivery vector. It was reported that monomethoxy-poly (hydroxyalkanoates) (mPHA-acrylated) with branched poly (ethyleneimine) (bPEI) on binding to small interfering ribonucleic acid (siRNA) prevented nuclease degradation of siRNA (Thakur et al., 2018).

4.5 Bioplastics in cancer research

Due to its inherent biocompatibility, PHB is used for cancer detection (Tokiwa & Calabia, 2004). According to the study, it was found that cancer cells adhered well to PHB sheets, while normal cells did not, and this adhesion of cells was detected with the help of contact

angle techniques. It is also to be noted that when compared to other techniques, the PHB-based cancer detection is a faster and less painful process. Besides cancer detection, bioplastics were analyzed for their ability to inhibit cancer. PHBHHx nanoparticles-based phosphoinositide-3-kinase inhibitor was studied for its ability to inhibit cancer cell line proliferation (Trivedi et al., 2016).

4.6 Bioplastics in surgical dressing

Bioplastics are also used in wound dressings, and the biodegradable and biocompatible polymers used to make nanofibrous wound dressings have sparked a lot of research interest (Chauhan et al., 2024). PHB/chitosan nanofibrous membranes with varying chitosan ratios was used as post-surgical wound dressing (Sariipek, 2024). Furthermore, adding polyvinylidene difluoride (PVDF) nanofibers to the PHB/chitosan layer increased its mechanical strength and resulted in the successful development of a novel bilayer electrospun nanofibrous membrane (UNEP, 2009).

5. The Potential of P4HB in Therapeutic Applications

It was reported that PHAs containing 4-hydroxybutyrate (4HB) monomers likely held potential therapeutic value (Deeken et al., 2023). Like P3HB, P4HB (Vaidya et al., 2019), is a naturally occurring substance in many organisms (Van Immersel et al., 2006), and they both belong to the bacterial PHA family (Van Loosdrecht et al., 1997). The potential therapeutic value of 4HB was recognized as early as the 1960s, as exhibited by pharmaceutical companies' interest. Since P(3HB-co-4HB) is a biodegradable and biocompatible copolymer, it can potentially be used in the controlled release of 4HB for therapeutic purposes. For clinical applications, PHA-PEG conjugates and hybrids are extremely effective instruments. Utilizable conjugates for targeted drug delivery and tissue engineering are made possible by the combination of the hydrophobic PHB and hydrophilic polyethylene glycol (PEG) characteristics of the two biocompatible polymers. PEGylation could be conducted *in vivo* through bioprocessing, such as end-capping of microbial PHAs. Several succinct synthetic methods and blending processes have been established, making it simple to obtain these conjugates. For these PHA-PEG medical applications over the past few years, the potential for micelle and nanoparticle synthesis as well as the creation of films have drawn growing attention. The biological, physicochemical, and material properties of PHAs can be efficiently modified through PEGylation (Winnacker & Rieger 2017).

5.1 P4HB in de-addiction

The use of 4HB in the treatment of alcoholism, as well as heroin and nicotine addiction, involves the controlled release of 4HB, and a patent describing the use of 4HB-containing PHA as a slow-releasing system for biomedical purposes was filed (Williams & Peoples 1996; Martin et al., 1997).

5.2 P4HB in anesthesia

4HB (also known as g-hydroxybutyrate [GHB]) was originally used as an intravenous anesthetic agent due to its rapid ability to cross the blood-brain barrier to induce a sleep-like state with cardiovascular stability (Vickers, 1968; Verlinden et al., 2007). It is to be

noted that the Food and Drug Administration (FDA) in the United States approved the use of 4HB in investigational research, such as narcolepsy trials. Several studies have also shown that P4HB can reduce energy substrate consumption in both brain and peripheral tissues, and it has the potential to protect these tissues from the damaging effects of anoxia or excessive metabolic demand (Volova et al., 2010). The sodium salt of p(4HB) has been widely used as an anesthetic (Ali et al., 2017)**,** and in investigational research, for oral or intravenous administration. Although P4HB offers an array of therapeutic benefits, the compound is prone to degradation, and lipases from different sources are capable of hydrolyzing P(4HB). According to Doi et al. (1995), the studies show that P(3HB-co-4HB) implantation causes some sort of degradation *in vivo*. By controlling the feeding regimen of carbon sources to the bacteria, PHA copolymers with random distributions of 4HB can also be produced. As a result, precise control of the release of 4HB in a predetermined dosage over a short/long period might be possible. However, more clinical research is necessary before the potential therapeutic value of 4HB-containing PHA can be recognized.

6. Limitations and Ways to Overcome the Limitations

Polyhydroxyalkanoates (PHAs) are the most used bioplastics and Poly-3-hydroxybutyrate (PHB) and polyhydroxyvalerate (PHV) are the most important PHAs with considerable applications in various industries. PHA has promising applications in a variety of industries and the medical field. Nevertheless, the high cost of PHA production has been a significant disadvantage. As a result, scientists have made tremendous progress in isolating new bacterial strains, developing new types of recombinant strains, and curating a new approach to the production of PHA to reduce production costs. Significant efforts have been made to reduce production costs by developing efficient bacterial strains, fermentation, and recovery processes (Lee, 1996; Grothe et al., 1999). PHA is hence expected to be available for applications in a variety of fields soon because of ongoing commercialization efforts in many countries. Bioplastics produced aseptically in fermenters are significantly more expensive than petrochemical-based plastics. The use of low-cost raw materials and technological innovations to reduce bioplastic production costs remains critical for the bioplastic industry and applications. However, implementing the following techniques will help to diminish the cost of bioplastic PHAs: The cost of the substrate is the most expensive part of the PHA production process (Ward et al., 2005). Thus, selecting an appropriate carbon substrate is a critical factor in determining the overall performance of bacterial fermentation as well as the cost of the final product. Hence, the most straightforward approach is to select renewable, inexpensive, readily available carbon substrates that can efficiently support microbial growth and PHA production. Agriculture generates 140 billion metric tons of biomass each year. Therefore, biomass wastes have a high potential as raw material for large-scale industries and community-level enterprises involved in bioplastic production (Trivedi et al., 2016). The organic residues of municipal solid wastes, liquid wastes, food processing wastes, or agricultural wastes are also considered suitable substrates for production. The organic residues of municipal solid wastes, liquid wastes, food processing wastes, or agricultural wastes are also considered suitable substrates for production. According to Serafim et al. (2008), agricultural wastes predominantly include unbaled straw; coconut fronds, husks, and shells; corn cobs, stalks, corn stover; cotton (stalks), nutshells; rice hull, husk, straw, and stalks, sugarcane bagasse, silage effluent; horticulture residues and farmyard manure can be utilized. Using these waste materials as a carbon source for PHA production not only lowers the substrate cost but also lowers the

cost of waste disposal (Yamane, 1993; Yang et al., 2007; Wu, 2012; Williams et al., 2013). Non-aseptic batches or the continuous cultivation of mixed bacterial cultures for bioplastic biosynthesis can help in diminishing the cost significantly (Lu et al., 2011). The continuous process has the potential of producing about 1 kg of PHAs/day/m^3 of bioreactor while batch biosynthesis of bioplastic despite being a simple process has low productivity (Rebah et al., 2009). Semi-continuous cultivation of a mixed culture in one bioreactor utilizes a feast-famine cycle with a feast phase and a famine phase. This cycling process enhances the accumulation of PHAs in the biomass, but it also facilitates the selection of PHA-producing microorganisms (Beun et al., 2002; Van Immerseel et al., 2006). Under non-aseptic conditions, organic wastes can be converted to organic acids via acidogenic fermentation of organics, and organic acids can then be converted to PHAs (Yİlmaz & Beyatli, 2005; Yao et al. 2008; You et al., 2011; Zhou et al. 2012; Zeller et al., 2013). Chemical treatment, filtration, centrifugation, or flotation are some of the cost-effective options for the recovery of bioplastics. These are some of the major techniques and ways in which the production cost of bioplastics can be lowered.

7. Conclusions

Microbial bioplastics like PHAs have sparked considerable interest in both academia and industry. Their structural versatility and properties have been analyzed, and new areas of application are being identified. The recent advancements in metabolic engineering, aided by genomics and bioinformatics, have generated a cascade of opportunities for the introduction of new metabolic pathways and this has led to considerable enhancement in the synthesis and yields of PHA. PHAs have become indispensable in a broad array of applications, including agriculture, industry, medicine, and therapy. Currently, numerous strategies and sources to obtain high concentrations of sustainable PHA are increasing extensively. The advancements in genetics and metabolic engineering have led to the identification of a broad range of bioplastics. Using advanced techniques like Crispr-Cas 9 technology, bioplastic production can be elevated. Research in synthetic biology can be developed to formulate a consortium of microbes that can synergistically produce a higher yield of bioplastics. Chemical engineers can optimize the physiochemical parameters in bioreactors for efficient large-scale bioplastic production. The utilization of waste as a raw material for bioplastic production is an interesting area of research as it can lead to sustainability. The role of bioplastics in novel therapeutic and clinical applications is to be further investigated. Hence, it is anticipated that besides polyhydroxyalkanoates, many more bioplastics with diverse structures, properties, and applications can be obtained if the appropriate organism are selected and genetically manipulated.

8. Acknowledgments

This work was funded by DST WOS-B (DST/WOS-B/WWM-8/2021) and ICMR (35/14/2020-NAN/BMS), the Government of India. The authors are thankful to the School of Life Sciences, B.S. Abdur Rahman Crescent Institute of Science and Technology, Chennai, for providing the necessary facilities.

9. Conflicts of Interest

The authors declare that they have no known competing interests.

ORCID

Sneha Unnikrishnan https://orcid.org/0000-0001-7090-7941

Karthikeyan Ramalingam https://orcid.org/0000-0002-9334-427X

References

Abe, M., Kobayashi, K., Honma, N., & Nakasaki, K. (2010). Microbial degradation of poly (butylene succinate) by *Fusarium solani* in soil environments. *Polymer Degradation and Stability*, 95(2), 138-143. https://doi.org/10.1016/j.polymdegradstab.2009.11.042

Aburas, M. M. A. (2016). Degradation of poly(3-hydroxybuthyrate) using *Aspergillus oryzae* obtained from uncultivated soil. *Life Science Journal*, 13(3), 51-56.

Adamus, G., Sikorska, W., Janeczek, H., Kwiecień, M., Sobota, M., & Kowalczuk, M. (2012). Novel block copolymers of atactic PHB with natural PHA for cardiovascular engineering: Synthesis and characterization. *European Polymer Journal*, 48(3), 621-631. https://doi.org/10.1016/j.eurpolymj.2011.12.017

Adane, L., & Muleta, D. (2011). Survey on the usage of plastic bags, their disposal and adverse impacts on environment: A case study in Jimma City, Southwestern Ethiopia. *Journal of Toxicology and Environmental Health Sciences*, 3(8), 234-248.

Adhikari, D., Mukai, M., Kubota, K., Kai, T., Kaneko, N., Araki, K. S., & Kubo, M. (2016). Degradation of bioplastics in soil and their degradation effects on environmental microorganisms. *Journal of Agricultural Chemistry and Environment*, 5(1), 23-34. https://doi.org/10.4236/jacen.2016.51003

Ahuja, V., Singh, P. K., Mahata, C., Jeon, J.-M., Kumar, G., Yang, Y.-H., & Bhatia, S. K. (2024). A review on microbes mediated resource recovery and bioplastic (polyhydroxyalkanoates) production from wastewater. *Microbial Cell Factories*, 23, Article 187. https://doi.org/10.1186/s12934-024-02430-0

Ajellal, N., Durieux, G., Delevoye, L., Tricot, G., Dujardin, C., Thomas, C. M., & Gauvin, R. M. (2010). Polymerization of racemic β-butyrolactone using supported catalysts: a simple access to isotactic polymers. *Chemical Communications*, 46(7), 1032-1034. https://doi.org/10.1039/B923546A

Ali, S. S., Abdelkarim, E. A., Elsamahy, T., Al-Tohamy, R., Li, F., Kornaros, M., Zuorro, A., Zhu, D., & Sun, J. (2023). Bioplastic production in terms of life cycle assessment: A state-of-the-art review, *Environmental Science and Ecotechnology*, 15, Article 100254. https://doi.org/10.1016/j.ese.2023.100254

Ali, W. S., Zaki, N. H., & Obiad, S. Y. N. (2017). Production of bioplastic by bacteria isolated from local soil and organic wastes. *Current Research in Microbiology and Biotechnology*, 5(2), 1012-1017.

Amini, F., Semnani, D., Karbasi, S., & Banitaba, S. N. (2019). A novel bilayer drug-loaded wound dressing of PVDF and PHB/Chitosan nanofibers applicable for post-surgical ulcers. *International Journal of Polymeric Materials and Polymeric Biomaterials*, 68(13), 772-777. https://doi.org/10.1080/00914037.2018.1506982

Anderson, A. J., & Dawes, E. (1990). Occurrence, metabolism, metabolic role, and industrial uses of bacterial polyhydroxyalkanoates. *Microbiological Reviews*, 54(4), 450-472. https://doi.org/10.1128/mr.54.4.450-472.1990

Ang, S. L., Sivashankari, R., Shaharuddin, B., Chuah, J.-A., Tsuge, T., Abe, H., & Sudesh, K. (2020). Potential applications of polyhydroxyalkanoates as a biomaterial for the aging population. *Polymer Degradation and Stability*, 181, Article 109371. https://doi.org/10.1016/j.polymdegradstab.2020.109371

Anjum, A., Zuber, M., Zia, K. M., Noreen, A., Anjum, M. N., & Tabasum, S. (2016). Microbial production of polyhydroxyalkanoates (PHAs) and its copolymers: A review of recent advancements. *International Journal of Biological Macromolecules*, 89, 161-174. https://doi.org/10.1016/j.ijbiomac.2016.04.069

Atiwesh, G., Mikhael, A., Parrish, C. C., Banoub, J., & Le, T.-A. T. (2021). Environmental impact of bioplastic use: A review. *Heliyon*, 7(9), Article e07918. https://doi.org/10.1016/j.heliyon.2021.e07918

Bano, S., Aslam, A. A., Khan, A., Shabbir, A., Qayyum, F., Wahab, N., Jabar, A., Islam, I. U., & Ng, S. L. (2024). A mini-review on polyhydroxyalkanoates: Synthesis, extraction, characterization, and applications. *Process Biochemistry*, 146, 250-261. https://doi.org/10.1016/j.procbio.2024.07.033

Barnard, G. N., & Sanders, J. K. M. (1989). The poly-β-hydroxybutyrate granule in vivo. A new insight based on NMR spectroscopy of whole cells. *Journal of Biological Chemistry*, 264(6), 3286-3291. https://doi.org/10.1016/S0021-9258(18)94064-0

Beun, J. J., Dircks, K., Van Loosdrecht, M. C. M., & Heijnen, J. J. (2002). Poly-β-hydroxybutyrate metabolism in dynamically fed mixed microbial cultures. *Water Research*, 36(5), 1167-1180. https://doi.org/10.1016/s0043-1354(01)00317-7

Blinková, M., & Boturová, K. (2017). Influence of bacteria on degradation of bioplastics. In *IOP Conference Series: Earth and Environmental Science*, 92, Article 012004. https://doi.org/10.1088/1755-1315/92/1/012004

Boyandin, A. N., Prudnikova, S. V., Karpov, V. A., Ivonin, V. N., Đỗ, N. L., Nguyễn, T. H., Lê, T. M. H., Filichev, N. L., Levin, A. L., Filipenko, M. L., Volova, T. G., & Gitelson, I. I. (2013). Microbial degradation of polyhydroxyalkanoates in tropical soils. *International Biodeterioration and Biodegradation*, 83, 77-84. https://doi.org/10.1016/j.ibiod.2013.04.014

Brandl, H., Gross, R. A., Lenz, R. W., & Fuller, R. C. (2005). Plastics from bacteria and for bacteria: poly(β-hydroxyalkanoates) as natural, biocompatible, and biodegradable polyesters. In A. Fiechter (Ed.). *Microbial Bioproducts. Advances in Biochemical Engineering/Biotechnology. Vol 41*. (pp. 77-93). Springer. https://doi.org/10.1007/BFb0010232

Brulé, E., Gaillard, S., Rager, M.-N., Roisnel, T., Guérineau, V., Nolan, S. P., & Thomas, C. M. (2011). Polymerization of racemic β-butyrolactone using gold catalysts: a simple access to biodegradable polymers. *Organometallics*, 30(10), 2650-2653. https://doi.org/10.1021/om200271q

Cesário, M. T., Raposo, R. T., de Almeida, M. C. M. D., Keulen, F. V., Ferreira, B. S., & da Fonseca, M. M. R. (2014). Enhanced bioproduction of poly 3 hydroxybutyrate from wheat straw lignocellulosic hydrolysates. *New Biotechnology*, 31(1), 104-113. https://doi.org/10.1016/j.nbt.2013.10.004

Chacón, M., Wongsirichot, P., Winterburn, J., & Dixon, N. (2024). Genetic and process engineering for polyhydroxyalkanoate production from pre- and post-consumer food waste. *Current Opinion in Biotechnology*, 85, Article 103024. https://doi.org/10.1016/j.copbio.2023.103024

Chauhan, K., Kaur, R., & Chauhan, I. (2024). Sustainable bioplastic: a comprehensive review on sources, methods, advantages, and applications of bioplastics. *Polymer-Plastics Technology and Materials*, 63(8), 913-918. https://doi.org/10.1080/25740881.2024.2307369

Chee, J.-Y., Yoga, S.-S., Lau, N.-S., Ling, S.-C., Abed, R. M. M., & Sudesh, K. (2010). Bacterially produced polyhydroxyalkanoate (PHA): converting renewable resources into bioplastics. In A. Méndez-Vilas (Ed.). *Current research, technology, and education topics in Applied Microbiology and Microbial Biotechnology* (pp. 1395-1404). Formatex Research Center.

Chen, G.-Q., & Wu, Q. (2005). The application of polyhydroxyalkanoates as tissue engineering materials. *Biomaterials*, 26(33), 6565-6578. https://doi.org/10.1016/j.biomaterials.2005.04.036

Colombo, B., Sciarria, T. P., Reis, M., Scaglia, B., & Adani, F. (2016). Polyhydroxyalkanoates (PHAs) production from fermented cheese whey by using a mixed microbial culture. *Bioresource Technology*, 218, 692-699. https://doi.org/10.1016/j.biortech.2016.07.024

Dalton, D. A., Ma, C., Murthy, G. S., & Strauss, S. H. (2012). Bioplastic production by transgenic poplar. *Information Systems for Biotechnology News Report*, 2012, 7-10.

Dawes, E. A., & Senior, P. J. 1973. The role and regulation of energy reserve polymers in micro-organisms. *Advances in Microbial Physiology*, 10, 135-266. https://doi.org/10.1016/s0065-2911(08)60088-0

Deeken, C. R., Chen, D. C., Lopez-Cano, M., Martin, D. P., & Badhwar, A. (2023). Fully resorbable poly-4-hydroxybutyrate (P_4HB) mesh for soft tissue repair and reconstruction: A scoping review. *Frontiers in Surgery*, 10. Article 1157661. https://doi.org/10.3389/fsurg.2023.1157661

Defoirdt, T., Halet, D., Vervaeren, H., Boon, N., Van de Wiele, T., Sorgeloos, P., Bossier, P. & Verstraete, W. (2007). The bacterial storage compound poly-β-hydroxybutyrate protects *Artemia franciscana* from pathogenic *Vibrio campbellii*. *Environmental Microbiology*, 9(2), 445-452. https://doi.org/10.1111/j.1462-2920.2006.01161.x

Dias, J. M. L., Lemos, P. C., Serafim, L. S., Oliveira, C., Eiroa, M., Albuquerque, M. G. E., Ramos, A. M., Oliveira, R. & Reis, M. A. M. (2006). Recent advances in polyhydroxyalkanoate production by mixed aerobic cultures: from the substrate to the final product. *Macromolecular Bioscience*, 6(11), 885-906. https://doi.org/10.1002/mabi.200600112

Ding, Y., Li, W., Müller, T., Schubert, D. W., Boccaccini, A. R., Yao, Q., & Roether, J. A. (2016). Electrospun polyhydroxybutyrate/poly (ε-caprolactone)/58S sol–gel bioactive glass hybrid scaffolds with highly improved osteogenic potential for bone tissue engineering. *ACS Applied Materials and Interfaces*, 8(27), 17098-17108.

Doi, Y., Kitamura, S., & Abe, H. (1995). Microbial synthesis and characterization of poly(3-hydroxybutyrate-co-3-hydroxyhexanoate). *Macromolecules*, 28(14), 4822-4828. https://doi.org/10.1021/ma00118a007

El-malek, F., Khairy, H., Farag, A., & Omar, S. (2020). The sustainability of microbial bioplastics, production and applications. *International Journal of Biological Macromolecules*, 157, 319-328. https://doi.org/10.1016/j.ijbiomac.2020.04.076

Fukui, T., Kato, M., Matsusaki, H., Iwata, T., & Doi, Y. (1998). Morphological and ^{13}C-nuclear magnetic resonance studies for polyhydroxyalkanoate biosynthesis in *Pseudomonas* sp. 61-3. *FEMS Microbiology Letters*, 164(1), 219-225. https://doi.org/10.1111/j.1574-6968.1998.tb13089.x

Giosafatto, C. V. L., Fusco, A., Al-Asmar, A., & Mariniello, L. (2020). Microbial transglutaminasee as a tool to improve the features of hydrocolloid-based bioplastics. *International Journal of Molecular Sciences*, 21(10), Article 3656. https://doi.org/10.3390/ijms21103656

Gonzalez-Gutierrez, J., Partal, P., Garcia-Morales, M., & Gallegos, C. (2010) Development of highly-transparent protein/starch-based bioplastics. Bioresource Technology, 101(6), 2007-2013. https://doi.org/10.1016/j.biortech.2009.10.025

Grothe, E., Moo-Young, M., & Chisti, Y. (1999). Fermentation optimization for the production of poly (β-hydroxybutyric acid) microbial thermoplastic. *Enzyme and Microbial Technology*, 25(1-2), 132-141. https://doi.org/10.1016/S0141-0229(99)00023-X

Hamdy, S. M., Danial, A. W., El-Rab, S. M. F. G., Shoreit, A. A. M. & Hesham, A. E.-L. (2022). Production and optimization of bioplastic (Polyhydroxybutyrate) from *Bacillus cereus* strain SH-02 using response surface methodology. *BMC Microbiology*, 22, Article 183. https://doi.org/10.1186/s12866-022-02593-z

Hempel, F., Bozarth, A. S., Lindenkamp, N., Klingl, A., Zauner, S., Linne, U., Steinbüchel, A. & Maier, U. G. (2011). Microalgae as bioreactors for bioplastic production. *Microbial Cell Factories*, 10, Article 81. https://doi.org/10.1186/1475-2859-10-81

Hermann-Krauss, C., Koller, M., Muhr, A., Fasl, H., Stelzer, F., & Braunegg, G. (2013). Archaeal production of polyhydroxyalkanoate (PHA) co- and terpolyesters from biodiesel industry-derived by-products. *Archaea*, 2013(1), Article 129268. https://doi.org/10.1155/2013/129268

Hrabak, O. (1992). Industrial production of poly-β-hydroxybutyrate. *FEMS Microbiology Letters*, 103(2-4), 251-255. https://doi.org/10.1016/0378-1097(92)90317-H

Hu, F.-Q., You, S., & Chen, G.-Q. (2005). [Synthesis of medium chain length polyhydroxyalkanoate in type I PHA synthase negative mutant of *Aeromonas hydrophila*.] *Sheng Wu Gong Cheng Xue Bao*, 21(4), 524-529.

Ishii, N., Inoue, Y., Tagaya, T., Mitomo, H., Nagai, D., & Kasuya, K.-I. (2008). Isolation and characterization of poly (butylene succinate)-degrading fungi. *Polymer Degradation and Stability*, 93(5), 883-888. https://doi.org/10.1016/j.polymdegradstab.2008.02.005

Jau, M.-H., Yew, S.-P., Toh, P. S. Y., Chong, A. S. C., Chu, W.-L., Phang, S.-M., Nazalan, N. & Sudesh, K. (2005). Biosynthesis and mobilization of poly(3-hydroxybutyrate) [P (3HB)] by *Spirulina platensis*. *International Journal of Biological Macromolecules*, 36(3), 144-151. https://doi.org/10.1016/j.ijbiomac.2005.05.002

Jia, Q., Wang, H., & Wang, X. (2013). Dynamic synthesis of polyhydroxyalkanoates by bacterial consortium from simulated excess sludge liquid. *Bioresource Technology*, 140, 328-336. https://doi.org/10.1016/j.biortech.2013.04.105

Jung, H.-W., Yang, M.-K., & Su, R.-C. (2018). Purification, characterization, and gene cloning of an Aspergillus fumigatus polyhydroxybutyrate depolymerase used for degradation of polyhydroxybutyrate, polyethylene succinate, and polybutylene succinate. *Polymer Degradation and Stability*, 154, 186-194. https://doi.org/10.1016/j.polymdegradstab.2018.06.002

Khatami, K., Perez-Zabaleta, M., Owusu-Agyeman, I., & Cetecioglu, Z. (2021). Waste to bioplastics: How close are we to sustainable polyhydroxyalkanoates production? *Waste Management*, 119, 374-388. https://doi.org/10.1016/j.wasman.2020.10.008

Kourtz, L., Dillon, K., Daughtry, S., Peoples, O. P., & Snell, K. D. (2007). Chemically inducible expression of the PHB biosynthetic pathway in Arabidopsis. *Transgenic Research*, 16, 759-769. https://doi.org/10.1007/s11248-007-9067-1

Kucera, D., Pernicová, I., Kovalcik, A., Koller, M., Mullerova, L., Sedlacek, P., Mravec, F., Nebesarova, J., Kalina, M., Marova, I., Krzyzanek, V., & Obruca, S. (2018) Characterization of the promising poly(3-hydroxybutyrate) producing halophilic bacterium *Halomonas halophila*. *Bioresource Technology*, 256, 552-556. https://doi.org/10.1016/j.biortech.2018.02.062

Kumbar, S. G., Laurencin, C. T., & Deng, M. (2014). *Natural and synthetic biomedical polymers*. Elsevier.

Laborit, H. (1964). Sodium 4-hydroxybutyrate. *International Journal of Neuropharmacology*, 3(4), 433-451. https://doi.org/10.1016/0028-3908(64)90074-7

Lee, K. M., Gimore, D. F., & Huss, M. J. (2005). Fungal degradation of the bioplastic PHB (Poly-3-hydroxy-butyric acid). *Journal of Polymers and the Environment*, 13(3), 213-219.

Lee, S. Y. (1996). Plastic bacteria? Progress and prospects for polyhydroxyalkanoate production in bacteria. *Trends in Biotechnology*, 14(11), 431-438. https://doi.org/10.1016/0167-7799(96)10061-5

Lizarraga-Valderrama, L. R., Nigmatullin, R., Taylor, C., Haycock, J. W., Claeyssens, F., Knowles, J. C., & Roy, I. (2015). Nerve tissue engineering using blends of poly (3-

hydroxyalkanoates) for peripheral nerve regeneration. *Engineering in Life Sciences*, 15(6), 612-621. https://doi.org/10.1002/elsc.201400151

Lu, Q., Zhou, Y., Sui, Q., & Zhou, Y. (2023). Mechanism and characterization of microplastic aging process: a review. *Frontiers of Environmental Science and Engineering*, 17(8), Article 100. https://doi.org/10.1007/s11783-023-1700-6

Lu, X. Y., Ciraolo, E., Stefenia, R., Chen, G. Q., Zhang, Y., & Hirsch, E. (2011). Sustained release of PI3K inhibitor from PHA nanoparticles and in vitro growth inhibition of cancer cell lines. *Applied Microbiology and Biotechnology*, 89(5), 1423-1433.

Lü, Y. (2007). Advance on the production of polyhydroxyalkanoates by mixed cultures. Frontiers in Biology, 2(1), 21-25. https://doi.org/10.1007/s11515-007-0003-9

Luengo, J. M., García, B., Sandoval, A., Naharro, G., & Olivera, E. R. (2003). Bioplastics from microorganisms. *Current Opinion in Microbiology*, 6(3), 251-260. https://doi.org/10.1016/S1369-5274(03)00040-7

Ma, Y., Li, L., & Wang, Y. (2018). Development of PLA-PHB-based biodegradable active packaging and its application to salmon. *Packaging Technology and Science*, 31(11), 739-746. https://doi.org/10.1002/pts.2408

Madison, L. L., & Huisman, G. W. (1999). Metabolic engineering of poly(3-hydroxyalkanoates): from DNA to plastic. *Microbiology and Molecular Biology Reviews*, 63(1), 21-53.

Maestro, B., & Sanz, J. M. (2017). Polyhydroxyalkanoate-associated phasins as phylogenetically heterogeneous, multipurpose proteins. *Microbial Biotechnology*, 10(6), 1323-1337. https://doi.org/10.1111/1751-7915.12718

Malik, M. R., Yang, W., Patterson, N., Tang, J., Wellinghoff, R. L., Preuss, M. L., Burkitt, C., Sharma, N., Ji, Y., Jez, J. M., Peoples, O. P., Jaworski, J. G., Cahoon, E. B., & Snell, K. D. (2015) Production of high levels of poly-3-hydroxybutyrate in plastids of *Camelina sativa* seeds. *Plant Biotechnology Journal*, 13(5), 675-688. https://doi.org/10.1111/pbi.12290

Mamelak, M. (1989). Gammahydroxybutyrate: an endogenous regulator of energy metabolism. *Neuroscience and Biobehavioral Reviews*, 13(4), 187-198. https://doi.org/10.1016/S0149-7634(89)80053-3

Marang, L., Jiang, Y., van Loosdrecht, M. C. M., & Kleerebezem, R. (2014). Impact of non-storing biomass on PHA production: an enrichment culture on acetate and methanol. *International Journal of Biological Macromolecules*, 71, 74-80. https://doi.org/10.1016/j.ijbiomac.2014.04.051

Martin, D. P., Skraly, F., & Williams, S. F. (1997). *Polyhydroxyalkanoate compositions having controlled degradation rates*. United States. Patent No. US6878758B2. USPTO Patent Center.

Matsusaki, H., Manji, S., Taguchi, K., Kato, M., Fukui, T., & Doi, Y. (1998). Cloning and molecular analysis of the Poly(3-hydroxybutyrate) and Poly(3-hydroxybutyrate-co-3-hydroxyalkanoate) biosynthesis genes in *Pseudomonas* sp. strain 61-3. *Journal of Bacteriology*, 180(24), 6459-6467. https://doi.org/10.1128/jb.180.24.6459-6467.1998

McAdam, B., Fournet, M. B., McDonald, P., & Mojicevic, M. (2020). Production of polyhydroxybutyrate (PHB) and factors impacting its chemical and mechanical characteristics. *Polymers*, 12(12), Article 2908. https://doi.org/10.3390/polym12122908

McQualter, R. B., Petrasovits, L. A., Gebbie, L. K., Schweitzer, D., Blackman, D. M., Chrysanthopoulos, P., Hodson, M. P., Plan, M. R., Riches, J. D., Snell, K. D., Brumbley, S. W., & Nielsen, L. K. (2014). The use of an acetoacetyl-CoA synthase in place of a β-ketothiolase enhances poly-3-hydroxybutyrate production in sugarcane mesophyll cells. *Plant Biotechnology Journal*, 10, 569-578. https://doi.org/10.1111/pbi.12298

Mergaert, J., & Swings, J. (1996). Biodiversity of microorganisms that degrade bacterial and synthetic polyesters. *Journal of Industrial Microbiology*, 17, 463-469. https://doi.org/10.1007/BF01574777

Miyake, M., Kataoka, K., Shirai, M., & Asada, Y. (1997) Control of poly-beta-hydroxybutyrate synthase mediated by acetyl phosphate in cyanobacteria. *Journal of Bacteriology*, 179, 5009-5013. https://doi.org/10.1128/jb.179.16.5009-5013.1997

Mostafa, Y. S., Alrumman, S. A., Alamri, S. A., Otaif, K. A., Mostafa, M. S., & Alfaify, A. M. (2020). Bioplastic (poly-3-hydroxybutyrate) production by the marine bacterium *Pseudodonghicola xiamenensis* through date syrup valorization and structural assessment of the biopolymer. *Scientific Reports*, 10(1), Article 8815. https://doi.org/10.1038/s41598-020-65858-5

Muhammadi, Shabina, Afzal, M., & Hameed, S. (2015). Bacterial polyhydroxyalkanoates-eco-friendly next generation plastic: production, biocompatibility, biodegradation, physical properties and applications. *Green Chemistry Letters and Reviews*, 8(3-4), 56-77. https://doi.org/10.1080/17518253.2015.1109715

Müller, H.-M., & Seebach, D. (1993). Poly(hydroxyalkanoates): A fifth class of physiologically important organic biopolymers? *Angewandte Chemie International Edition in English*, 32(4), 477-502. https://doi.org/10.1002/anie.199304771

Nadhman, A., Hasan, F., Shah, Z., Hameed, A., & Shah, A. A. (2012). Production of poly (3-hydroxybutyrate-co-3-hydroxyvalerate) depolymerase from *Aspergillus* sp. NA-25. *Applied Biochemistry and Microbiology*, 48(5), 482-487.

Nakasaki, K., Matsuura, H., Tanaka, H., & Sakai, T. (2006). Synergy of two thermophiles enables decomposition of poly-ε-caprolactone under composting conditions. *FEMS Microbiology Ecology*, 58(3), 373-383. https://doi.org/10.1111/j.1574-6941.2006.00189.x

Nelson, T., Kaufman, E., Kline, J., & Sokoloff, L. (1981). The extraneural distribution of γ-hydroxybutyrate. *Journal of Neurochemistry*, 37(5), 1345-1348. https:/doi.org/10.1111/j.1471-4159.1981.tb04689.x

Niaounakis, M. (2015). *Biopolymers: applications and trends*. William Andrew. https://doi.org/10.1016/C2014-0-00936-7

Nigmatullin, R., Thomas, P., Lukasiewicz, B., Puthussery, H., & Roy, I. (2015). Polyhydroxyalkanoates, a family of natural polymers, and their applications in drug delivery. *Journal of Chemical Technology and Biotechnology*, 90(7), 1209-1221. https://doi.org/10.1002/jctb.4685

Novikova, L. N., Pettersson, J., Brohlin, M., Wiberg, M., & Novikov, L. N. (2008). Biodegradable poly-β-hydroxybutyrate scaffold seeded with Schwann cells to promote spinal cord repair. *Biomaterial*, 29(9), 1198-1206. https://doi.org/10.1016/j.biomaterials.2007.11.033

Obruca, S., Marova, I., Melusova, S., & Ondruska, V. (2009). Production of polyester-based bioplastics by *Bacillus megaterium* grown on waste cheese whey substrate under exogenous stress. *New Biotechnology*, 25(Suppl.), S257. https://doi.org/10.1016/j.nbt.2009.06.574

Oppermann-Sanio, F. B., & Steinbüchel, A. (2002). Occurrence, functions and biosynthesis of polyamides in microorganisms and biotechnological production. *Naturwissenschaften*, 89(1), 11-22. https://doi.org/10.1007/s00114-001-0280-0

Page, W. J. (1989). Production of poly-β-hydroxybutyrate by *Azotobacter vinelandii* strains UWD during growth on molasses and other complex carbon sources. *Applied Microbiology and Biotechnology*, 31(4), 329-333. https://doi.org/10.1007/BF00257598

Panda, B., & Mallick, N. (2007). Enhanced poly-beta-hydroxy-butyrate accumulation in a unicellular cyanobacterium, *Synechocystis* sp. PCC 6803. *Letters in Applied Microbiology*, 44(2), 194-198. https://doi.org/10.1111/j.1472-765X.2006.02048.x

Panith, N., Assavanig, A., Lertsiri, S., Bergkvist, M., Surarit, R., & Niamsiri, N. (2016). Development of tunable biodegradable polyhydroxyalkanoates microspheres for controlled delivery of tetracycline for treating periodontal disease. *Journal of Applied Polymer Science*,133(42), Article 44128. https://doi.org/10.1002/app.44128

Peng, Q., Zhang, Z.-R., Gong, T., Chen, G.-Q., Sun, X. (2012). A rapid-acting, long-acting insulin formulation based on a phospholipid complex loaded PHBHHx nanoparticles. *Biomaterials*, 33(5), 1583-1588. https://doi.org/10.1016/j.biomaterials.2011.10.072

Penkhrue, W., Khanongnuch, C., Masaki, K., Pathom-aree, W., Punyodom, W., & Lumyong, S. (2015). Isolation and screening of biopolymer-degrading microorganisms from northern Thailand. *World Journal of Microbiology and Biotechnology*, 31, 1431-1442. https://doi.org/10.1007/s11274-015-1895-1

Piyathilake, U., Lin, C., Bolan, N., Bundschuh, J., Rinklebe, J., & Herath, I. (2024). Exploring the hidden environmental pollution of microplastics derived from bioplastics: A review. *Chemosphere*, 355, Article 141773. https://doi.org/10.1016/j.chemosphere.2024.141773

Rebah, F. B., Prévost, D., Tyagi, R. D., & Belbahri, L. (2009). Poly-β-hydroxybutyrate production by fast-growing Rhizobia cultivated in sludge and in industrial wastewater. *Applied Biochemistry and Biotechnology*, 158(1), 155-163. https://doi.org/10.1007/s12010-008-8358-1

Reddy, C. S. K., Ghai, R., & Kalia, V. (2003). Polyhydroxyalkanoates: an overview. *Bioresource Technology*, 87(2), 137-146. https://doi.org/10.1016/S0960-8524(02)00212-2

Reddy, M. V., & Mohan, S. V. (2015). Polyhydroxyalkanoates production by newly isolated bacteria *Serratia ureilytica* using volatile fatty acids as substrate: Bio-electro kinetic analysis. *Journal of Microbial and Biochemical Technology*, 7(1), 26-32.

Ruiz, C., Kenny, S. T., Narancic, T., Babu, R., & O' Connor, K. (2019). Conversion of waste cooking oil into medium chain polyhydroxyalkanoates in a high cell density fermentation. *Journal of Biotechnology*, 306, 9-15. https://doi.org/10.1016/j.jbiotec.2019.08.020

Sabarinathan, D., Chandrika, S. P., Venkatraman, P., Easwaran, M., Sureka, C. S., & Preethi, K. (2018). Production of polyhydroxybutyrate (PHB) from *Pseudomonas plecoglossicida* and its application towards cancer detection. *Informatics in Medicine Unlocked*, 11, 61-67. https://doi.org/10.1016/j.imu.2018.04.009

Sadat-Shojai, M., Khorasani, M.-T., & Jamshidi, A. (2016). A new strategy for fabrication of bone scaffolds using electrospun nano-HAp/PHB fibers and protein hydrogels. *Chemical Engineering Journal*, 289, 38-47. https://doi.org/10.1016/j.cej.2015.12.079

Sankhla, I. S., Sharma, G., & Tak, A. (2020). Fungal degradation of bioplastics: An overview. In J. Singh & P. Gehlot (Eds). *New and future developments in microbial biotechnology and bioengineering* (pp. 35-47). Elsevier. https://doi.org/10.1016/B978-0-12-821007-9.00004-8

Sarıipek, F. B. (2024). Biopolymeric nanofibrous scaffolds of poly(3-hydroxybuthyrate)/chitosan loaded with biogenic silver nanoparticle synthesized using curcumin and their antibacterial activities. *International Journal of Biological Macromolecules*, 256(Part 1), Article 128330. https://doi.org/10.1016/j.ijbiomac.2023.128330

Serafim, L. S., Lemos, P. C., Albuquerque, M. G., & Reis, M. A. (2008). Strategies for PHA production by mixed cultures and renewable waste materials. *Applied Microbiology and Biotechnology*, 81, 615-628.

Shah, A. A., Hasan, F., Hameed, A., & Ahmed, S. (2008). Biological degradation of plastics: a comprehensive review. *Biotechnology Advances*, 26(3), 246-265. https://doi.org/10.1016/j.biotechadv.2007.12.005

Sharma, L., Singh, K. A., Panda, B., & Mallick, N. (2007). Process optimization for poly-β-hydroxybutyrate production in a nitrogen fixing cyanobacterium, *Nostoc muscorum*

using response surface methodology. *Bioresource Technology*, 98(5), 987-993. https://doi.org/10.1016/j.biortech.2006.04.016

Shishatskaya, E. I., Nikolaeva, E. D., Vinogradova, O. N., & Volova, T. G. (2016). Experimental wound dressings of degradable PHA for skin defect repair. *Journal of Materials Science: Materials in Medicine*, 27(11), Article 165. https://doi.org/10.1007/s10856-016-5776-4

Simó-Cabrera, L., García-Chumillas, S., Hagagy, N., Saddiq, A., Tag, H., Selim, S., AbdElgawad, H., Agüero, A. A., Sánchez, F. M., Cánovas, V., Pire, C. & Martínez-Espinosa, R. M. (2021). Haloarchaea as cell factories to produce bioplastics. *Marine Drugs*, 19(3), Article 159. https://doi.org/10.3390/md19030159

Srubar, W. V., III, Pilla, S., Wright, Z. C., Ryan, C. A., Greene, J. P., Frank, C. W., & Billington, S. L. (2012). Mechanisms and impact of fiber–matrix compatibilization techniques on the material characterization of PHBV/oak wood flour engineered biobased composites. *Composites Science and Technology*, 72(6), 708-715. https://doi.org/10.1016/j.compscitech.2012.01.021

Stal, L. J. (1992). Poly(hydroxyalkanoates) in cyanobacteria: an overview. FEMS Microbiology Letters, 103(2-4), 169-180. https://doi.org/10.1016/0378-1097(92)90307-A

Steinbüchel, A., & Schlegel, H. G. (1991). Physiology and molecular genetics of poly (β-hydroxyalkanoic acid) synthesis in *Alcaligenes eutrophus*. *Molecular Microbiology*, 5(3), 535-542.

Sudesh, K., Abe, H., & Doi, Y. (2000). Synthesis, structure and properties of polyhydroxyalkanoates: biological polyesters. *Progress in Polymer Science*, 25(10), 1503-1555. https://doi.org/10.1016/S0079-6700(00)00035-6

Sudesh, K., Loo, C. Y., Goh, L. K., Iwata, T., & Maeda, M. (2007). The oil-absorbing property of polyhydroxyalkanoate films and its practical application: a refreshing new outlook for an old degrading material. *Macromolecular Bioscience*, 7(11), 1199-1205.

Suriyamongkol, P., Weselake, R., Narine, S., Moloney, M., & Shah, S. (2007). Biotechnological approaches for the production of polyhydroxyalkanoates in microorganisms and plants—a review. *Biotechnology Advances*, 25(2), 148-175. https://doi.org/10.1016/j.biotechadv.2006.11.007

Swetha, T. A., Bora, A., Ananthy, V., Ponnuchamy, K., Muthusamy, G., & Arun, A. (2024). A review of bioplastics as an alternative to petrochemical plastics: Its types, structure, characteristics, degradation, standards, and feedstocks. *Polymers for Advanced Technologies*, 35(6), Article e6482. https://doi.org/10.1002/pat.6482

Thakur, S., Chaudhary, J., Sharma, B., Verma, A., Tamulevicius, S., & Thakur, V. K. (2018). Sustainability of bioplastics: Opportunities and challenges. *Current Opinion in Green and Sustainable Chemistry*, 13, 68-75.

Tokiwa, Y., & Calabia, B. P. (2004). Review degradation of microbial polyesters. *Biotechnology Letters*, 26, 1181-1189.

Trivedi, P., Hasan, A., Akhtar, S., Siddiqui, M. H., Sayeed, U., & Khan, M. K. A. (2016). Role of microbes in degradation of synthetic plastics and manufacture of bioplastics. *Journal of Chemical and Pharmaceutical Research*, 8(3), 211-216.

UNEP. (2009). *Converting waste agricultural biomass into a resource-compendium of technologies*. United Nations Environment Programme.

Vaidya, A. A., Collet, C., Gaugler, M., & Lloyd-Jones, G. (2019). Integrating softwood biorefinery lignin into polyhydroxybutyrate composites and application in 3D printing. *Materials Today Communications*, 19, 286-296. https://doi.org/10.1016/j.mtcomm.2019.02.008

Van Immerseel, F., Russell, J. B., Flythe, M. D., Gantois, I., Timbermont, L., Pasmans, F., & Ducatelle, R. (2006). The use of organic acids to combat Salmonella in poultry: a mechanistic explanation of the efficacy. *Avian Pathology*, 35(3), 182-188.

Van Loosdrecht, M. C. M., Pot, M. A., & Heijnen, J. J. (1997). Importance of bacterial storage polymers in bioprocesses. *Water Science and Technology*, 35(1), 41-47. https://doi.org/10.1016/S0273-1223(96)00877-3

Verlinden, R. A., Hill, D. J., Kenward, M. A., Williams, C. D., & Radecka, I. (2007). Bacterial synthesis of biodegradable polyhydroxyalkanoates. *Journal of Applied Microbiology*, 102(6), 1437-1449. https://doi.org/10.1111/j.1365-2672.2007.03335.x

Vickers, M. D. (1968). Gamma hydroxybutyric acid: Clinical pharmacology and current status. *Proceedings of the Royal Society of Medicine*, 61(8), 821-824.

Volova, T. G., Boyandin, A. N., Vasiliev, A. D., Karpov, V. A., Prudnikova, S. V., Mishukova, O. V., Boyarskikh, U. A., Filipenko, M. L., Rudnev, V. P., Xuân, B. B., Dũng, V.V., & Gitelson, I. I. (2010). Biodegradation of polyhydroxyalkanoates (PHAs) in tropical coastal waters and identification of PHA-degrading bacteria. *Polymer Degradation and Stability*, 95(12), 2350-2359. https://doi.org/10.1016/j.polymdegradstab.2010.08.023

Wang, B., Sharma-Shivappa, R. R., Olson, J. W., & Khan, S. A. (2013). Production of polyhydroxybutyrate by Alcaligenes latus using sugarbeet juice. *Industrial Crops and Products*, 43(1), 802-811. https://doi.org/10.1016/j.indcrop.2012.08.011

Wang, L., Wang, Z. H., Shen, C. Y., You, M. L., Xiao, J. F., & Chen, G. Q. (2010). Differentiation of human bone marrow mesenchymal stem cells grown in terpolyesters of 3-hydroxyalkanoates scaffolds into nerve cells. *Biomaterials*, 31(7), 1691-1698. https://doi.org/10.1016/j.biomaterials.2009.11.053

Ward, P. G., de Roo, G., & O'Connor, K. E. (2005). Accumulation of polyhydroxyalkanoate from styrene and phenylacetic acid by *Pseudomonas putida* CA-3. *Applied and Environmental Microbiology*, 71(4), 2046-2052.

Williams, S. F., & Peoples, O. P. (1996). Biodegradable plastics from plants. *Chemtech*, 26(9), 38-44.

Williams, S. F., Rizk, S., & Martin, D. P. (2013). Poly-4-hydroxybutyrate (P_4HB): a new generation of resorbable medical devices for tissue repair and regeneration. *Biomedizinische Technik/Biomedical Engineering*, 58(5), 439-452. https://doi.org/10.1515/bmt-2013-0009

Winnacker, M., & Rieger, B. (2017). Copolymers of polyhydroxyalkanoates and polyethylene glycols: recent advancements with biological and medical significance. *Polymer International*, 66(4), 497-503. https://doi.org/10.1002/pi.5261

Wong, P. A. L., Cheung, M. K., Lo, W.-H., Chua, H., & Yu, P. H. F. (2004). Investigation of the effects of the types of food waste utilized as carbon source on the molecular weight distributions and thermal properties of polyhydroxy-butyrate produced by two strains of microorganisms. *e-Polymers*, 4(1), Article 031. https://doi.org/10.1515/epoly.2004.4.1.324

Wu, C.-S. (2012). Characterization and biodegradability of polyester bioplastic-based green renewable composites from agricultural residues. *Polymer Degradation and Stability*, 97(1), 64-71. https://doi.org/10.1016/j.polymdegradstab.2011.10.012

Yamane, T. (1993). Yield of poly-D (-) -3-hydroxybutyrate from various carbon sources: A theoretical study. *Biotechnology and Bioengineering*, 41(1), 165-170. https://doi.org/10.1002/bit.260410122

Yang, H., Yan, R., Chen, H., Lee, D. H., & Zheng, C. (2007). Characteristics of hemicellulose, cellulose and lignin pyrolysis. *Fuel*, 86(12-13), 1781-1788.

Yang, L., Zhang, Y.-Y., Yang, G.-W., Xie, R., & Wu, G.-P. (2021). Controlled ring-opening polymerization of β-butyrolactone via bifunctional organoboron catalysts. *Macromolecules*, 54(12), 5509-5517.

Yao, Y.-C., Zhan, X.-Y., Zhang, J., Zou, X.-H., Wang, Z.-H., Xiong, Y.-C., & Chen, G.-Q. (2008). A specific drug targeting system based on polyhydroxyalkanoate granule

binding protein PhaP fused with targeted cell ligands. *Biomaterials*, 29(36), 4823-4830. https://doi.org/10.1016/j.biomaterials.2008.09.008

Yİlmaz, M., & Beyatli, Y. (2005). Poly-β-hydroxybutyrate (PHB) production by a *Bacillus cereus* M5 strain in sugarbeet molasses. *Sugar Industry*, 130(2), 109-112.

You, M., Peng, G., Li, J., Ma, P., Wang, Z., Shu, W., Peng, S. & Chen, G.-Q. (2011). Chondrogenic differentiation of human bone marrow mesenchymal stem cells on polyhydroxyalkanoate (PHA) scaffolds coated with PHA granule binding protein PhaP fused with RGD peptide. *Biomaterials*, 32(9), 2305-2313. https://doi.org/10.1016/j.biomaterials.2010.12.009

Yu, P. H. F., Chua, H., Huang, A. L., Lo, W. H., & Ho, K. P. (1999). Transformation of industrial food wastes into polyhydroxyalkanoates, *Water Science and Technology*, 40(1), 365-370. https://doi.org/10.1016/S0273-1223(99)00402-3

Zeller, M. A., Hunt, R., Jones, A., & Sharma, S. (2013). Bioplastics and their thermoplastic blends from *Spirulina* and *Chlorella* microalgae. *Journal of Applied Polymer Science*, 130(5), 3263-3275. https://doi.org/10.1002/app.39559

Zhou, J., Liu, J., Cheng, C. J., Patel, T. R., Weller, C. E., Piepmeier, J. M., Jiang, Z., & Saltzman, W. M. (2012). Biodegradable poly (amine-co-ester) terpolymers for targeted gene delivery. *Nature Materials*, 11(1), 82-90. https://doi.org/10.1038/nmat3187