



Microbial Factories for Sustainable Bioplastic Precursors

Chukwudi Anthony Ugwuanyi

Department of Applied Microbiology Ebonyi State University Nigeria

Email:ugwuanyitony@gmail.com

ABSTRACT

The growing environmental burden of petroleum-based plastics has intensified interest in bioplastics as sustainable alternatives. Among various strategies, microbial factories offer a promising route for the production of bioplastic precursors, leveraging renewable feedstocks and advanced metabolic engineering. This review highlights the potential of microorganisms such as *Escherichia coli*, *Pseudomonas spp.*, and cyanobacteria in synthesizing polyhydroxyalkanoates (PHAs), polylactic acid (PLA) precursors, and other biopolymer intermediates. Advances in synthetic biology, systems biology, and fermentation technology have enabled the optimization of microbial metabolism for improved yield, productivity, and cost-effectiveness. Challenges remain, however, including feedstock availability, scale-up efficiency, metabolic burden, and downstream processing costs, which hinder commercial competitiveness with petrochemical plastics. Emerging strategies such as adaptive laboratory evolution, CRISPR-based genome editing, and valorization of agro-industrial residues are discussed as solutions to these limitations. The review underscores the importance of integrating biotechnology, process engineering, and circular economy principles to advance microbial bioplastic production toward industrial-scale sustainability. Ultimately, microbial factories represent a pivotal platform for reducing reliance on fossil resources and mitigating plastic pollution.

Keywords: Bioplastics, Microbial Metabolism, Polyhydroxyalkanoates (PHAs), Fermentation and Synthetic Biology.

INTRODUCTION

The utilization of non-renewable petrochemical resources has led to global warming and environmental pollution. Bioplastics produced from renewable biomass resources provide an alternative to petrochemical plastics, but their high production cost prevents them from replacing conventional plastics. Microorganisms and their associated enzymes can degrade raw materials to acids that can be microbially fermented to synthesize bioplastic materials. Microbial synthetic and molecular biology enables the engineering of microbial cell factories to efficiently convert renewable biomass into commodity bioplastics and their precursors. These bioplastic materials include polyhydroxyalkanoates (PHAs), polylactic acid (PLA), polyethylene-furanoate (PEF), and polybutylene succinate (PBS). Bioplastics degrade faster compared to petrochemical-derived plastics and represent a sustainable alternative to alleviating environmental hazards. Accelerated research progress on microbial metabolic engineering of bioplastic precursors from renewable biomass supports pertinent microbial-biorefinery technologies [1].

Microbial Metabolism and Bioplastic Production

Microbial Metabolism and Bioplastic Production Plastics have been a versatile commodity across various sectors, yet their environmental detriments have attracted significant attention towards sustainable alternatives. Such alternatives are bioplastics, biopolymers derived from biomass or synthesized from microorganisms. Various microbial bioconversion routes to produce bioplastic precursors have been explored, with microbial species exhibiting adaptability to diverse raw materials and conditions, capacity to degrade certain bioplastic polymers, and potential to produce diverse polymers [2]. Ample microbial tools are available to improve bioplastic yield and properties, ensuring compatibility with existing manufacturing processes. Microbial metabolism underlines the synthesis of bioplastic precursors such as succinic acid, lactic acid, 3-hydroxypropionic acid, and 1,4-butanediol. Cell factories like *Trenharia virus*, *Pseudomonas putida*, *Saccharomyces cerevisiae*, and *Escherichia coli* can be engineered to optimize these pathways; for example, *E. coli* strains have been modified to utilize glycerol for

metabolite production [1]. Analogous to precursors synthesized through non-microbial routes, these metabolites are polymerized to generate bioplastics. PHAs, polyhydroxycarbonates with plastic properties are produced in microbial cells as survival materials during nutrient stress. They degrade into crop-friendly products rather than pollutants. Several species are potential PHA producers, including *Cupriavidus* sp., *Pseudomonas* sp., and *Bacillus* sp., with recombinant *E. coli* strains also capable of secretion. Other bioplastics include starch-based polymers (its derivatives and blends), cellulose-based polymers (cellophane, cellulose acetate), and poly-lactic acid (PLA), each attainable through microbial activity [1, 2].

Overview of Microbial Metabolism

Microbes live everywhere on the planet and thus hold a great potential to mitigate climate change and pollution. Various microbial groups have evolved the ability to metabolize renewable resources and convert them into valuable chemicals and biopolymers [2]. This natural diversity provides inspiration to construct cell factories and eco-friendly bioprocesses that can yield a wide spectrum of materials through the sustainable biorefinery approach. Microorganisms adapt to a wide range of habitats and, as a result, present a large diversity of metabolic pathways and substrates they can utilize. This characteristic has been exploited to produce many different compounds with important industrial applications. Metabolic pathways can be combined and tuned through the development of metabolic models to increase the yield of target compounds. Both natural and synthetic pathways can be designed using well-known metabolic reactions to reach all six carbon metabolic derivatives such as pyruvate, acetyl-CoA, oxaloacetate, α -ketoglutarate, succinyl-CoA, and fumarate [1, 2]. There are many commercially available bioplastics, produced using physical, chemical, or biological processes. Commercial production of bioplastics requires low-cost manufacturing, and the overall environmental impact must be lower than that of petroleum-based plastics. Microbial approaches offer the potential to expand the available range of compounds and lower the environmental impact of these bioplastics [2].

Key Microbial Species for Bioplastics

Microorganisms are the natural producers of bioplastics, and metabolic engineering offers a fruitful approach to produce these materials [2]. Polyhydroxyalkanoates (PHAs), for instance, are produced by a wide range of microorganisms as a carbon and energy storage material. The production of PHAs typically involves the use of microbial species such as *Alcaligenes*, *Pseudomonas*, *Azotobacter*, *Bacillus*, and recombinant *Escherichia coli* strains. In contrast, L-aspartate 4-semialdehyde, a precursor for poly-amino-alkanoates (PAAs), has been synthesized from aspartate 4-semialdehyde, which is related to amino acid metabolism catalysed by L-aspartate- β -semialdehyde dehydrogenase and aspartase. As the conversion of polymers into monomers involves high energy consumption, the use of polymer precursors offers an efficient route for polymer production [1, 2].

Types of Bioplastics

Bioplastics biodegradable or bio-based plastics are typically produced with microorganisms harboring prodigious biosynthetic machinery. Some of these materials tend to deteriorate rapidly and degrade completely into H₂O and CO₂, and they are therefore considered environmentally friendly. Many microbial strains can synthesize a plethora of bioplastic precursors. Genetic circuits in engineered microorganisms have also been cajoled for high-yield production of these versatile chemicals. On that basis, bioplastic precursors can be commercially produced in fermenters with several classical modes of operation [1, 2]. Bioplastics are broadly categorized as: poly-hydroxy-alkanoates (PHAs), starch-based bioplastics, cellulose-based bioplastics, protein-based bioplastics, and bio-derived monomer-based bioplastics. In recent history, Polyhydroxyalkanoates (PHAs) have come to represent the forefront of bioplastics innovation. PHAs consist of biodegradable polyesters produced through microbial intracellular processes [1, 2]. These compounds are thermoplastic like polypropylene and resistant to thermally induced degradation. Ecologically, PHAs biodegrade faster than conventional polypropylene and can be produced in diverse grades suitable for specialized applications. Several bacteria, archaea, and eukaryotic microorganisms have been identified as natural PHA rates, noting lipophilic PHA granules in their cytosol. When stressed by nutrient or oxygen deficiency, these microorganisms excessively accumulate PHAs and various derivatives. This process has furnished systematic strategies for constructing efficient bioplastic-producing microbial “factories.” Starch is a natural polysaccharide with a granular microstructure widely used in food, textile, paper manufacturing, and pharmaceutical sectors [2]. Researchers have endeavored to develop industrial-scale processes that exploit starch-based biodegradable polymers. This class of bioplastics may be combined with other biodegradable polymers to impart improved mechanical properties in plastics. Starch-based bioplastics are competitively priced among bioplastics and have a cost and performance advantage over PHAs [1, 2].

Polyhydroxyalkanoates (PHAs)

Polyhydroxyalkanoates (PHAs) constitute a diverse family of microbially produced polyesters that can be tailored to mimic a large variety of petroleum-based plastics in terms of material properties like melting temperature, crystallinity, and elasticity. All natural PHAs are synthesized from hydroxyfatty acid building blocks that are derived from sugar, lipids, or alkanes and thus coincide with the three major branches of the microbial carbon

metabolism. Because the polymer properties largely depend on the monomeric composition and the microstructure, different microbiological, synthetic-biological, biochemical, chemical- and process-engineering approaches have been developed for the manufacture of tailor-made PHAs [3]. A biological alternative to chemically produced plastics would be the best solution for the environment and economy, since bioplastics with the same properties as today's plastics can be produced in an environmentally sustainable manner. PHAs exhibit a great variety of material properties and are considered to be a promising solution to the plastic sustainability problem. PHAs are synthesised by a wide variety of archaeal and bacterial strains [4]. They serve as carbon and energy reserves as well as species-specific stress protection agents, which foster the PHA accumulation in cases of cellular stresses such as heat, free radicals, osmotic pressure, or UV radiation. Their secondary metabolism, their dependence on well-balanced physicochemical culture conditions, and their basal biopolymer degradation activities inside the cells limit the overall productivity in industrial scale. Multifarious approaches, which cover the entire process chain from strain development via culture and downstream to tailoring of the polymer material, are therefore necessary in order to realise a commercially competitive and ecologically sustainable biotechnological production [5].

Starch-Based Bioplastics

Starch represents a versatile biopolymer with a critical transition potential from petroleum-based materials to renewable resources, such as starch-based bioplastics [6]. From packaging to nutraceuticals, starch is the most promising raw material for eco-friendly alternatives to traditional plastics. Comprising primarily amylose and amylopectin, starch granules are characterized by their size and concentration within the source [2]. Various biomass sources, including cereals (corn, rice, wheat) and tubers (cassava, potato), serve as the basis for starch extraction processes, which involve disintegrating plant cells, separating fibres, deproteinization, concentration, and drying. While industrial starch extraction often employs alkaline solutions, environmental concerns over effluent disposal prompt the adoption of hydrothermal processing combined with microwave-assisted extraction, a greener, safer, and more efficient process that uses water as the solvent, along with reduced reaction times and solvent consumption. Economic and environmental viability direct the selection of cellulose sources to accessible, cost-effective agro-wastes suitable for efficient biomass processing. Although renewable starch-based bioplastics extensively address petroleum-free plastic manufacturing, several challenges persist, including production costs, material properties, and feedstock suitability. Overcoming these barriers demands continued investment to optimize microbial strains, substrates, polymerization techniques, and processing methods, thereby enhancing overall yield and competitiveness [2, 6].

Other Bioplastic Types

Apart from PHAs, starch-based polymers constitute a substantial portion of bioplastic production. Polysaccharides such as starch offer various advantages, including biodegradability, economic competitiveness, renewability, availability, and wide applications. Starch is a copolymer comprising linear amylose and highly branched amylopectin; its production is bulk-scale and cost-effective. However, pure thermoplastic starch becomes brittle and lacks appropriate mechanical properties, requiring additional plasticizers [7]. Bioplastics can be classified as zeroth, first, and second generation, based on raw materials used for production. Zeroth generation encompasses PHAs, synthesized by microbial strains [2]. First-generation bioplastics originate from edible sources like wheat, corn, and potato starch; for instance, thermoplastic starch is derived from wheat or corn starch [1]. Second-generation bioplastics are synthesized from non-edible feedstocks, including lignocellulosic biomass, green and municipal waste, and industrial waste.

Microbial Fermentation Processes

Microbial fermentation is the method of choice for bioplastics production based on sustainability and efficiency. The principal techniques are batch fermentation, continuous fermentation, and fed-batch fermentation [2]. During batch fermentation, microorganisms are inoculated into a vessel containing the growth medium. This session proceeds through sequential phases: the lag phase, during which the culture adapts to the substrate; the exponential phase, in which cellular mass accumulates rapidly; and the stationary phase, when unfavorable conditions cause biomass and bioplastic production to plateau. This last phase represents the optimal harvest point, as bioplastic accumulation peaks and nutrients are depleted. The method requires no further intervention after inoculation, making it the simplest strategy. Nevertheless, the production timeline can be lengthy due to low final biomass. Batched systems are suitable for precise assessments of polymer-producing capabilities before scaling up. Batch cultivation also reduces the metabolic flux towards cell maintenance, favoring biomass and polymer precursors accumulation [2]. Continuous fermentation systematically removes culture from a bioreactor supplied with fresh medium. Under steady-state conditions, concentrations of all components remain constant. This approach consumes substrates, cell mass, and bioplasm in equal quantities to those synthesized by the bacteria. The longer cultivation times yield higher biomass and, consequently, more bioplastic. However, the need to maintain steady-state growth limits individual cell productivity. While the system provides high product titers, excessive removal of bioplastic-expressing cells at high flow rates impacts overall yields. Continuous fermentation

is well-suited to large-scale industrial processes [2]. Fed-batch fermentation supplements a batch system with fresh nutrients, prolonging the exponential growth phase and rapidly increasing biomass density. Feeding strategies include constant- and exponential-rate modes, the latter requiring more precise control but yielding higher mass. Upon attaining a predetermined biomass concentration, nutrient supply halts, prompting cell entry into the stationary phase favorable for polymer accumulation. Fed-batch balances the advantages of batch and continuous fermentation, achieving elevated biomass coupled with efficient bioplastic synthesis [2]. All three fermentation modes have advantages for various bioplastic production scenarios as well as drawbacks, and research continues to optimize the commercialization of bioplastic materials [1, 2, 8, 9].

Batch Fermentation

Batch fermentation involves incubating microorganisms such as bacteria or yeast in a partially filled fermentation tank with a specific batch of nutrient medium. The entire process forms a closed system, where substrates are carbon or nutrient compounds like hydrocarbons or food wastes, converted into various products such as alcohol, enzymes, or bioplastics. The batch continues until the microbial cells consume a major portion of the nutrients, at which point the process ceases. Batch fermentation typically progresses through four distinct phases: lag, log, stationary, and death phases. An estimated 240 million tons of plastics are produced globally each year, largely from petroleum feedstocks. Most of these are resistant to degradation, resulting in widespread pollution. Polyhydroxyalkanoates (PHAs), including polyhydroxybutyrate and poly (3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV), are biodegradable, biocompatible, and non-toxic thermoplastics produced by bacteria as carbon and energy storage reserves. Because of these reasons, PHAs are considered among the most suitable alternative reservoirs to fossil fuel counterparts [8, 9]. However, slow microbial growth and the high expense of the carbon source have been major factors limiting market growth [8]. In a comparative study on cultivation media for batch fermentations, the highest PHA concentration was achieved using glucose-rich hydrolyzate derived from enzymatic saccharification of pulp and paper mill sludge. *Bacillus thuringiensis*, a strain known for versatile substrate utilization and PHA accumulation, was employed in batch fermentation experiments at optimum conditions to produce PHA from this hydrolyzate [9].

Continuous Fermentation

Unlike batch fermentation, continuous fermentation enables incremental product formation without interrupting the operation [10]. In this process, reactants are added continuously, and products are simultaneously removed, without halting the overall operation. Eliminating downtimes improves volumetric productivity, potentially compensating for lower product concentrations compared to batch processes. Furthermore, prolonged broth accumulation can present downstream processing challenges. Fed-batch fermentation, hermetically sealing the vessel to prevent contamination, permits extended fermentation periods, supporting cell growth and elevated product accumulation beyond 60 h. Fed-batch external feedstock supply balances variables such as pH, oxygen, and other process parameters, mitigating substrate inhibition and toxicity that restrict productivity. Although continuous or fed-batch fermentation require continuous substrate provision and thus higher energy maintenance, recent research indicates continuous fermentation can enhance productivity in biotechnological productions [8].

Fed-Batch Fermentation

Fed-batch fermentation involves the sequential addition of nutrients to a bioreactor, allowing cells to grow to high densities and maintaining substrate concentrations within optimal ranges. This approach addresses many shortcomings of batch fermentation, such as nutrient depletion and the accumulation of inhibitory by-products, while also mitigating washout issues common in continuous fermentation [11]. The strategy entails the continuous or intermittent feeding of a concentrated nutrient solution during cell growth, ensuring substrate levels remain beneath inhibitory thresholds [8]. Harvesting can occur at a desired endpoint or be combined with cell recycling techniques to further enhance productivity. These features render fed-batch fermentation particularly attractive for industrial bioprocesses, where maintaining stable operating conditions and achieving elevated product yields are paramount. Consequently, many industrial-scale processes utilize fed-batch fermentation to exploit its operational advantages [8, 11].

Genetic Engineering in Microbial Production

Recent advances in CRISPR-Cas9 and synthetic biology protocols have enabled the production of bioplastic precursors by genetically modified microbes with improved properties and cost-effective approaches. Organisms with superior growth rates, abundant precursor molecules, and tolerance to substrate and products are favorable for the synthesis of bioplastics. Microbial fermentation approaches combined with microbial engineering strategies can enhance the productivity and efficacy of bioplastic precursors. Although more process optimization, microbial engineering, and high production cost reduction are needed, the process is a promising alternative to petroleum-based compounds because it employs inexpensive carbon sources and non-hazardous by-products and makes valuable use of microbial diversity [2, 1].

CRISPR Technology

The CRISPR system has emerged as an effective tool for the precise and targeted modification of genomic DNA [12]. The combined efforts of gene editing and synthetic biology will enable the rapid engineering of production strains [13].

Synthetic Biology Approaches

Synthetic biology integrates engineered components and constructs into host cells to create new biological functions or enhance existing pathways. The discipline employs a design-build-test-learn cycle to develop functions ranging from biosensors to synthetic organisms [1]. Key advancements in genome editing have heightened the interest in synthetic biology approaches. The CRISPR–Cas system has become the predominant tool for genome engineering due to its ability to create targeted strand breaks and facilitate manipulations such as insertions, deletions, and replacements. Examples of its successful applications include *Corynebacterium glutamicum*, *Yarrowia lipolytica*, *Bacillus subtilis*, *Pseudomonas putida*, *Scenedesmus obliquus*, and *Acinetobacter baylyi* ADP[1]. Microfluidic technologies enable the rapid assembly and optimization of synthetic biology components and systems. Genetic engineering facilitates the creation of new metabolic pathways and the optimization of existing ones for enhanced bioplastic production. Synthetic biology and metabolic engineering are crucial for designing cell factories, which serve as efficient microbial platforms for bioplastic precursor synthesis [2].

Sustainability and Environmental Impact

The sustainability of bioplastics depends on their production methods. Life cycle assessment studies indicate that bioplastics possess a carbon footprint approximately 60% lower than that of polymeric materials derived from fossil fuels [1]. This reduced environmental impact, coupled with their non-petrochemical origin and therefore lower dependence on oil prices, presents opportunities to alleviate current concerns about the negative climate impact of the chemical, packaging, and automotive industries. Despite extensive efforts and technological advancements, bioplastics face significant challenges that hinder their widespread adoption. One primary concern pertains to achieving sufficient production efficiency to economically compete with fossil-based materials[1]. Various strategies aimed at decreasing production costs while preserving bioplastic quality and allowing efficient mass production have been explored. However, reaching optimal production conditions remains elusive, as each bioplastic requires specific parameters that are challenging to ascertain and implement. Additionally, waste management constraints pose limitations, since bioplastics may not be compatible with existing recycling facilities. Consequently, further assessment of production efficiency, waste management, and environmental impacts is imperative before bioplastics can realize their full potential [1, 2].

Life Cycle Assessment

The ability of bioplastics to diminish dependence on oil resources and decrease environmental impact is intimately linked with microbial metabolism, illustrating the importance of life cycle assessment (LCA). The LCA of bacterial cellulose production demonstrates that wastewater treatment contributes significantly to climate change, fossil depletion, and human toxicity, primarily due to steam and calcium hydroxide production [14]. Materials production notably affects climate change, human toxicity, and terrestrial ecotoxicity, while cooling and heating agent generation influences fossil depletion and freshwater consumption. These processes collectively dominate natural resource usage and freshwater emissions. An attributional cradle-to-factory gate LCA quantifies resource utilization and emissions associated with the manufacture of bio-based 1,4-butanediol (BDO) from wheat straw via fermentation in a hypothetical Italian biorefinery. Allocation of wheat cultivation impacts to straw considers economic value, with 85% attributed to grains and 15% to straw [15]. Collectively, LCAs affirm the environmental sustainability achievable through innovative microbiology.

Carbon Footprint Analysis

Bioplastics have potential to decrease reliance on fossil-based fuels and reduce environmental impacts, such as climate change and toxicity [16]. A life cycle assessment quantified direct and indirect effects of the cradle-to-grave life cycle of compostable bioplastics. A consequential approach was used to account for the global net effects of bioplastic production, including indirect land use change and any avoided emissions. Activities were included in the system only if they are expected to change with demand for the bioplastics. The main aim was to assess the greenhouse gas mitigation potential of different bioplastic feedstocks, employing impact assessment with climate change as the midpoint indicator and the resulting contribution expressed as a global warming potential (GWP) over 100 years[16]. GWP values are based on the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report, and were modified to distinguish methane emissions from both biogenic and fossil sources. Environmental burden factors for GHGs are provided in the supplementary information. The environmental impacts of four different biomass feedstocks were studied. For each, 20 kg of biomass were assumed to produce 1 kg of bioplastic. One of the feedstocks examined was low-value wood obtained as a residue from Sitka spruce sawmill processing [16].

Economic Viability of Bioplastics

The shift to sustainable plastics is driven not only by environmental concerns but also by the prospect of converting renewable materials into commodity bioplastics. Global plastic production reuse must achieve cost-effectiveness to retain market relevance. Petrochemical polymers benefit from cost, properties, and sound supply chains. Bioplastics offer enhanced biodegradability, CO₂ neutrality, and potential use of waste streams, yet economic viability remains a challenge [2]. Competitive scenarios affect economic viability and sustainability, influenced by subsector commodities, intermediates, or waste solutions. Anticipated petroleum price escalations could increase the price premium on bioplastics, incentivizing investment in development and market leadership. In light of widespread environmental concerns, the cost advantage of synthetic polymers may diminish as sustainability gains prominence [17].

Cost Analysis of Production

The cost of producing bioplastics remains a major barrier despite benefits such as biodegradability and a near-neutral carbon footprint. Successful markets have emerged in the personal care sector, where consumers accept a premium for environmental responsibility. Analysis of production costs is ambiguous due to confidential process details. A scenario study modeled the production of plastics from whey protein, applying process economics to laboratory-scale processes to estimate prices and investment requirements for an industrial plant [17]. Both scenarios targeted an annual throughput of 3,200 tonnes, closely matching the annual disposal of whey solids from a processing plant with 40,000 dairy cows. The first scenario extended laboratory co-polymerization to industrial scale; the second involved upscaling whey protein isolate production before applying the co-polymerization process.

Market Trends and Demand

Expanding interest in bio-based plastics has been growing since the early 1970s owing to issues related to the depletion of petrochemical feedstocks and the contamination caused by the accumulation of non-degradable plastics [1]. Bioplastics attributed to short biobased carbon-life cycles and non-toxicity have displayed great promise for sustainable applications and exhibited superior biodegradability compared to conventional plastics [2]. Global bioplastic production capacity is expected to reach 7.59 million tons by 2026 at a compound annual growth rate (CAGR) of 16.1% during the forecast period from 2021. The demand for bioplastics for packaging applications is predicted to increase significantly since packaging accounts for approximately 50.0% of total plastic consumption, followed by textile material, consumer goods goods, and building & construction. Such a sustained growth is feasible due to the ongoing and growing concern regarding the detrimental effect of petroleum-based plastics and a simultaneous increase in awareness for an environmentally friendly circular economy [1, 2].

Regulatory Framework for Bioplastics

Bioplastics occupy a niche in sustainability that capitalizes either on renewable carbon sources or on biogenic carbon already present in the carbon cycle. Their commercial translation is constrained by multiple factors, including production costs, regulations and certifications, societal trust, and their diversity [2]. Usually described through three dimensions biobased, biodegradable, and compostable, they find themselves exposed to variable local legislation and frameworks. For instance, the US Federal Trade Commission's green guides specify which terminology reflects the specific attributes of a material or product but do not propose a unified bioplastics classification [1]. Meanwhile, the European Commission's Single Market for Green Products initiative provides a policy framework and emphasizes a life cycle approach to product sustainability, highlighting the need to assess environmental impacts beyond end-of-life. In addition, Europe is the first region to introduce a harmonized standard (EN 13432) for biodegradability and compostability based on either industrial or home composting. More localized regulations exist at the individual country level. Governments must address these inconsistencies as well as the overlapping challenges of waste management and trade barriers to unlock bioplastics' innovative potential and widespread adoption [1, 2].

Global Standards and Regulations

Global standards and regulations play an important role in the formalisation of the bioplastics sector and the translation from research to commercialisation. International cooperation is key, correlating climate change initiatives, waste management and the circular economy [2]. Bioplastics definitions and certification schemes not only underscore the sustainability benefits and help to further validate product claims but also constitute an important organising force towards market development. A span of key organisations, including the EU, China, the Bioplastics International Organisation, and the Ellen Macarthur Foundation, amongst others, have come together to formulate a widely yet not universally accepted bioplastics definition that can be considered under the same umbrella [2]. At its core, a bioplastic refers to a biobased and/or biodegradable plastic. A growing number of countries and regions have developed laws and regulations to specifically refer to bioplastics. These often pertain to multiple aspects that include the circular economy, bioeconomy, waste reduction, product recycling, and carbon emissions reduction. For example, the China National Sword policy aims to eliminate the import of waste, with the stated goal of improving domestic waste handling and treatment capacities. The EU Plastics Strategy and

the Directive on Packaging and Packaging Waste set targets to use 50% recycled plastic by 2030 and achieve 100% reusable or recyclable packaging by 2030, respectively. Other bodies underpinning bioplastics criteria and requirements include the Bioplastics International Organisation, the Ellen MacArthur Foundation, the independent association 'Together Against Plastic Waste' and the AMERIPEN Packaging Advocacy Group [2].

Certification Processes

The widespread implementation of bioplastics as substitutes for conventional plastics presents numerous challenges that require urgent intervention by the scientific community and regulatory authorities. Clearly defining bioplastics and establishing a unified framework for their classification and certification constitute significant difficulties for researchers, manufacturers, and practitioners. Bioplastics differ fundamentally from petrochemical plastics in terms of biodegradability, production methods, and raw materials. Their classification depends on synthesis pathways rather than feedstock, underscoring the pivotal role of microbial systems in bioplastic production [13]. The overall biodegradation time also serves as a distinguishing characteristic. Certification processes for bioplastics are primarily undertaken by three agencies: the European Union, TÜV Austria, and the Biodegradable Products Institute (BPI). Bioplastics that comply with the regulations of one or more of these organizations are eligible for commercial use across sectors such as packaging and textiles. Simple bioplastic certification processes are available for standardized commercial products that are yet to undergo uncontrolled environmental exposure. This pre-qualification recertification is efficient unless the material faces contamination through uncontrolled use [18]. In the event of contamination, a rescoring protocol is initiated, which parallels the original certification but targets the pollutant. This step is particularly critical in waste treatment environments within the packaging industry. Incineration-based certification also exists if decomposition of packaging materials occurs in an incinerator. Upon complete incineration, the process is deemed approved within a typically one-month assessment. Biodegradability characterization of materials in open environments forms another key aspect of the certification process. A material demonstrates biodegradability through complete conversion to carbon dioxide, implying that the total carbon content has transformed into this gas. It simultaneously excludes all other developments, including methane production, which might arise in open environments. To ensure complete safeguarding of the degradation ecosystem, controlled environmental conditions must be established to guarantee zero leakage. These conditions are efficiently monitored by cold extraction followed by analytical analysis of the closed environment [13, 18].

Challenges in Bioplastic Production

Unlike conventional petrochemical plastics, bioplastics represent one of the most reliable green materials and an alternative for reducing the carbon footprint because they are derived from renewable resources, and their degradation results in water and biomass [2]. Bioplastic production can occur via batch, continuous, or fed-batch fermenters, normally operated at 30–37 °C and pH 6.8–7.4, with the type of fermentation affecting biopolymer productivity. The use of fermenters under well-controlled conditions helps maintain the pre-established environmental parameters during the process, favoring microorganism growth and biopolymer accumulation. Some researchers have applied genetic engineering tools such as CRISPR-Cas9 and synthetic biology to improve biopolymer synthesis and modulate metabolic pathways; however, this approach remains time-consuming and complex. In particular, the synthesis of short-chained bases is difficult due to the enzymes in lipid and amino acid metabolism, which are classified as highly toxic and volatile chemical materials and require high energy to produce. Additionally, essential components needed for microbial metabolism must be added to the media for microorganism growth and biopolymer formation, increasing the cost of the culture media and, consequently, the bioplastic production process. To make production more sustainable, the use of waste biomass as a substrate has been investigated; however, although this reduces production costs, it also reduces biopolymer productivity, and waste materials often require pre-treatment to be used as substrates [2]. Nevertheless, extraction and purification of biopolymers are expensive and energy-intensive, often involving harmful chemicals. Although bioplastic production continues to rise due to increasing demand and feasible manufacturing, it remains largely unclear whether bioplastic materials can substitute petroleum-based polymers until costs decrease and properties improve. Additional investment and research are imperative to overcome these challenges and promote increased utilization of microbial cell factories for synthesizing bioplastics with improved properties [2].

Technical Challenges

Several technical challenges limit industrial implementation of bioplastics [2]. Microbial synthesis of bioplastics precursors constitutes a multidisciplinary intricate problem. Strains must produce products of industrial interest with high productivity and yields, but substrate and environment exert important effects on these parameters. Genetic engineering strategies for yield and productivity improvements remain time-consuming, and balances of feedstock and residual biomass are critical for enhanced sustainability. Purification of final compounds constitutes a bottleneck, involving costly and energy-intensive procedures, with optimization requiring substantial effort. Material properties are often weak, so ongoing research aims to enhance physicochemical characteristics while

lowering costs [2]. The overall objective is to generate a substantial market shift as bioplastics offer timely solutions to persistent waste and natural resource depletion challenges.

Market Acceptance Issues

Bioplastics polymers derived from fossil fuels or biomasses are emerging as a sustainable alternative to conventional plastic. Their growing commercial applications include a variety of polymers such as starch blends, polylactic acid (PLA), and polyhydroxyalkanoate (PHA), all of which display biodegradability and have significant environmental advantages compared to conventional plastics. Nevertheless, despite their potential environmental benefits and increasing global production levels, these materials remain in their infancy, and further investment is required to reduce production costs and improve properties to compete with petrochemical-based polymers [2]. Production optimization demands attention to parameters including microbial strain, substrate, polymerization technique, processing method, and manufacturing approach, each of which can also introduce challenges. Key issues encompass the enhancement of yield and productivity, the advancement of synthesis through genetic engineering, the identification of sustainable and cost-effective feedstocks, and the development of efficient and economical processing techniques. Although bioplastics occupy an increasing share of the global market, it remains uncertain whether biopolymers can fully compete with conventional plastics. Continued research focused on improving material properties and reducing production costs holds promise for shifting the market dynamic, particularly because bioplastics offer a pathway to mitigate waste-related problems and to reduce dependence on nonrenewable resources [2].

Future Perspectives in Bioplastics

The anticipated progression of sustainable bioplastic adoption hinges on the seamless integration of innovative research, pilot-scale validation, and industrial implementation [2]. Biotechnology is at the forefront, with a surge in eco-friendly technologies and the deployment of green microbial strains poised to replace non-renewable plastics. Deciphering cellular metabolism through genome-scale modeling informs strain engineering across diverse economic, environmental, and performance objectives. Microbial fermentation and the utilization of low-cost waste substrates will sustain productivity improvements in terms of yield, rate, and titer. Potential metabolic bottlenecks that constrain productivity may be overcome as the molecular basis of capabilities emerges and the metabolic space for industrially viable heterologous pathways expands. Strategies designed to accelerate microbial growth and synthetic pathway flux allow a greater rate of product accumulation along with the ability to avoid feedback regulation [1]. Opportunities do not arise solely from metabolic processes or novel catalytic activities; the discovery and construction of microorganisms that host new functionalities at scale and integrate into fluid bio-systems constitute a critical objective. The extensive metabolic capacity of living systems will continue to fuel the explosive evolution of microbially produced commodity chemicals that complement petrochemicals. Access to a steadily expanding portfolio of well-characterized microbial hosts will enable the use of heterotrophic, phototrophic, autotrophic, and even lithoautotrophic production platforms to improve titers of commodity chemicals, biofuel precursors and additives, building block chemicals, and bioplastics [1, 2].

Innovative Research Directions

The development of bioplastics as an alternative to petrochemical-based plastics addresses the depletion of fossil resources and environmental contamination. Traditional plastics' nonbiodegradability leads to negative environmental consequences and public health effects, motivating research into sustainable alternatives [2]. For the future, identified innovative research directions and industrial applications have been discussed, stressing that bioplastics offer opportunities to reduce carbon footprints and environmental impact. Three main areas of interest have been identified. Wastewater can be used as an environmental source of mixed cultures, which can be directed into the production of polyhydroxyalkanoates (PHAs) such as PHB, a type of bioplastic. Mixed cultures can improve yield and process economics. However, challenges remain in process optimization and yield enhancement [2]. Municipal organic waste emerges as a biowaste substrate for both enzyme production and direct use in PHA production, contributing to the circular economy. The incorporation of microplastics as an alternative carbon source has also received attention, exploiting the synergistic effects of microplastics and PHA production. Genetic engineering focused on the metabolic modification of key bacterial strains facilitates bioplastic production from methane and methanol. Genetically engineered microorganisms can extend the range of usable substrates, overcoming cost and availability limitations [2].

Potential for Industrial Application

This section overviews the potential for industrial application of microbially produced bioplastic precursors. Research centers on microbial strains able to convert low-cost and renewable substrates such as glycerol, sugars, and organic wastes into compounds like lactic acid, succinic acid, and 3-hydroxypropionaldehyde, which serve as key chemical building blocks for bioplastics [2]. Efficient microbial production depends on optimized operation of batch, continuous, and fed-batch fermentation systems, along with strain and process engineering to enhance yield and ease downstream processing. Selection of microbial strains capable of metabolizing impure industrial substrates (e.g., crude glycerol or lignocellulosic hydrolysates) is critical for minimizing downstream purification

and reducing costs. Advances in genetic tools including CRISPR/Cas systems, multiplex automated genome engineering (MAGE), and synthetic biology facilitate targeted strain improvement, enabling tailored biosynthetic pathways or enhanced precursor production [2]. Bioplastics comprise a family of naturally occurring or synthetic polymers certified as biodegradable, such as polyhydroxyalkanoates (PHAs), polylactic acid (PLA), and polyethylene (PE) derived from bio-ethanol. Commercial production of bioplastics is steadily increasing, with PHAs, PLA, starch blends, and bio-PE dominating the market. Fermentation processes currently constitute approximately 30 % of the global bioplastics market. However, various factors such as a wide range of substrates, diverse bacterial candidates, multiple fermentation modes, complex downstream processes, and regulatory constraints challenge the rapid transition from laboratory to commercial scale. Addressing substrate selection, strain development, and process scale-up remains crucial for realizing the industrial viability of microbially produced bioplastic precursors and contributing to a sustainable bioeconomy [2].

Case Studies in Microbial Bioplastic Production

Microbial Factories for Sustainable Bioplastic Precursors; microorganisms represent efficient platforms for bioplastic production. Numerous metabolically diverse species have been identified within the bacterial community. Their crude extracts serve as producers of the monomeric units needed for bioplastic formation. Additionally, genetically engineered microbial strains have been developed for the large-scale production of bioplastic precursors [1]. Thus, microbial technology plays a pivotal role in promoting bioplastic production through the metabolism of diverse bacterial species and metabolic engineering of strains. Batch, continuous, and fed-batch fermentation procedures have been applied to evaluate the potential of these microbial cultures in synthesizing biodegradable plastics [1, 2]. Together with unconventional substrates, these processes reduce the overall cost of bioplastic production. Genetic engineering, particularly methods such as the CRISPR platform and synthetic biology techniques, has substantially advanced the production of biodegradable plastics and their precursors. Environmental metrics measured in terms of life cycle assessment and carbon footprint reveal clearly that the use of biological materials for bioplastic production embodies a sustainable concept that strongly contributes to addressing ecological problems like global warming, fossil fuel depletion, and plastic accumulation in the environment. Accordingly, the bioplastics market increasingly demands products with enhanced properties, cost-effectiveness, and compliance with regulatory frameworks governing production and use [2].

Successful Microbial Strains

Among the many microbes known to accumulate PHAs, *Cupriavidus necator* (previously *Ralstonia eutropha* or *Alcaligenes eutrophus*) has been widely studied [2]. Its versatile metabolism allows the consumption of sugars and organic acids. Under stressful conditions, bacteria channel surplus carbon flux into mcl-PHA synthesis. High production costs restrict large-scale PHA use. Consequently, maintaining wild-type strains is necessary until technologies are affordable. Other microbes include *Haloferax mediterranei*, a halophile thriving in hypersaline environments and capable of using a wide variety of sugar monomers. Its high salinity milieu limits contaminant growth, resulting in high PHA productivity. The yeast *Pichia pastoris* can produce short-chain-length PHAs (scl-PHAs). Mixed microbial cultures from wastewater decomposers can degrade biodegradable plastics; employing such treatment has driven PHA production using mixed cultures [1, 2].

Industrial Implementations

Various sectors are applying biopolymer-derived products [2]. Biological applications of biopolymers, such as the production of lactic acid, also hold promising prospects. Chemical industries produce terrestrial, marine, and dairy biopolymers from bioplastics. For example, techniques have been developed to produce the pathway in *Escherichia coli* and *Bacillus* species. A co-CRISPR method enhances genome editing in *Bacillus subtilis* through the co-editing of two genes, aiming to enhance PHA production. Heterologous metabolic pathways enable the utilization of novel carbon sources for trans-3-hydroxy-l-proline production, and the genome-scale metabolic model iGEL604 has been constructed to predict gene targets that improve acetoin synthesis through flux-scanning-based optknock analysis [1, 2].

CONCLUSION

Microbial factories present a viable and sustainable pathway for producing bioplastic precursors, offering an eco-friendly alternative to conventional petroleum-based plastics. Advances in metabolic engineering, synthetic biology, and fermentation technologies have significantly enhanced microbial productivity and broadened the range of usable feedstocks. However, high production costs, limited scalability, and challenges in downstream processing remain critical barriers to industrial adoption. Future progress will depend on integrating low-cost renewable substrates, optimizing microbial strains through genetic innovation, and adopting circular economy approaches that valorize waste streams. Collaborative efforts across biotechnology, chemical engineering, and policy frameworks will be essential to transition bioplastics from laboratory innovations to commercially competitive materials. With continued innovation, microbial-based bioplastic production can contribute substantially to reducing plastic pollution and advancing global sustainability goals.

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