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Biodegradable Microbial Bioplastics as Alternatives to Petroleum-Based Plastics: Production Technologies, Environmental Impacts, and Industrial Challenges

Stuti Jain[1], Khushboo Mohammed[2]
[1]Bangkok Patana School, Bangkok 10260, Thailand
[2]Indian Council for Technical Research and Development, Bhamti, Nagpur, 440022

ABSTRACT: As the Amount of petroleum-based plastics is increased in production and in the environment, there are growing interests in biodegradable substances from renewable biological resources. Microbial bioplastics, especially the polyhydroxyalkanoates, are promising alternatives, as they can be produced through microorganisms, modified for various applications, and broken down under proper environmental conditions. The reviews discuss the technologies for microbial production of bio-plastics, environmental impacts and challenges for industrial commercialization. The microbial producers, such as bacteria, halophilic microorganisms and engineered microbial cell factories, are described and the metabolic pathways involved in biosynthesis of polymers are discussed. Focus is placed on traditional fermentation, combination of microbial cultures, use of waste feedstocks, metabolic engineering, as well as new fermentation systems based on carbon-dioxide. The potential of downstream recovery technologies, polymer modification and industrial applications in packaging, agriculture and biomedicine are critically assessed. Life cycle assessment is used to evaluate the environmental performance, including greenhouse gas emissions, energy use, land use, resource depletion, and end-of-life management. Microbial bioplastics offer a way to lessen reliance on fossil resources, but their sustainability depends on the sources of the feedstocks, the electricity used in production, the efficiency of the fermentation process, and the biodegradation conditions. The high production costs, small scale of the industries, the variability of material characteristics and the lack of waste management infrastructure are still great challenges. The following points are also identified as future opportunities: continuous fermentation, synthetic biology, integrated biorefineries, environmentally friendly extraction, and standardisation of biodegradability testing. Overall, the potential of microbial bioplastics to contribute to a circular bioeconomy is high, but the transition of these bio-resources to replace petroleum-based polymers will require horizontal technological innovations, transparent environmental assessment, product design and economically viable industrialization in a variety of manufacturing sectors and waste management systems worldwide.

1. INTRODUCTION

Plastics made from petroleum are indispensable and increasingly important materials in our modern society due to their versatility, relatively low production costs, durability and excellent mechanical properties. Polyethylene, polypropylene, polystyrene, polyethylene terephthalate and other synthetic polymers are used in a wide variety of products including packaging, agriculture, construction, healthcare, transportation and consumer goods. Yet their widespread use has raised significant environmental issues related to fossil-dependence, greenhouse gas emissions, poor waste management and the build-up of long-lasting plastic pollution.

The molecular structure of conventional plastics tend to resist rapid biological degradation under normal environmental conditions, thus resulting in long lasting plastics in the environment. Fragmentation can produce micro and nanoplastics, which can spread across aquatic and terrestrial ecosystems. These challenges have driven research into new materials with their ability to provide the same functional attributes, but with fewer environmental impacts.

Bioplastics can be produced from any natural raw material and are biodegradable, or both, and encompass a wide range of materials. Notably, bio-based and biodegradable are two different sets of terms. A bio-based plastic is one plastic that is sourced, in part or totality, from biological carbon sources, but which is not necessarily biodegradable. In contrast, there are some biodegradable polymers that can be made from fossil fuels.

Microbial bioplastics are especially intriguing since the microorganisms can directly synthesize polymeric materials via biological metabolic pathways. Of these materials, polyhydroxyalkanoates (PHAs) have received considerable interest as naturally occurring polyesters that are stored as carbon and energy reserves by a variety of microorganisms.

Microbiological production of PHAs provides the possibility of utilizing renewable substrates, industrial residues, agricultural wastes and some carbon-containing gasses. They can also be chemically modified to make polymers of various mechanical, thermal and degradation characteristics.

The importance of microbial metabolism, the availability of nutrients and intracellular polymer accumulation has been established through research in PHA biosynthesis by bacteria (Urtuvia et al., 2014). Later on, enhancements of microbial strains, substrate usage, fermentation methods and copolymer production have been described (Anjum et al., 2016).

But the potential to replace petroleum-based plastics with alternatives from microbes comes with a significant hurdle. The challenges of the industrial production of PHA include the cost of feed stock, infrastructure for fermentation, extraction, purification and processing of polymer, which result in a relatively high cost of industrial PHA production. In addition, it is not a guarantee of environmental superiority in all production and disposal situations.

Therefore, a comprehensive evaluation needs to be performed considering the technological feasibility and environmental performance as a whole life cycle of the polymer.

The main focus of this review is on the microbial synthesis of biodegradable bioplastics, novel production technologies, renewable and waste-derived raw materials, recovery technologies, material characteristics, applications and life cycle effects as well as industrial challenges. The conditions that microbial bioplastics can offer a valuable environmental benefit over petroleum-based plastics in particular are emphasized.

2. CLASSIFICATION AND CHARACTERISTICS OF MICROBIAL BIOPLASTICS

2.1 Distinguishing bio-based and biodegradable polymers

Bioplastics' terminology is often misinterpreted. Bio-based plastics are plastics produced from renewable biological sources while biodegradable plastics can be converted to simpler products by microbes under certain conditions.

For instance, bio-based polyethylene can be derived from renewable ethanol but is chemically indistinguishable from traditional polyethylene and will not be biodegradable simply because it is made from renewable ethanol. Likewise, polylactic acid (PLA) is typically chemically polymerized from lactic acid that is produced by living organisms, and not stored as an intracellular polymer of the microorganisms themselves.

The difference in PHA is that they are produced in the cells themselves via enzyme mediated metabolic routes. This distinction is relevant to the assessment of production technologies, environmental claims and end-of-life behavior.

2.2 Polyhydroxyalkanoates

PHAs are a family of microbial polyester that are synthesized from hydroxyalkanoate monomers.

They are generally categorized based on the length of the polymer chain (monomer):

- Short-chain-length PHAs, including poly(3-hydroxybutyrate), or PHB.
- Medium-chain-length PHAs, which often exhibit greater flexibility.

- Copolymers containing different hydroxyalkanoate units, such as poly(3-hydroxybutyrate-co-3-hydroxyvalerate), or PHBV.

PHB is one of the widely researched microbial bioplastics. It is relatively highly crystallized and stiff, and can also be brittle and have a narrow processing window. The introduction of other monomers can affect crystallinity, flexibility, melting properties and mechanical properties. The dependence of molecular composition, production processes and suitability for replacement of conventional polymers was highlighted in a review of modern production technologies for PHA (Medeiros Garcia Alcântara et al., 2020).

2.3 Important microbial producers

PHAs are synthesized by a variety of microorganisms, including bacteria, archaea and some photosynthetic microorganisms. Cupriavidus necator is an extensively studied industrial strain which is able to store high levels of PHAs under certain nutritional conditions. Species belonging to *Pseudomonas, Bacillus* and *Halomonas* are also important producers. The different microorganisms have different substrate utilization, growth requirements, polymer composition and tolerance to the environmental conditions.

More recently, the development of diversified microbial cell factories and their possible applications in industrial PHA production have been reviewed (Diankristanti et al., 2024). More than the production of polymers needs to be taken into account when choosing a production organism. Other factors, such as growth rate, resistance to contamination, process stability, genetic accessibility, and downstream recovery needs, are also important for industrial suitability.

3. MICROBIAL BIOSYNTHESIS OF POLYHYDROXYALKANOATES

3.1 Biological function of PHAs

PHAs are synthesized as an intracellular energy store in many microorganisms when there is excess carbon available compared to other nutrients. Cells can secrete polymer granules under suitable conditions that can then be utilized as an internal carbon source and also as an energy source. PHA accumulation is often related to the deficiency of one or more nutrients but the exact mechanism of regulation differs between microorganisms.

Ability to store carbon means advantage in metabolism if nutrients are not available. The biological property is being used in industrial production systems by controlling substrate supply and culture conditions to promote polymer accumulation.

3.2 Principal biosynthetic pathways

There are three important enzyme-catalysed reactions in the classical PHB biosynthesis pathway. Acetoacetyl-CoA is formed by the condensation of two molecules of acetyl-coenzyme A with the help of β-ketothiolase. Next, acetoacetyl-CoA reductase will convert this intermediate to 3-hydroxybutyryl-CoA. Lastly, PHA synthase catalyzes the formation of polymer by repeatedly adding hydroxyacyl-CoA monomers.

The polymer composition depends on precursor molecules available and the substrate specificity of PHA synthase. Synthesis of medium-chain-length PHAs can also occur via pathways linked to fatty acid metabolism. This correlation between microbial biosynthesis, polymer composition and degradation has been studied extensively and reviewed in the field of PHA metabolism and circular resource utilization (Zhou et al., 2023).

3.3 Nutrient limitation and carbon partitioning

In industrial fermentations, biomass often grows while the polymer is not produced. In a first growth phase, nutrients are provided to boost the numbers of microbes. A subsequent accumulation phase can be performed with a constant supply of carbon and a restricted supply of selected nutrients. This can allow more available carbon to be directed towards the polymer storage.

But, nutrient limitation can also result in lower growth rates and impact productivity. The best strategy depends on the microorganism, feedstock, the design of bioreactor, and the desired properties of the polymer.

3.4 Polymer composition and metabolic control

The ultimate properties of the polymer depend on the composition of the polymer. The stiffness can be achieved from the PHB rich materials, however, they are also brittle and need to be modified. Adding 3-hydroxyvalerate or other monomer unit

can create flexibility and change the thermal properties. The availability of precursors, enzyme specificity, and carbon flow can be altered by metabolic engineering. But production of a desired copolymer must take into account microbial growth, cost of substrates, and uniformity of polymer composition.

4. CONVENTIONAL FERMENTATION TECHNOLOGIES

4.1 Batch fermentation

Batch fermentation is common in the laboratory and some industrial processes. Microorganisms are grown in a bioreactor with a known amount of medium, nutrients and substrates are added in the beginning or in limited quantities. The process is relatively simple and easy to operate; can control culture purity.

But there may be limits to productivity due to nutrient changes and build-up of inhibitory substances and loss of substrate. There may also be periods between production cycles for cleaning, sterilizing and preparing for batch processing.

4.2 Fed-batch fermentation

The fed-batch fermentation is a cultivation process where substrates are added to culture to control the growth of micro-organisms and the production of polymers. This approach can ensure that there are no high levels of substrate and no inhibition from the substrate. It also enables an operator to adjust carbon and nutrient availability at various production stages.

For high-cell-density PHA production, fed-batch systems are widely explored. Industrial competitiveness of PHA production has been highlighted in a recent review of advances in fermentation modes, substrates, microbial strain characteristics and downstream processing (Li & Wilkins, 2020).

4.3 Continuous fermentation

The continuous fermentation process is a process in which the culture broth is continuously removed and the substrate is continuously added. Benefits may be greater equipment utilization, less downtime and relatively stable operating conditions. But continuous systems may be susceptible to contamination, genetic instability, fluctuation of microbial population and fluctuation of polymer accumulation. It is difficult to maintain high biomass productivity with high content of intracellular polymers. Poly-production systems in the future may use multistage continuous systems to separate poly-production from microbial production.

4.4 Process optimization

The fermentation parameters that are important are the temperature, pH, dissolved oxygen, carbon to nitrogen ratio, substrate concentration, and mixing intensity. Oxygen transfer is especially significant in aerobic, high cell density cultures. Too little oxygen can reduce growth or change metabolism, and too much aeration and agitation will result in increased energy usage.

Thus, in order to optimize fermentation performance, it is important to consider polymer yield, volumetric productivity, energy demand and operating cost. The characteristics of a laboratory culture cannot be simply assumed to be unaffected from a transfer to a much larger culture system in the industrial bioreactor.

5. WASTE-DERIVED FEEDSTOCKS FOR SUSTAINABLE BIOPLASTIC PRODUCTION

5.1 Agricultural and lignocellulosic residues

The traditional microbial fermentation process usually utilizes purified sugars or other relatively high-cost carbon sources. These substrates can offer a predictable microbial activity and consistency of composition, but might require agricultural land, fertilizers, water and energy to produce.

Agricultural residues are an alternative carbon source and can help decrease the need for food-grade substrates. Crops straw, sugarcane residues, corn stover, fruit-processing waste, and other lignocellulosic wastes can be used as potential feedstocks. But the cellulose, hemicellulose, and lignin in lignocellulosic biomass are complex structures and are generally not readily accessible to microorganisms for efficient utilization without first treating and hydrolyzing the biomass. Pretreatment can produce inhibitory substances, use chemicals, and require more energy.

The agricultural waste resources available for PHA production were reviewed, identifying potential sources of lignocellulosic wastes, lipid containing wastes, molasses and whey, and the need for optimizing the PHA fermentation and scaling up to the industrial level (Wang et al., 2021).

5.2 Food-processing residues

The organic residues from food processing industries contain significant amounts of fermentable carbohydrates, proteins and lipids. These include food processing effluents such as fruit-processing by-products, dairy residues, sugar-processing waste and selected food manufacturing effluents. The streams can be used as microbial substrates after proper treatment.

A detailed study of PHA obtained from organic waste streams identified opportunities to value-add food, milk and sugar-processing wastes (Ganesh Saratale et al., 2021). But the waste composition can change with the seasons and at different production facilities. Therefore it is necessary to characterise the feedstock to prevent inconsistent fermentation performance.

5.3 Cheese whey and dairy by-products

The organic components of cheese whey are able to facilitate microbial proliferation, including lactose. The potential benefit for PHA production could help to minimize the environmental impact of disposal and add value to dairy processing. But all the microorganisms which produce the PHA cannot use lactose as a feed directly.

Further hydrolysis or strain selection or metabolic engineering may be required. Production of PHA from whey is economically viable based on the transport distances, whey concentration, competing applications, and processing needs.

5.4 Crude glycerol

With the production of biodiesel, crude glycerol is produced as a by-product and it may be available as a relatively cost-effective carbon source. It's composition depends on the processing conditions and feedstock for biodiesel. The contaminants can be methanol, salts, soaps and catalyst residues.

Such constituents can inhibit the growth of the microorganisms or can make the purification more difficult when downstream processing is required. Hence crude glycerol must be assessed based on its nutrient composition and not as a generic “low cost substrate”. Glycerol has been identified as one of the promising feedstock for circular biomanufacturing based on the reviews on waste-derived PHA production (Pakalapati et al., 2018).

5.5 Wastewater-derived carbon

Biodegradable organic compounds are available in municipal and industrial wastewater which can be used for microbial conversion. The recovery of these compounds as PHAs could provide a combined pollution control and resource production. But variability in feedstocks, contamination, polymer purity and process stability need to be addressed with wastewater-based processes.

A review of PHA recovery from wastewater highlighted the potential of mixed microbial cultures, waste-based production platforms and discussed significant challenges from upstream and downstream (Mannina et al., 2020). Wastewater-derived PHAs can be used in some industrial applications, but for use in food contact or biomedical applications, it is necessary to conduct rigorous purity and safety evaluations.

6. MIXED MICROBIAL CULTURES AND RESOURCE RECOVERY

6.1 Concept of mixed microbial culture production

The traditional production of PHA is often based on the use of specific and pure microbial strains, which are cultured in controlled conditions. Mixed microbial culture: More than one microbial population is intermingled in the same environment. These can be supplemented with activated sludge or other microbial communities.

The benefit of their potential is that they can ferment variable substrates that are taken from waste without needing to be sterilized to the same extent as pure-culture fermentation. But the composition of the microbial community and the properties of the polymer might change with time.

6.2 Feast-and-famine selection

One of the most popular mixed culture enrichment techniques is the alternating high-low substrate method. Another advantage could be that during the feast phase, microorganisms that can quickly sequester carbon as intracellular polymers might be able to outcompete others. Stored reserves can be used for survival and maintenance during the famine phase.

Selection cycles can increase the percentage of individuals in a population with desirable PHA storage traits. The process needs proper hydraulic retention time, substrate and operating conditions.

6.3 Volatile fatty acid production

Many complex organic wastes can be fermented to produce volatile fatty acids (VFA) prior to PHA production. The acids can be acetate, propionate, butyrate and/or valerate. The relative concentrations have an influence on microbial metabolism and may even affect the monomer composition of the obtained PHA.

A two-stage process is thus able to separate waste fermentation from polymer build-up. The extra processing steps, however, add to equipment needs and increase the level of operation.

6.4 Pilot-scale experience

Production of PHA by mixed cultures has moved from laboratory to field. The literature search revealed reported pilot installations and identified differences of the feedstocks and enrichment methods, polymer yields, and recovery strategies (Estévez-Alonso et al., 2021). This evidence shows technological advancements, but also the discrepancy between the feasibility of pilot scale and effective industrial commercialization. Commercial systems may not have the research funding, waste streams or level of technical supervision required by pilot systems.

6.5 Industrial integration

Microbial mixed cultures can be included in wastewater treatment plants, food-processing plants and other waste management systems. These include opportunities for shared facilities, lower waste disposal needs and better resource recovery. But integrated facilities need to keep in mind the operational priorities of their main processes.

For instance, wastewater treatment plants need to keep the effluent quality regulated even if the production of polymer is not favorable for a period of time. Polymer recovery from industrial waste-derived PHA production was reviewed and possibility discussed to integrate polymer recovery in biogas production and other biorefinery products (De Donno Novelli et al., 2021).

7. METABOLIC ENGINEERING AND SYNTHETIC BIOLOGY

7.1 Improving microbial carbon utilization

Metabolic engineering involves making changes to cellular pathways to enhance the production of the desired product from the substrate. Potential goals for PHA production would be to increase carbon flux directed towards polymer precursors, decrease competing metabolic pathways and widen the range of available substrates.

Another area of engineering that could be used to aid microorganisms in processing sugars, organic acids or industrial residues that they aren't able to process efficiently by natural means. Growth, stability and stress tolerance can, however, be impacted by genetic modification. Successful industrial strains require long term cultivation without problems.

7.2 Engineering polymer composition

The monomers that can be used in polymer chains vary from one PHA synthase to another. The possibility of changing substrate specificity and aiding in the production of materials with desirable properties is an additional benefit of enzyme engineering. This can help to better control flexibility, crystallinity and processability.

The review on microbial biotechnology for PHA production revealed three key areas to further lower production costs: biosynthetic pathway modification, substrate expansion, and better recovery (González-Rojo et al., 2024).

7.3 Halophilic microorganisms

High salt conditions are suitable for the growth of halophilic microorganisms. Use of them in the production of PHA has been interesting because they could grow under the saline conditions that would limit contaminants and also eliminate the need for

normal sterilization requirements. Some strains of *Halomonas* have been explored as a platform for open, or less stringently sterile, fermentation.

But salinity causes problems such as corrosion of equipment, handling of salts, treating wastewater, and recovering polymers. As a result, the balance of decreased sterilization demand needs to be considered with the comprehensive operational and environmental costs of saline bioprocessing.

7.4 Thermophilic production systems

Thermophilic microorganisms are microorganisms that can grow at high temperatures and can offer benefits in certain industrial processes. Raising the cultivation temperature might have an impact on contamination risk, reaction rate, and cooling needs. Still, temperature control and stability of the organisms and qualities of the product are significant factors.

The waste-derived substrates, recovery methods and technical barriers for industrial implementation of thermophilic microorganisms for the production of PHA were reviewed (Chavan et al., 2021).

7.5 Carbon dioxide and single-carbon substrates

Recent research is exploring the use of carbon dioxide, methane, carbon monoxide and other one-carbon substrates for producing microbial PHA. These strategies can help to decrease reliance on traditional agricultural carbon sources. There are, however, different microbial pathways, reactor configurations and energy input requirements for different C1 substrates. Carbon dioxide utilization might need significant reducing power or external energy; in the case of methane-based processes, gas transfer and methane leakage would be issues.

An overview of C1-based PHA production was presented, highlighting the potential and opportunities offered by microorganisms, natural and engineered (Jo et al., 2021). It is not a given that using captured carbon makes a product carbon neutral. The environmental impact of the energy source, carbon accounting, conversion efficiency and the final fate of the polymer are important.

8. DOWNSTREAM RECOVERY AND PURIFICATION TECHNOLOGIES

8.1 Importance of downstream processing

PHA polymers are found in microbial cells in general. Following fermentation, the polymer needs to be separated from the cellular biomass and purified to the desired level of purity for the targeted applications. Downstream recovery can significantly add to the cost of production and environmental impacts. Even a process that has good fermentation productivity could be economically unfeasible if too much expensive solvent or energy is needed to extract the product.

8.2 Solvent-based extraction

The polymer can be separated from cellular components by solvent extraction. Conventional methods have relied on halogenated solvents, which could have environmental, occupational and regulatory issues. Selected esters, ketones, carbonates and other solvent systems are used as alternatives.

Although a solvent that is environmentally preferable as a solvent is a step in the right direction, it must still be evaluated for toxicity, energy requirement, recovery and suitability for polymer quality.

A review of the recovery methods from pure and mixed microbial cultures included the solvent extraction and cellular lysis methods, highlighting the importance of maintaining the purity of the polymer, the recovery yield, and the molecular weight of the polymer after recovery (Pagliano et al., 2021).

8.3 Chemical and enzymatic cell disruption

Cell disruption can be achieved using chemical and/or enzymatic methods.Chemical and enzymatic cell disruption are possible. The objective of the cell disruption approaches is to allow the removal of nonpolymeric biomass without loss of PHA granules. The methods can include alkaline treatment, surfactant, oxidizing agents, enzymes, or a combination of physical and chemical.

Enzymatic methods may be reducing the need for the use of harsh chemicals but enzyme prices and processing times may be a limiting factor. Excessive chemical reaction could cause destruction of the polymer chains and the decrease in molecular weight. Hence it is necessary to consider recovery efficiency along with quality of material.

8.4 Mechanical and physical recovery

Biomass processing may be provided by mechanical disruption, filtration, centrifugation, and membrane separation. These techniques can save solvents, but can be expensive and energy intensive.

Their suitability depends on the characteristics of the cell, the size of the polymer granules, the biomass concentration, and the desired purity. Hybrid recovery processes can involve physical pretreatment and controlled chemical or enzymatic purification.

8.5 Process selection

An effective recovery process should have the following attributes: minimize polymer loss; maintain molecular characteristics; have low hazardous emissions; and be able to reuse processing materials. The recovery technologies have to be scalable and meet the industrial safety standards.

Comparative research has highlighted the importance of comparing the purity, recovery, environmental compatibility and economic performance of the extraction methods used (Kurian & Das, 2021).

9. MATERIAL PROPERTIES AND INDUSTRIAL APPLICATIONS

9.1 Mechanical and thermal properties

In order to be used as commercial bio-plastics, microbial bio-plastics must meet application-specific performances. The important characteristics are tensile strength, elongation at break, impact resistance, thermal stability, crystallinity, and permeability.

PHB may have high stiffness, but may have brittleness relative to some of the more traditional packaging polymers. It may also have a melting and degradation temperature that are too close to make melt processing difficult.

Performance can be enhanced by copolymerization, blending, plasticization and optimization of processing. Modifications, however, could affect biodegradability and recyclability and should therefore be considered for the final formulation and not the base polymer.

9.2 Packaging applications

An important potential market for biodegradable microbial plastics is packaging.

These can be films, trays, coatings, containers and specific food contact materials. But various packaging products call for a combination of moisture-proofing, oxygen barrier, flexibility, transparency and heat-resisting properties.

However, PHA materials might be appropriate for specific applications and should not be used for all applications where conventional plastics are used without reformulation. The food-contact applications also have to meet the applicable migration, purity and safety requirements.

9.3 Agricultural applications

Fertilizer products can be biodegradable mulch films, controlled-release systems, and certain temporary mulch materials. So some products may not need to be retrieved after use with biodegradable polymers.

But the field biodegradability is variable and is dependent on the type of soil, polymer composition, film thickness and environmental exposure.

Soil is a type of condition in which products should be tested if they are meant to biodegrade there. A material that has been certified for industrial composting does not necessarily qualify as an appropriate material for use in agriculture in soil.

9.4 Biomedical applications

Selected PHAs have been found to be biocompatible and to degrade in a controlled manner, which has led to biomedical applications being investigated. Some possible applications are tissue engineering scaffolds, drug delivery systems, materials for wound applications and temporary medical devices.

However, there is a high level of requirement for the purity of the polymer and its molecular properties, degradation products and biological responses in order to be considered as suitable for biomedical applications.

The purification and validation of materials derived from microbial cultures from waste may be more challenging. The microbial production, recovery issues, and potential benefits of waste feedstocks were discussed in the context of PHA characterization and applications (Getino et al., 2024).

9.5 Blends and composites

The mechanical properties and processing characteristics can be modified by PHA blending. Other biodegradable polymers, natural fibres and starch-based materials, as well as selected additives, are possible blending partners.

Although they can enhance the stiffness or lower the material cost, they can also introduce new limitations in terms of moisture sensitivity, interfacial compatibility, and degradation behaviour. Therefore industrial formulation should take the performance, safety, processability and end-of-life management into consideration.

10. BIODEGRADATION MECHANISMS AND ENVIRONMENTAL FATE

10.1 Biological degradation

In PHA biodegradation, microorganisms and extracellular enzymes are involved that break down polyester chains. Polymer breakdown may result in smaller molecules, which then can be metabolized by microorganisms.

Ultimate biodegradation can yield carbon dioxide, water and biomass under appropriate aerobic conditions. Depending on the microbial environment and the treatment process, methane can also form from these processes under anaerobic conditions.

The degradation rate is influenced by polymer chemistry, crystallinity, surface area, temperature, moisture, presence of oxygen, and the composition of microbial community. A comprehensive review was carried out on synthesis and degradation of PHA, which gave insights on the role played by microorganisms, enzymes, metabolic pathways and environmental parameters (Zhou et al., 2023).

10.2 Industrial composting

Industrial composting systems are designed with specific parameters that allow biological decomposition to take place. The degradation of polymers is affected by the following factors: temperature, moisture, aeration, and treatment time. But, industrial composting does not necessarily mean the same performance in soil, freshwater, marine or home compost settings.

Certification standards also specify particular testing conditions and performance requirements. Therefore, the product labelling shall be clear and should differentiate between product biodegradability and industrial compostability.

10.3 Soil and freshwater environments

Microbial activity, polymer properties, water content, and temperature are all factors in the biodegradation of PHAs in soil. There may be considerable variability among soils in the degradation rates.

Likewise, the nutrient, microbial, oxygen and seasonal-temperature levels of freshwater vary. An extensive biodegradability assessment of bioplastics under managed and unmanaged environments highlighted the need of material-based and environment-based assessment (Gadaleta et al., 2025).

10.4 Marine biodegradation

The biodegradation in marine environments has been a specific concern as plastic waste is persistent and impacts coastal and ocean ecosystems. Some of the PHAs can break down in seawater, but it takes time for this to happen.

A meta-study analyzing degradation of PHA in marine conditions calculated a mean degradation rate of ~0.04-0.09 mg per day per cm2 for the conditions represented by the studies analyzed here (Dilkes-Hoffman et al., 2019). The authors demonstrated that it would take about 1.5-3.5 years for a hypothetical PHA bottle to fully decompose. The following estimates illustrate the importance of using biodegradable materials not to be used as substitutes for non-biodegradable ones as harmless materials.

10.5 Microplastic formation and ecological concerns

Biodegradable plastics can break down into smaller pieces before the complete mineralization. Intermediate fragments can be present in the environment for different times, and can be associated with organisms and contaminants. Uncertainties were identified in a recent review of biodegradable plastics in marine environments such as microplastic formation, interactions of contaminants, microbial colonization and long term ecological effects (Velayudhan et al., 2026). Even if biodegradable materials are employed, prevention of environmental release is vital.

11. LIFE CYCLE ASSESSMENT OF MICROBIAL BIOPLASTICS

11.1 Importance of life cycle assessment

Life Cycle Assessment (LCA) is an assessment of the environmental impact of a product over a well-defined life cycle stage. Microbiological bioplastics are applicable for the different stages of feedstock production or collection, pretreatment, fermentation, polymer recovery, drying, compounding, product manufacturing, transportation, use, and end-of-life management.

The comparison of the petrol based plastics and the bio-plastics should consider the differences in the property of the materials and their product performance. Comparing one kilogram of PHA with one kilogram of polyethylene might not be enough if different amounts of PHA and polyethylene are needed to do the same job.

11.2 Feedstock-related impacts

The selection of feedstock has a significant impact on environmental performance. Agricultural substrates could include land use, irrigation, fertilizer manufacturing and emissions. The use of waste derived substrates can lower the virgin resource requirements, but may also add burdens in the collection, transportation and pretreatment of waste.

Allocation of environmental impacts between waste generators and recovery facilities is particularly important. For instance, if no upstream burden is assigned to a waste feedstock, the results are different than if part of the production burden was assigned to the same feedstock.

11.3 Energy consumption

Energy is needed for microbial cultivation for mixing, aeration, temperature control, sterilization, and downstream processing. Aerobic fermentation can be very energy intensive, especially if high rates of oxygen transfer are required.

Additional environmental impacts can be significant for polymer extraction, solvent recovery and drying. Thus, the carbon footprint can be significantly affected by the electric energy mix and process efficiency.

11.4 Comparison of feedstock pathways

A comparative LCA of PHA production was performed, comparing conventional corn-based pathways with emerging carbon dioxide-based pathways (Koch et al., 2023). The study demonstrates that there is a need to consider alternative production routes, and that not all renewable feedstocks can be taken for granted in terms of their environmental impacts. Carbon dioxide production can decrease some of the impacts of agriculture, but its effectiveness is dependent on energy supply, energy conversion efficiency and supporting infrastructure.

11.5 Waste-derived oil feedstocks

By-products of biodiesel and used cooking oil have been studied for PHA production. The results of an LCA of PHA production scenarios using either vegetable oil or biodiesel by-products or used vegetable oil showed that the choice of feedstock can have a significant impact on environmental outcomes (Nitkiewicz et al., 2020). These findings help in considering feedstock options as opposed to assuming waste-derived production is sustainable.

11.6 Climate impacts and carbon accounting

The production of microbial bioplastics may also decrease fossil carbon consumption but still emit greenhouse gases. Emissions from electricity generation, chemical production, transport and processing are not prevented by using renewable carbon. The question of whether the carbon temporarily remains in the product or is released in the biodegradation, composting, incineration or other treatment process should also be taken into account when compiling biogenic carbon accounts.

One study which also took climate tipping into its PHA life cycle assessment showed the importance of methodological choices in considering climate-related performance (Vea et al., 2021).

11.7 End-of-life scenarios

End-of-life options include recycling, incineration, composting, anaerobic digestion and landfill. It will depend on the type of polymer product, contamination of the product, collection infrastructure and local treatment conditions. Even if biodegradable plastics comply with some of the selected certification criteria they may not be compatible with existing composting sites. Likewise, blending biodegradable plastics with other recyclable plastic streams can also pose sorting issues. LCA should thus consider possible scenarios for collection and treatment instead of ideal disposal behavior.

12. TECHNO-ECONOMIC ASSESSMENT AND INDUSTRIAL FEASIBILITY

12.1 Major cost drivers

The production of commercial PHA is only possible in the presence of costs involved in the use of carbon substrates, nutrients, fermentation equipment, utilities, labor, downstream recovery, purification and product formulation. Feedstock costs may be high especially if refined substrates are used. Feeding waste does not, however, necessarily reduce overall costs, when compared to feeding refined sugars. Waste streams might include the need for conveyance, pretreatment, contamination control, and further purification.

12.2 Productivity and recovery yield

Polymer concentration, accumulation of polymer in the cells, volumetric productivity and recovery efficiency are essential for the industrial profitability. The amount of nonpolymeric biomass to be treated can be decreased if there is a high content of intracellular polymers. High volumetric productivity can enhance the rate of the reactor utilisation. These metrics need to be taken as a whole, however.

A slow process that produces a highly concentrated polymer might not be as appealing as a fast process with less concentrated polymer.

12.3 Industrial scale-up

Fermentation is a process that can be transferred from a laboratory tank to an industrial bioreactor, which presents problems of oxygen transfer, heat removal, mixing, contamination, and monitoring of the process. Variability in composition and supply from waste derived substrates.

During a discussion on challenges of scale-up, it was concluded that integration of PHA production with existing waste management and biorefinery operations was important (Rodriguez-Perez et al., 2018). To make a product successful, it has to be produced for long time with constant product characteristics.

12.4 Market competition

Advantages of petroleum-based plastics include well-known infrastructure and supply chains, high production volumes and long experience in processing.

Aside from environmental attributes, the microbial bioplastics will have to be competitive with plastics on price and performance as well as availability and compatibility with existing production lines. In some of the more expensive applications, the cost of the materials may be more acceptable. However, when it comes to commodity packaging the price sensitivity can be significant.

12.5 Integrated biorefineries

Multiple products can be extracted from a single feedstock in an integrated biorefinery. The process of PHA manufacturing can be integrated with wastewater treatment, biogas production, nutrient recovery, or other biochemical processes. This can lead to better use of resources and spreading the infrastructure costs between multiple products.

But the actual results of the performance depend on product markets, on the integration of processes and on the reliability of the entire facility.

13. COMPARATIVE ASSESSMENT OF MICROBIAL AND PETROLEUM-BASED PLASTICS

Table 1. Comparison of Microbial and Petroleum-based plastics

Characteristic	**Microbial PHAs**	**Conventional petroleum-based plastics**
Primary carbon source	Renewable biomass, waste carbon, or selected gaseous substrates	Predominantly fossil hydrocarbons
Production method	Microbial fermentation and polymer recovery	Petrochemical synthesis and polymerization
Biodegradability	Possible under suitable conditions; varies by polymer and environment	Generally limited for major commodity polymers
Mechanical performance	Highly dependent on PHA composition and formulation	Broad range of mature, optimized materials
Production costs	Often comparatively high	Generally lower for established commodity grades
Industrial capacity	More limited and developing	Extensive global manufacturing infrastructure
Feedstock variability	Significant when waste substrates are used	Relatively standardized industrial feedstocks
Processing compatibility	May require specialized formulations and controls	Established extrusion, molding, and film processes
End-of-life management	Requires appropriate collection, treatment, or recovery	Recycling, energy recovery, and disposal systems vary
Environmental performance	Potential advantages, but highly process-dependent	Significant fossil-resource and persistence concerns

The comparison shows that microbial bioplastics are not a clear-cut winner in all the technical and environmental aspects. The benefits they offer will vary according to the products, the production process, the local energy system and realistic end-of-life treatment.

14. INDUSTRIAL CHALLENGES AND COMMERCIALIZATION BARRIERS

14.1 Production economics

One of the key challenges for the mass production of microbial bioplastics is still their high production cost. Special facilities, including fermentors, and continuous monitoring are needed for industrial fermentation.

Waste derived feedstocks can help to lower substrate cost, but can also increase the amount of pretreatment and purification needed. Thus, in order to cut costs, optimization needs to be done throughout the whole production chain.

14.2 Feedstock consistency

Seasonal feedstock availability, moisture content, contamination and composition differences are all challenges to waste-based fermentation systems. These changes have the potential to affect the growth of the microorganisms, the production of the polymers, and the quality of the product.

Higher quality feedstocks, monitoring, and contingency plans are needed for industrial facilities. If these controls are not in place, then inexpensive substrates can cause inconsistent manufacturing performance.

14.3 Product quality and processing limitations

Some formulations of PHA are brittle, thermally sensitive, or incompatible with standard processing methods. Their limitations could hinder their application in higher demands for packaging and engineering.

Modifications can enhance the performance of materials and can be done by blending and/or copolymerization, but this may lead to a higher cost and/or to a change in biodegradability. Application-specific performance would be a priority when developing industry than the idea of using all traditional polymers to be replaced with microbial material.

14.4 Downstream environmental burdens

It will take a great amount of energy, solvents, chemicals, and water to recover processes. These burdens might balance some of the environmental benefits of renewable feedstocks. The recycling of solvents, reuse of enzymes, efficient separation and less drying requirements are therefore research priorities.

14.5 End-of-life infrastructure

There are appropriate collection and treatment facilities for biodegradable products. Products can go to landfill, incineration or conventional recycling where industrial composting or processing facilities are not available.

The environmental performance obtained can vary significantly from laboratory biodegradation studies. Appropriate waste management and clear labeling are crucial.

14.6 Standards and consumer communication

The terms green, eco friendly and biodegradable can cause confusion if there are no conditions of use. The products should indicate both if they have been proven to be biodegradable and if, and where, biodegradation is proven.

The full commercial formulation, and not the polymer alone, should be certified. Clear environmental communication can help to avoid false claims and wrong disposal practices.

15. RESEARCH PRIORITIES FOR SUSTAINABLE INDUSTRIAL IMPLEMENTATION

The future research should combine microbial biotechnology, chemical engineering, polymer science, environmental assessment and industrial economics.

A key research focus is the creation of strong microbial strains that will be able to work with a range of feedstocks, and retain high productivity and stable polymer composition. Better designs of bioreactors can decrease the need for aeration and mixing. Though microbial stability and control of contamination issues are important, continuous production strategies may be beneficial in equipment utilization.

Efforts required for downstream processing should be directed towards minimizing solvent use, maximizing recovery of process chemicals and maintaining polymer molecular weight. Research should focus on applications where there is a clear functional benefit in using biodegradable material and this does not compromise on important functional properties.

Technology development needs to be accompanied by environmental assessment from early laboratory development to pilot and industrial development. Prospective LCA can help to pinpoint environmental hotspots that can be addressed before the massive costs of infrastructure decisions.

Likewise, a techno-economic analysis can be used to assess if there are commercial benefits to be gained from improved yield, recovery, or energy efficiency. To create viable pathways toward commercialization, cooperation among researchers, manufacturers, waste management companies, and regulatory bodies is essential.

16. LIMITATIONS AND CHALLENGES

While considerable efforts have been made to research the production of microbial bioplastics, some drawbacks limit the conclusions and applications of existing studies. One of the difficulties is that most research conducted is at the laboratory level, and often includes optimized substrates, controlled fermentation conditions, and small-sized bioreactors. These results may not be representative of a plant where feedstock variations increase, oxygen transfer limits may be important, contamination is more of an issue, and equipment cost is a more significant criterion.

Another restriction is related to the diversity of microbial production systems. Comparisons of polymer yield and production cost are difficult because of the differences in microorganisms, carbon source, nutrient media, fermentation process, and extraction processes. In addition, economic estimates may not include infrastructure depreciation, waste pretreatment, solvent recovery and long-term maintenance.

Uncertainty regarding environmental assessment arises as well. Various functional units, allocation methods, electricity usage and end-of-life scenarios are often used in life cycle studies. This means that the conclusions that can be drawn regarding the superior properties of microbial bioplastics compared to petroleum-based plastics can differ significantly between studies.

There are also challenges in methodology when it comes to biodegradation research. Laboratory composting experiments do not necessarily simulate natural soil, freshwater or marine conditions. Because many factors affect degradation rates, including microbial activity, temperature, additives, crystallinity and polymer thickness, statements of general biodegradability should be interpreted with caution.

However, inconsistent mechanical properties, processing sensitivity, limited manufacturing capacities and competition from cheap conventional polymers are still hampering the use of industrial applications. It also limits environmental benefits, due to poor collection and treatment systems.

This narrative review also has some drawbacks as it is not conducted as a systematic review, which involves conducting systematic database searches and applying a predetermined risk of bias assessment.

Standard testing, environmental reporting, representative industrial demonstrations, realistic economic modelling and independent product performance and biodegradability verification are needed to address these challenges.

17. FUTURE PERSPECTIVES

Future microbial bioplastics developments shall build on the incorporation of advanced biotechnology, sustainable feedstocks, efficient manufacturing and evidence based environmental assessment. Biological approaches such as synthetic biology and metabolic engineering can be used to create microbial cell factories that can be used to produce polymers with regulated molecular composition, with enhanced material properties, and to utilize a wide variety of carbon sources. Computational metabolic modeling of the genome and high throughput screening can help to identify productive strains and optimal cultivation conditions more quickly.

Processing waste as feedstocks will continue to be important to boost the economic and environmental value. A combination of PHA production, wastewater treatment, organic acid fermentation, biogas production and nutrient recovery in an integrated biorefinery may raise the resource efficiency and split up the operational costs between several products.

Several new fermentation technologies, such as the continuous culture, mixed microbial cultures, and halophilic production systems, can decrease processing costs. In the industrial world, however, it is important to prove that the product is stable in operation over time, the polymer quality is maintained and the performance is consistent even if the feedstocks vary.

Another research priority is downstream processing. Environmentally compatible solvents, enzymatic recovery, membrane-based separation and reduced-energy purification may help to reduce environmental burdens without compromising polymer integrity.

Future environmental studies on harmonized life cycle assessment methods and realistic electricity sources, infrastructure requirements, product lifetimes and waste management scenarios can and should be used. Industrial, home, soil, freshwater and marine environments should be treated separately for standardized biodegradation testing.

Fermentation optimization and quality assurance could benefit from Digital process monitoring and predictive modelling. Policy measures such as clear labelling, proper certification, sustainable procurement, and investment in waste management infrastructure, could help to enable responsible commercialisation.

Finally, future studies should focus on applications in which microbial bioplastics can be shown to offer clear environmental benefits and performance in the technical application.

18. CONCLUSION

The use of microbial bioplastics that are biodegradable is a future technology option that can reduce the reliance on polymers derived from petroleum and contribute to the transition towards a circular bioeconomy. The synthesis of PHAs using renewable substrates, wastes, and emerging alternative carbon sources makes them especially appealing. They can have a wide range of monomers which can be used to achieve specific properties for specific applications such as mechanical properties, processability, and biodegradability.

This review focuses on advances in microbial strain development, optimization of fermentation processes, metabolic engineering of microbes, mixed microbial culture and production of polymers from waste. Production potential could be further widened by emerging technologies based on halophilic microorganisms, thermophilic fermentation and the use of carbon dioxide. However, downstream recovery is still a challenging technical and economical task, which demands a better separation efficiency, chemical usage and preserving the quality of the polymers.

Biological origin and biodegradability are not enough to achieve environmental sustainability. Feedstock choice, electricity use, fermentation efficiency, recovery methods, delivery and end-of-life treatment are all factors which impact life cycle performance. In addition, biodegradable polymers can break down slowly in the natural environment, so it is important to take care of their disposal.

Barriers exist for the industrial commercialization in the areas of high production costs, low manufacturing capacity, variable material characteristics and lack of recovery infrastructure. To solve these problems, a research coordination should be established in the fields of microbiology, biochemical engineering, polymer science, environmental assessment, and industrial economy.

Future developments should focus on integrated biorefineries, on the development of efficient microbial cell factories, on environmentally friendly extraction processes, on the establishment of standardized biodegradation testing, and on the product development suitable for application.

Overall, with considerate management of production and disposal, microbial bioplastics could make a significant contribution to more sustainable material systems. The successful uptake of their implementation will be dependent on showing measurable environmental benefits, economic feasibility, reliability of performance and compatibility with circular resource management strategies.

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AUTHOR CONTRIBUTIONS

Dr. Khushboo Mohammed: Conceptualization, Investigation.

Stuti Jain: Literature review and analysis

Stuti Jain: Manuscript Drafting

Dr. Khushboo Mohammed: Supervision, Writing—Review & Editing

CONFLICT OF INTEREST

The author declares no conflicts of interest to disclose.

ETHICS STATEMENT

This manuscript is a literature-based review of previously published research and does not involve the recruitment of human participants, collection of primary patient data, or experimentation on animals. Therefore, institutional ethics committee approval and informed consent were not required for the preparation of this review.

DATA AVAILABILITY STATEMENT

Data supporting the findings of this study are available from the corresponding author upon reasonable request.

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