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REVIEW ARTICLE

Blending Applications of Microbial-Derived PHB Bioplastics: Innovations and Sustainability Perspectives

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ABSTRACT

Bioplastics have emerged as sustainable alternatives to conventional petroleum-based plastics, addressing environmental concerns and the need for biodegradable materials. Among these, polyhydroxy butyrate (PHB), a microbial biopolymer, has garnered significant attention due to its inherent biodegradability and biocompatibility. However, the limited thermal stability, high production costs, and intrinsic brittleness of pure PHB pose challenges to its widespread industrial application. Enhancing the physicochemical properties of PHB through blending with other polymers, including synthetic and natural types, represents a viable strategy to overcome these limitations and broaden its applicability. This review provides a comprehensive analysis of microbial strains, metabolic pathways, and fermentation methodologies employed in PHB biosynthesis. It highlights the challenges associated with pure PHB and underscores the critical role of polymer blending techniques in addressing these constraints. The discussion encompasses the mechanical, thermal, and biodegradation characteristics of PHB-based blends, as well as their diverse applications in sectors such as consumer goods, packaging, agriculture, and biomedical fields. Furthermore, the review evaluates the economic and environmental implications of PHB blends, emphasizing their potential as sustainable alternatives to traditional plastics. Emerging advancements, including the incorporation of nanocomposites and innovations in blending technologies, are also explored. The study concludes by delineating current challenges and identifying future research directions, providing insights for the development of high-performance, cost-effective PHB-based bioplastics tailored for practical applications.

KEYWORDS

• Bioplastic • Blending • Polyhydroxybutyrate

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INTRODUCTION

Bioplastics are a class of plastics derived from renewable biological resources such as plant starch, vegetable oils, or microorganisms. Unlike conventional plastics synthesized from fossil fuels, bioplastics are designed to reduce environmental impacts, offering biodegradability and a lower carbon footprint.[1,2]

Bioplastics can be broadly categorized into three groups:

1. **Bio-based Non-biodegradable Plastics:** Examples include bio-polyethylene (bio-PE) and bio-polyethylene terephthalate (bio-PET). These materials are derived from renewable sources but exhibit similar degradation profiles as their petrochemical counterparts.[3]
2. **Biodegradable Plastics:** These include polyhydroxyalkanoates (PHAs), polylactic acid (PLA), and starch-based plastics. They degrade under natural conditions, reducing environmental persistence.[4]
3. **Plastics that are Both Bio-based and Biodegradable:** Examples include polyhydroxybutyrate (PHB) and some PLA blends. These combine renewable sourcing with effective environmental degradation.[5]

Environmental Significance

1. **Reduction of Plastic Waste:** Bioplastics offer a solution to the growing problem of plastic pollution, as many degrade into non-toxic by-products in natural environments. This is particularly beneficial for mitigating oceanic and terrestrial plastic accumulation.[5]
2. **Lower Carbon Emissions:** The production of bioplastics from renewable resources emits significantly less carbon dioxide compared to petrochemical plastics. This contributes to the reduction of greenhouse gas emissions and combats climate change.[4]
3. **Sustainability:** Bioplastics can be produced from agricultural residues and non-edible biomass, ensuring minimal competition with food supplies and enhancing resource utilization efficiency.[3]
4. **Applications in a Circular Economy:** Bioplastics support the principles of a circular economy by enabling recycling and composting. This reduces dependency on virgin materials and minimizes waste[4].

Despite their benefits, bioplastics face challenges such as higher production costs, limited industrial composting facilities, and concerns over land use for biomass production. Research is focused on enhancing material properties, optimizing production processes, and developing efficient recycling methods to overcome these limitations[5]. Polyhydroxybutyrate (PHB) is a naturally occurring biopolymer synthesized by various microorganisms under nutrient-limited conditions with excess carbon. It serves as an intracellular carbon and energy reserve and is a member of the polyhydroxyalkanoates (PHAs) family. PHB has gained attention as an eco-friendly substitute for petroleum-derived plastics due to its biodegradability, biocompatibility, and desirable mechanical properties[6,7]. PHB is a linear polyester composed of repeating 3-hydroxybutyrate units. Its high crystallinity (50%-80%) significantly influences its mechanical strength and stiffness. The polymer exhibits a glass transition temperature (Tg) between -15°C and 9°C and a melting temperature (Tm) ranging from 160°C to 180°C, which are critical parameters for its processing and applications.[8,9]

Properties of PHB

1. **Mechanical Properties:** PHB exhibits a tensile strength of approximately 40 MPa, comparable to polypropylene. However, it is more brittle with limited elongation at break, requiring copolymerization or blending for enhanced flexibility[8].
2. **Thermal Properties:** PHB has a narrow processing window due to the close proximity of its melting and degradation temperatures. Careful optimization during processing is necessary to prevent thermal degradation[9,10].
3. **Barrier Properties:** PHB demonstrates excellent oxygen and moisture barrier properties, making it suitable for applications like food packaging[9].
4. **Biocompatibility:** PHB is biocompatible, which makes it ideal for medical applications such as sutures, drug delivery systems, and tissue engineering. Its non-toxic degradation products ensure safety for biological use[10].

Biodegradability of PHB: PHB is biodegradable in various environments, including soil, water, and compost. Microbial enzymes like depolymerases break it down into 3-hydroxybutyrate monomers, which are further metabolized into carbon dioxide and water under aerobic conditions, or methane under anaerobic conditions. Factors such as crystallinity, molecular weight, and environmental conditions affect the degradation rate[10]. The biodegradability of PHB addresses the issue of plastic pollution as it does not persist in the environment. Its potential for production from renewable resources adds to its appeal as a sustainable alternative to traditional plastics.[8,10]

MICROBIAL PRODUCTION OF PHB

Microbial Strains (Bacteria and Archaea) Involved in PHB Synthesis

Polyhydroxybutyrate (PHB) is synthesized by various microorganisms, including bacteria and archaea, as a carbon and energy storage material under nutrient-limited conditions. These microorganisms accumulate PHB in the form of intracellular granules when the supply of essential nutrients like nitrogen, phosphorus, or oxygen is restricted, while an excess of carbon is available.[11,12]

Bacterial Strains Involved in PHB Synthesis

1. **Gram-negative Bacteria:** Several Gram-negative bacteria are known for their ability to produce PHB. Some well-characterized strains include: *Rhodobactersphaeroides, Pseudomonas putida, Alcaligenes eutrophus* (now known as *Cupriavidusnecator*) These bacteria typically accumulate PHB under nutrient limitation conditions such as nitrogen or phosphorus deficiency.[13,14]
2. **Gram-positive Bacteria:** Certain Gram-positive bacteria are also capable of PHB synthesis, such as: *Bacillus megaterium, Bacillus subtilis, Corynebacterium glutamicum* These bacteria are promising candidates for industrial PHB production due to their high growth rates and the ability to accumulate large amounts of PHB.[15]
3. **Industrial Strains:** Strains like *Cupriavidusnecator* and *Ralstoniaeutropha* are widely used in industrial PHB production because of their ability to accumulate PHB at high yields. *Cupriavidusnecator*, in particular, can accumulate up to 80% of its dry weight as PHB under optimized conditions.[16,17]

Archaeal Strains Involved in PHB Synthesis

Archaea, although less studied than bacteria, also contribute to PHB production. Some archaeal species involved in PHB synthesis include:

1. **Haloarchaea:** *Halobacterium salinarum, Halococcusmorrhuae,* These extremophiles are found in high salinity environments and can accumulate PHB under conditions where other microorganisms might not survive. They represent a unique source of biopolymer production in extreme environments.[18]
2. **Methanogenic Archaea:** Some methanogenic archaea, such as *Methanosarcinabarkeri*, have also been reported to synthesize PHB under anaerobic conditions. These strains may hold potential for biotechnological applications in environments where oxygen is scarce[19].

Genetic Engineering for Enhanced PHB Production

Advancements in genetic engineering have led to the development of engineered microbial strains with enhanced PHB production. For instance, the introduction of recombinant genes from PHB-producing strains into non-productive strains can significantly improve yields. Additionally, metabolic pathway optimization in microorganisms like *Escherichia coli* and *Bacillus subtilis* has been used to enhance the efficiency of PHB biosynthesis.[20,21]

Biochemical Pathways and Metabolic Engineering for Enhanced Production of PHB

The biosynthesis of Polyhydroxybutyrate (PHB) in microorganisms occurs via a series of biochemical pathways that involve the conversion of carbon substrates into PHB. The production of PHB is primarily achieved through the accumulation of 3-hydroxybutyrate (3HB) monomers, which are polymerized to form the PHB polymer. Understanding the biochemical pathways involved in PHB synthesis is crucial for optimizing production processes and improving yields[22,23].

Key Biochemical Pathways:

1. **Acetyl-CoA Pathway:** The primary pathway for PHB synthesis begins with

the conversion of glucose to acetyl-CoA through glycolysis. Acetyl-CoA is then converted to 3-hydroxybutyryl-CoA by the enzyme *β-ketothiolase* (PhaA). This intermediate is then converted to PHB by the enzyme *phydroxybutyrate synthase* (PhaB), which polymerizes the 3-hydroxybutyryl-CoA into PHB granules.[24]

2. **Propionyl-CoA Pathway:** In some organisms, the synthesis of PHB can also involve the conversion of propionyl-CoA to 3-hydroxybutyryl-CoA, which is further polymerized to PHB. This pathway is commonly found in some Gram-negative bacteria like *Pseudomonas* species.[25]
3. **Microbial Conversion of Fatty Acids:** Some microorganisms also produce PHB from fatty acids via a modified β-oxidation pathway. Fatty acids are broken down to acetyl-CoA, which is then used in the acetyl-CoA pathway for PHB biosynthesis.[26]

Metabolic Engineering for Enhanced PHB Production

Metabolic engineering strategies aim to optimize microbial strains for high PHB yield by enhancing precursor availability, improving enzyme activities, and reducing competing pathways. Key strategies include:

1. **Overexpression of Key Enzymes:** The over expression of enzymes involved in PHB biosynthesis, such as *PhaA*, *PhaB*, and *PhaC*, can increase the production of PHB. This is often achieved through genetic modifications of the microbial strains to enhance their metabolic flux towards PHB synthesis.[27]
2. **Blockage of Competing Pathways:** Competing metabolic pathways, such as those involved in biomass production or the degradation of intermediates, can divert carbon away from PHB biosynthesis. The inhibition or knockout of genes encoding enzymes in these competing pathways helps to channel more carbon towards PHB production.[28]
3. **Optimizing Precursor Supply:** Increasing the availability of key precursors, such as acetyl-CoA and NADPH, is critical for enhancing PHB production. Genetic modifications that enhance the supply of these precursors, as well as the engineering of carbon fixation pathways, can significantly boost PHB synthesis.[29]

Fermentation Techniques and Optimization Strategies for PHB Production

Fermentation is a critical step in the industrial production of PHB. The choice of fermentation conditions, such as the type of culture, nutrient supply, and process parameters, plays a crucial role in determining the yield and efficiency of PHB production.[30]

1. **Batch Fermentation:** Batch fermentation is the most commonly used method for PHB production. In this process, the microbial culture is grown in a fixed volume of medium under controlled conditions, with nutrients added at the start. The microbial strain produces PHB during the stationary phase when nutrients are limited.[31]
2. **Fed-batch Fermentation:** Fed-batch fermentation involves the continuous addition of nutrients to the culture, allowing for prolonged production of PHB. This method helps to maintain an optimal nutrient concentration throughout the fermentation process, leading to higher yields compared to batch fermentation.[32]
3. **Continuous Fermentation:** In continuous fermentation, the culture is maintained in a steady-state by continuously feeding nutrients and removing excess biomass and by-products. This technique is suitable for large-scale PHB production due to its high productivity and efficient use of resources.[33]

Optimization Strategies

1. **Carbon Source Optimization:** The choice of carbon source significantly affects PHB yield. Glucose, glycerol, and organic acids such as acetic acid are commonly used as carbon sources in PHB production. Optimization of the carbon-to-nitrogen ratio is also important for maximizing PHB accumulation.[34]
2. **Oxygen Transfer Rate (OTR):** The oxygen transfer rate (OTR) is a critical factor in aerobic fermentation processes. Optimizing OTR helps to maintain the required oxygen levels for microbial growth and PHB production, especially when using oxygen-demanding microorganisms like *Cupriavidusnecator*.[35]

3. **Temperature and pH Control:** Maintaining optimal temperature and pH conditions is essential for PHB production. Generally, PHB-producing microorganisms grow best at temperatures between 30°C and 37°C, and the pH should be controlled between 6.5 and 7.5 to promote maximum enzyme activity.[36]
4. **Nutrient Limitation and Stress Induction:** The induction of PHB production is typically achieved through nutrient limitation, such as nitrogen or phosphorus deprivation, which triggers the microbial cells to accumulate PHB as a storage material. Optimization of the timing and degree of nutrient limitation is essential to achieve high PHB yields.[37]

Limitations of Pure PHB: Brittleness, Thermal Instability and Cost

Polyhydroxybutyrate (PHB) is a promising bioplastic with various environmentally friendly advantages. However, despite its biodegradability and renewability, pure PHB suffers from several limitations that restrict its broad application in commercial products. These limitations include brittleness, thermal instability, and high production costs.

Brittleness of Pure PHB: One of the most significant limitations of pure PHB is its inherent brittleness. PHB exhibits a high glass transition temperature, which makes it prone to cracking and breaking under mechanical stress, limiting its ability to be used in applications requiring flexibility and impact resistance. This brittleness is a major issue in packaging materials, where mechanical properties such as flexibility and stretchability are essential.[38,39]

Thermal Instability

PHB also demonstrates poor thermal stability, which restricts its processing temperature range. It tends to soften at relatively low temperatures (about 175°C), making it difficult to process in conventional thermoplastic molding equipment, especially for applications involving higher temperature conditions. This characteristic makes PHB less suitable for use in high-temperature applications compared to other thermoplastics such as polyethylene and polypropylene.[40]

High Production Cost

While PHB is a renewable and biodegradable alternative to petroleum-based plastics, its production cost remains a major barrier to widespread commercial adoption. The primary contributors to the high cost of PHB production include the cost of carbon feedstocks (such as sugars and glycerol), the need for high-value microbial strains, and the energy-intensive fermentation processes required for its synthesis. Additionally, the low yield of PHB in some microbial strains further contributes to high costs.[41]

Importance of Blending to Overcome These Challenges

Blending PHB with other materials is an effective strategy to mitigate the limitations of pure PHB. By combining PHB with other biopolymers or synthetic polymers, the resulting blends can exhibit enhanced mechanical properties, improved thermal stability, and reduced costs, making them more suitable for a wider range of applications.

Improving Mechanical Properties: Blending PHB with other polymers such as polylactic acid (PLA), polyvinyl alcohol (PVA), or polyhydroxyalkanoates (PHA) can significantly improve its flexibility, toughness, and impact resistance. For instance, the blending of PHB with PLA has been shown to reduce brittleness and increase the material's ductility, making it more appropriate for packaging applications and other products requiring better mechanical performance. Additionally, reinforcing PHB with natural fibers or plasticizers can further enhance its mechanical properties by reducing its brittleness.[42,43]

Enhancing Thermal Stability: Blending PHB with thermally stable polymers or incorporating stabilizers can improve its thermal processing characteristics. For example, blending PHB with poly (butylene succinate) (PBS) or polycaprolactone (PCL) has been demonstrated to improve the thermal stability of PHB while maintaining its biodegradability This blending strategy extends the processing temperature range and allows PHB to be used in a broader set of applications.[44]

Cost Reduction: Blending PHB with less expensive polymers, such as polyethylene or polypropylene, can reduce the overall material cost of the bioplastic. Additionally, blending with biopolymers that are produced from cheaper raw materials or by lower-cost fermentation processes helps to decrease the production cost of the final product. This cost reduction is essential for making PHB-based products competitive with conventional plastic materials on the market.[45]

Approaches for Blending PHB with Other Biopolymers

Blending PHB with other biopolymers, such as polylactic acid (PLA), polyhydroxyalkanoates (PHA), and starch, is an effective strategy to overcome the limitations of pure PHB, such as brittleness, thermal instability, and high production costs. These biopolymer blends combine the desirable properties of each component, enhancing the overall performance of the material for various applications.

Blending with PLA (Polylactic Acid): Polylactic acid (PLA) is one of the most widely used bioplastics, known for its good mechanical properties and ease of processing. When blended with PHB, PLA can improve the overall toughness, flexibility, and processability of the blend. PHB/PLA blends show enhanced ductility and impact resistance compared to pure PHB, making them suitable for packaging materials, agricultural films, and medical applications. The compatibility between PHB and PLA is enhanced by adjusting the molecular weight and blend ratios.[46,47]

Blending with PHA (Polyhydroxyalkanoates): Polyhydroxyalkanoates (PHA) are a group of biodegradable polymers similar to PHB but with a wider range of properties. Blending PHB with PHA improves the biodegradability and flexibility of the material while maintaining the environmental benefits of PHB. These blends are often used in applications where both biodegradability and improved mechanical properties are essential, such as in agricultural films and disposable packaging.[48]

Blending with Starch: Starch, a natural polysaccharide, is another attractive option for blending with PHB. The inclusion of starch in PHB blends can enhance the material's biodegradability and reduce production costs. Starch also acts as a plasticizer, making the PHB blend more flexible and easier to process. However, the hydrophilic nature of starch can sometimes negatively affect the mechanical properties and water resistance of the blend, which can be overcome by cross-linking and plasticizing agents.[49]

Use of Synthetic Polymers to Create Hybrid Materials: In addition to blending with biopolymers, PHB can also be combined with synthetic polymers to create hybrid materials. Synthetic polymers such as polyethylene (PE), polypropylene (PP), and polycaprolactone (PCL) are commonly used to improve the mechanical and thermal properties of PHB.

Hybrid Materials with Polyethylene (PE) and Polypropylene (PP): Blending PHB with synthetic polymers like polyethylene (PE) and polypropylene (PP) can significantly improve the material's mechanical properties, such as tensile strength and elongation at break, while also enhancing its thermal stability. These hybrid materials are especially useful in applications where high strength, stability, and flexibility are required. The hybrid materials may also offer cost reductions due to the relatively lower price of synthetic polymers.[50,51]

Hybrid Materials with Polycaprolactone (PCL): Polycaprolactone (PCL) is another synthetic polymer often blended with PHB to enhance its processability and flexibility. PCL has lower melting and processing temperatures compared to PHB, which can facilitate easier processing of the blend. The combination of PHB and PCL has been shown to yield materials that possess improved mechanical flexibility and better thermal stability, suitable for applications such as controlled drug release and medical devices.[52,53]

Role of Plasticizers, Fillers, and Cross-Linkers in PHB Blends

The incorporation of plasticizers, fillers, and cross-linkers plays a vital role in modifying the properties of PHB blends to improve their performance.

Plasticizers: Plasticizers are added to PHB blends to increase flexibility and reduce brittleness. Common plasticizers include sorbitol, glycerol, and citrates. These compounds lower the glass transition temperature of PHB, making it more flexible and easier to process. The addition of plasticizers can also enhance the film-forming ability of PHB, which is critical for packaging applications.[54]

Fillers: Fillers such as natural fibers (e.g., cellulose, flax, and jute) and inorganic materials (e.g., calcium carbonate, clay, and silica) are incorporated into PHB blends to improve mechanical properties, such as stiffness and strength. Fillers can also reduce the cost of PHB-based materials. The choice of filler material and its dispersion within the matrix are crucial for achieving the desired balance between mechanical strength and biodegradability. For example, the addition of cellulose fibers can improve the tensile strength and water resistance of PHB-based materials.[55]

Cross-Linkers: Cross-linkers, such as glutaraldehyde and epoxy compounds, are used to enhance the network structure of PHB blends, which in turn improves their mechanical properties and resistance to environmental degradation. Cross-linking can reduce the solubility of the polymer in solvents, increase its heat resistance, and improve its dimensional stability. In PHB blends, cross-linking is particularly important for enhancing the durability of the material in demanding applications.[56]

Properties of PHB Blends

Blending polyhydroxybutyrate (PHB) with other polymers or additives can significantly improve its properties, making it more versatile for various applications. The mechanical, thermal, and chemical properties of PHB blends are crucial for determining their suitability for different industrial uses. Furthermore, blending PHB with other materials can also affect its biodegradability and environmental performance, which are key advantages of bioplastics.

Mechanical Properties: The mechanical properties of PHB are often limited by its inherent brittleness. However, blending PHB with other polymers such as polylactic acid (PLA), polyhydroxyalkanoates (PHA), or synthetic polymers (e.g., polyethylene or polypropylene) can improve its mechanical characteristics. These blends typically exhibit enhanced tensile strength, elongation at break, and impact resistance compared to pure PHB, which makes them more suitable for applications that require flexibility and toughness, such as packaging materials, agricultural films, and biomedical devices.[57,58]

For instance, blending PHB with PLA increases the tensile strength and improves the ductility of the material, making it less prone to cracking and breaking under stress. The incorporation of natural fillers like cellulose or starch into PHB blends further enhances its mechanical strength, making it more suitable for structural applications.[59]

Thermal Properties

The thermal properties of PHB are another limiting factor, as it has a relatively low melting point and poor thermal stability compared to other polymers. The addition of other biopolymers like PLA or PHA can improve the thermal stability of PHB blends, allowing them to withstand higher processing temperatures and be used in a broader range of applications. For example, PHB/PLA blends show improved thermal stability, which helps overcome the low processing temperature of pure PHB.[60,61]

Blending with polycaprolactone (PCL) or synthetic polymers like polyethylene also enhances the thermal stability and processing characteristics of PHB. These blends can withstand higher temperatures, making them suitable for applications such as food packaging or medical devices that require greater thermal endurance.[62,63]

Chemical Properties

PHB blends generally retain the chemical resistance and biodegradability of pure PHB while exhibiting enhanced properties due to the addition of other materials. Blending PHB with synthetic polymers like polyethylene or polypropylene can improve its chemical resistance to solvents, oils, and acids, thus expanding its application in various fields[8]. However, some blends, such as PHB/starch composites, may exhibit reduced chemical resistance due to the hydrophilic nature of starch. The chemical properties of PHB blends depend on the compatibility between the blend components and their interactions at the molecular level.[64]

Biodegradability of PHB Blends

One of the main advantages of PHB as a bioplastic is its biodegradability. However, the biodegradability of PHB blends depends on the nature of the polymeric material with which it is blended. Biopolymer blends, such as PHB with PLA, PHA, or starch, generally maintain the biodegradability of PHB. For instance, PHB/PLA blends are still biodegradable in natural environments, although the degradation rate may be slower compared to pure PHB. This is because PLA, being more hydrophobic, decomposes at a slower rate than PHB.[65]

On the other hand, blends of PHB with starch can lead to faster biodegradation due to the starch's high water absorption and breakdown by microorganisms in the environment. However, the biodegradation rate is affected by the composition and ratio of the blend components. The incorporation of synthetic polymers, such as polyethylene or polypropylene, can reduce the biodegradability of PHB blends, as these materials are not biodegradable under natural conditions.[66,67]

Environmental Performance

Blending PHB with other biopolymers or synthetic polymers can also influence the environmental performance of the resulting material. Biodegradable PHB blends contribute to reducing plastic waste in the environment and offer a more sustainable alternative to petroleum-based plastics. The environmental performance of these blends can be enhanced by selecting biodegradable components that do not leave harmful residues after degradation.

For example, PHB/PLA and PHB/PHA blends offer a promising solution for reducing plastic pollution, as both PLA and PHA are biodegradable and derived from renewable resources. In contrast, PHB blended with synthetic polymers such as polyethylene or polypropylene may reduce environmental impact in terms of waste management, but they may not fully degrade in composting or landfill conditions . Additionally, the environmental benefits of these blends are highly dependent on the manufacturing processes and the raw materials used.[68]

Applications of PHB Blends

The unique properties of polyhydroxybutyrate (PHB) blends, such as biodegradability, mechanical strength, and flexibility, make them suitable for various applications across different industries. By blending PHB with other biopolymers or synthetic materials, the resulting composites can overcome some of PHB's limitations, such as brittleness, poor thermal stability, and processing challenges. The following are some key application areas for PHB blends:

Packaging Materials: Biodegradable Films and Containers

One of the most significant applications of PHB blends is in the production of biodegradable packaging materials. PHB-based packaging films are gaining popularity as an environmentally friendly alternative to conventional plastics made from petroleum. When blended with other biopolymers, such as polylactic acid (PLA) or starch, PHB films exhibit enhanced mechanical and thermal properties, making them more suitable for packaging applications like food packaging, single-use containers, and protective films. These blends can be composted and biodegrade over time, reducing plastic waste and environmental pollution. Moreover, the biodegradability of PHB blends ensures that packaging materials will not contribute to long-term waste accumulation in landfills or oceans.[69]

Agricultural Applications: Mulch Films and Controlled-Release Systems

PHB blends are widely used in agriculture, particularly in mulch films and controlled-release systems for fertilizers and pesticides. Mulch films made from PHB and its blends with other biopolymers, such as polyhydroxyalkanoates (PHA) or starch, are used to cover the soil in agricultural fields. These films provide several benefits, such as reducing water evaporation, suppressing weed growth, and enhancing crop yields. The biodegradable nature of these films ensures that they decompose after use, eliminating the need for post-harvest removal and disposal, which is a common issue with conventional plastic mulch.[70]

PHB blends are also used in controlled-release systems, where they can encapsulate fertilizers or pesticides, ensuring that these chemicals are slowly released into the soil over time. This reduces the need for frequent applications of fertilizers and pesticides, which can be harmful to the environment. The biodegradability of PHB blends allows for a more sustainable approach to agricultural practices.[71]

CONCLUSION

Summary of Key Findings:

1. **Blending with Other Polymers**: One of the most effective strategies for overcoming the limitations of pure PHB is blending it with other biopolymers

such as PLA, PHA, or synthetic polymers. This enhances the material's flexibility, toughness, and processability, making it more suitable for industrial applications. Additionally, the use of plasticizers, fillers, and cross-linkers further improves the performance of PHB blends.

2. **Environmental and Economic Benefits**: PHB blends offer significant environmental advantages over conventional plastics due to their biodegradability. They break down into natural products like water, carbon dioxide, and biomass, reducing the environmental pollution caused by plastic waste. However, the high cost of PHB production remains a key obstacle, and ongoing research focuses on improving the cost-efficiency of production processes and reducing the reliance on expensive feed-stocks.
3. **Application Potential**: The versatility of PHB blends in applications such as biodegradable packaging, agricultural mulch films, medical sutures, and consumer goods highlights their commercial potential. These applications align with the growing global demand for sustainable materials that contribute to a circular economy and reduce reliance on fossil fuels.
4. **Challenges and Future Directions**: Despite the advancements, several technical, commercial, and regulatory challenges remain. The development of more efficient production processes, the exploration of alternative feedstocks, and innovations in blending technologies are essential for achieving large-scale commercialization. Additionally, better understanding of biodegradation mechanisms, recycling practices, and consumer acceptance will be crucial for the future success of PHB blends.

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