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REVIEW ARTICLE

Advancing Sustainability: Polyhydroxy Butyrate (PHB) Unveiled - A Comprehensive Review of Eco-friendly Applications

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ABSTRACT

Plastic has become the most demanded substance in the various industries of manufacturing. The increased demand and extreme use of plastic is the biggest threat to global environmental pollution. Environmental plastic pollution is a challenge to all living forms on Earth, including terrestrial, celestial, and aquatic ecosystems. Bioplastic or biopolymer is a recommended alternative to overcome petrochemical plastic's consequences and pollution threats. Petrochemical materials can be replaced by using eco-friendly polymers. Eco-friendly polymers can be developed with the help of microorganisms using organic waste material as a substrate. Polyhydroxyalkanoates (PHAs) and polyhydroxybutyrate (PHB) are frequently known biopolymers. Their chemical and physical properties are compatible with the petrochemical polymers. The (PHA.) Polyhydroxyalkanoates are Ecological, Recyclable, and biodegradable. This article focuses on eco-friendly polymer production from microorganisms that use waste material as a carbon source for PHA accumulation.

Keywords: Polyhydroxyalkanoates, polyhydroxybutyrate, Eco-friendly polymers, Biodegradation, Waste material utilization.
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INTRODUCTION

Plastic has excellent worldwide applications and usage as a product of consumers.[1] Due to some properties of plastic, like its disposable nature, lightweightness, and low price, plastic has become the most demanded substance in various manufacturing.[2] The increased demand and extreme use of plastic is the biggest threat to global environmental pollution.[3] Environmental plastic pollution is a challenge to all living forms on Earth, including terrestrial, celestial, and aquatic ecosystems.[4] Globally increasing human population and technology-based development significantly increase plastic waste generation.[5] The unsustainable methods of used plastic disposal are responsible for increasing plastic pollution. Most of the Earth's surface is accumulated by post-consumer or used plastic. The buried plastic under the Earth's surface significantly threatens human health and the environment's safety. The global plastic market is growing compared to the total growth of other market products. In India, plastic and plastic products are in high demand.[7] Plastic industries are the most significant contributors to the Indian economy. About 12.8 million tons/year of plastic consumption is estimated in India. The daily generation of plastic waste in India is more than 25,000 tons/day. Households, markets, hospitals, office buildings, prisons, schools, restaurants, hotels, etc., generate plastic waste.

Various large-scale industries follow the generation of plastic waste in large amounts. Maharashtra, Uttar Pradesh, Andhra Pradesh, Gujrat, and Karnataka are India's top five plastic waste-generating states. Those states cause more than 0.4 million tons/year of plastic waste in India.[8]

As compared to rural regions, urban regions generate more plastic waste. However, in rural areas, the open burning practices of plastic wastes are used to carry out, which releases more toxic substances into the environment. This happens in rural areas due to a need for proper disposal knowledge and awareness.

Plastic is generally a derivative of the groups of polymers. It possesses a characteristic stable, hydrophobic, and durable nature. Plastics are lightweight, low density, inexpensive, corrosion-resistant, shock, and water-resistant properties.[9] Plastic is an organic polymer with high molecular weight.

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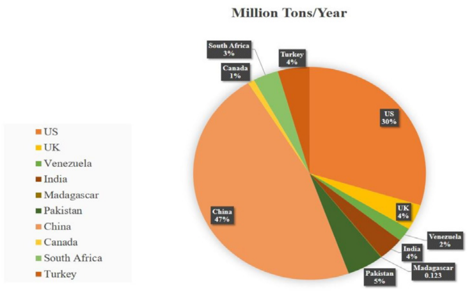


Figure 1: Representation of Global Scenario of Plastic Waste Generation.[8] [Goel, Malti & Tripathi, Neha. (2019)]

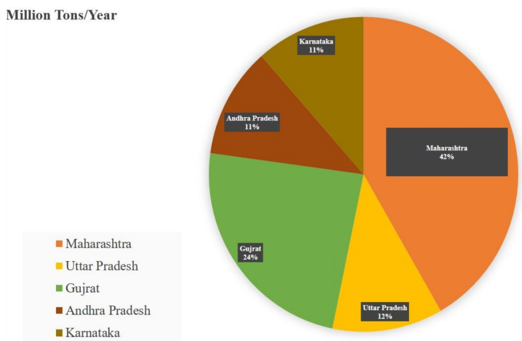


Figure 2: Representation of Indian Scenario of Plastic Waste Generation.[8] [Goel, Malti & Tripathi, Neha. (2019)]

Plastics are comprised of Polyethylene (PE), Polyethylene Terephthalate (PET), polyamide (PA)/nylon, polyvinyl chloride (PVC), and Polypropylene (PP), Polystyrene (PS). All those derivatives of plastic can be known as petrochemical plastics.[10]

To overcome the consequences and pollution threats of petrochemical plastic, bioplastic or biopolymer is a recommendable alternative.[11] Over the past few years, the developing technology and biological science studies on converting organic wastes into biomaterials like biopolymers and developing bioenergy. Petrochemical materials can be replaced by using eco-friendly polymers. Eco-friendly polymers can be created with the help of microorganisms using organic waste material as a substrate.[12] Generally, organic waste materials are a great renewable source that can be converted into many value-added products such as biopolymers, bioethanol, biodiesel, etc.[13] Some microorganisms have significant properties to produce biopolymers through an accumulation of extracellular substances like exopolysaccharides (EPS). Those biopolymers have great demand in the chemical, food, packaging, and cosmetics industries. Polyhydroxyalkanoates (PHAs) and polyhydroxybutyrate (PHB) are frequently known biopolymers. Their chemical and physical properties are compatible with the petrochemical polymers.[14]

Eco-Friendly Polymers

The PHA are ecological, recyclable, and biodegradable.[15] It is nothing but the type of linear polyester which is generally the by-product of the microbial fermenting process. Similar properties of non-recyclable, non-biodegradable traditional plastic have been observed in the PHA's Plastic. The production cost of PHA production is high compared to conventional petrochemical plastics.[16] Recently, the researcher generally focused on reducing the production cost of the PHA by using various microbiological and bacterial strains and the biotechnological process.

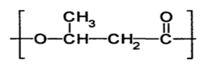
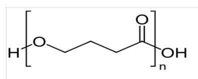
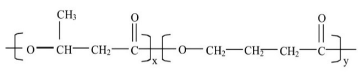
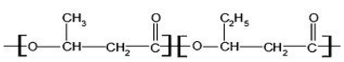
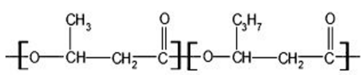
Conventional plastic is responsible for global environmental pollution. Polypropylene plastic types: Plastic replaced wood, metal, and other construction materials from 1940. The use of plastic since the age of 1940s has increased day by day, widespread all over the ecosystem.[17] The vital reason behind this is the properties of plastic: they are durable and thermally stable, and the production cost of this traditional plastic is low, but production of this type of plastic leads to the release of lots of chemical contaminants in the environment during the production as well as after burning of the same plastic. To avoid these fundamental environmental problems, biodegradable plastic is a great alternative, which is deemed by the global scenario. There are some naturally occurring plastics viz, starch, cellulose, polylactic acid, and polyhydroxyalkanoates.[18] The benefits of this naturally occurring plastic are eco-friendly, recyclable, and produced from renewable sources. The problem with this eco-friendly polymer is the production cost is greater than the conventional plastic production cost, which makes the negligence of the biodegradable plastic production research. But the recent trends of research are giving an output of the production of poly -3-hydroxybutyrate with the help of microbial isolates, which is natural, cost-efficient, and also belongs to the family of eco-friendly polymers, i.e., Polyhydroxyalkanoates. This poly -3-hydroxybutyrate (PHB) is Generally found in bacteria as the metabolic product of the microbial process.[19] The article aims to overview the production of eco-friendly polymers. Scientists and researchers are continuously working to solve the problem of plastic pollution, which is difficult to degrade due to its non-biodegradable polymeric nature. They are currently focused on developing an environmentally friendly and cost-effective biodegradable polymer.

Types of PHB

Polyhydroxyl alkanoates (PHAs), aliphatic polyesters, polylactides, and polysaccharides are biodegradable polyesters.[20] The polymer PHA (polyhydroxyalkanoates) are of different subtypes, which include PHB (polyhydroxybutyrate), PHH (polyhydroxyalkanoate), and PHV (polyhydroxy valerate), PHO (polyhydroxyalkanoate).[21] Among all the PHA polymers, PHB is the primary biodegradable polymer. PHB is an effective and biodegradable thermoplastic. PHB has similar characteristics to commercial plastic. PHB polymers are less flexible and completely biodegradable, and they don't leave any residue after degradation and do no harm to the environment.[22]

PHA is classified according to the number of carbon atoms present in the monomeric unit of PHA. Depending on the chain length, PHA is divided into two groups: SCL (Short chain-length) PHAs of 3-5 carbon atoms and MCL (medium chain-length) PHAs of 6-14 carbon atoms. PHB (polyhydroxy valerate) monomers have carbon numbers 3-5.[24]

Table 1: Types and Structures of PHA used as biopolymers in large-scale processing.23

Sr. No.	*Types of PHA Polymers*	*Structure of PHA polymers*
1	Poly(3-hydroxybutyrate)	
2	Poly(4-hydroxybutyrate)	
3	Poly(3-hydroxybutyrate-4-hydroxybutyrate)	
4	Poly(3-hydroxybutyrate-co-3-hydroxyvalerate)	
5	poly-(3-hydroxybutyrate-co-3-hydroxyhexanoate)	

PHB Producing Microorganisms

3-hydroxybutyrate has a copolymer, i.e., PHB. Bacteria intracellularly accumulate it under unfavorable conditions of nutrition or starvation. PHB is obtained intracellularly under starvation or specific nutritionally adverse conditions. It is a 3-hydroxybutyrate copolymer. Not all, but a few microorganisms can get 3-hydroxybutyrate in a large amount.

PHA-producing bacteria include *Alcaligenes eutrophus, Azotobacter vinelandii, Bacillus spp., Alcaligenes latus, pseudomonas spp., Escherichia coli, Rhizobium spp., methylotrophs.* Various recombinant strains of bacteria are under development by focusing on genetic, molecular biology, and metabolic study of those bacteria to increase the PHA synthesizing ability. *B. megaterium* was the first bacteria found with PHB-producing abilities.[24] *B. megaterium* accumulates PHB in a large amount. This material has excellent biocompatibility, biodegradability, and thermoplastic properties, making it highly suitable for various natural applications. It is used in drug delivery systems. An increase in carbon sources can increase PHB production among the bacteria. PHB production also needs to limit phosphorus, magnesium, nitrogen, oxygen, iron, and potassium. PHB is an intracellular polymer accumulated in a bacterial cell under stressed conditions with an excess carbon source. Bacteria like *Bacillus megaterium* and *Ralstonia eutropha* produce PHB in the microbial fermentation process. The salt concentration, pH, and temperature of growth media can also affect the PHB production.[24]

PHB Production from Waste Material

For the growth and development of PHB-producing bacteria, carbon is required to reach substrate.[26] Recently, food waste, agricultural waste, and dairy industry wastes have been focused on interaction as a substrate for PHB production. These wastes

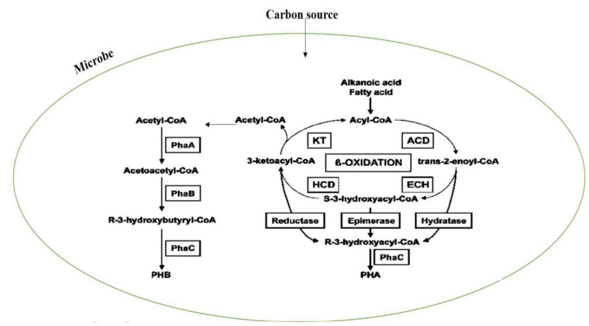


Figure 3: Pathway of PHB Biosynthesis using Carbon Source in Bacteria.[25] [Kavitha, G., Rengasamy, R., & Inbakandan, D. (2018).]

were rich in carbon and have potential nutrients required for microbial fermentation during value-added PHA production. Along with this waste from the sugar industry, waste lipids, starch, alcohols (methanol), and lignocellulosic feedstocks can also be used as a substrate for good PHB production. Lipid wastes can be made available from different plant oils, waste cooking, palm, and wastewater sources. Triacylglycerides are commonly utilized as a source of carbon. Lignocellulosic substances (hemicellulosic and cellulosic fibers, lignin's) and cellulosic substances can provide the highest quantity of feedstocks. Agriculture, paper, and wood-processing industries are significant sources of these waste materials.[27]

PHB Characterization Methods

Different analytical methods can be employed for the identification and characterization of PHB. Fourier transform infrared (FTIR) spectroscopy, nuclear magnetic resonance (NMR.) spectroscopy, Differential scanning calorimetry (DSC), liquid chromatography mass spectrometer, Thermo-gravimetric analysis, ultraviolet-visible spectroscopy, and gas chromatography-mass spectrometer are the frequently used characterization methods for PHB analysis. PHB is characterized based on its morphological and chemical nature. Some significant characteristics used to be focused on during PHB characterization are its high degree of crystallinity, brittle and stiff nature, and low thermal stability. Many PHB polymers have abilities similar to synthetic polymers.[38]

Bioremediation of Eco-friendly Polymers

Living organisms perform a biological activity of decomposition of complex waste matter into an organic compound that is lower molecular weight and non-toxic. The end product of this biodegradation process is usually utilized as a nutritional and energy source for the anabolic activities of non-producing organisms. PHA biodegradation is carried out either under anaerobic conditions for methane, water, and carbon dioxide production and in aerobic conditions for carbon dioxide production, and H_2O PHB can degrade into 3-hydroxybutyric acid by using the enzyme PHB depolymerase and hydrolase.[39] Using the degradation enzymes, 3-hydroxybutyric acid is oxidized to form acetyl acetate. Cell regenerating enzyme acetyl coenzyme A is formed due to the reaction between β-ketothiolase and acetyl acetate. Several fungi and bacteria,

Table 2: different types of waste materials as a substrate for PHB production and waste-generating industries.[28]

S. No	*Waste materials*	*Waste-generating industrial branches*	*References*
1	Whey	Dairy industry, Cheese industry	[26,30]
2	Non-edible starch	Agriculture	[31]
3	Cellulosic and Lignocellulosic	Agriculture, Food industry, Paper industry	[32]
4	Methanol	Biodiesel industry	[33]
5	Methane	Biogas industry	[34]
6	CO_2	Industry in general, Biogas conditioning	[34]
7	Waste lipids	Animal processing industry, Biodiesel industry	[35]
8	Crude glycerol	Biodiesel industry	[36,37]

e.g., *Actinomadura, Pseudomonas, Aspergillus spp., Bacillus spp., Penicillium, Saccharomonospora, Thermoactinomyces, Microbispora,* and *Streptomyces*, have the potential to degrade PHAs both anaerobically and aerobically. Several microorganisms in anaerobic sludges can degrade PHB in environments like fresh water, salt, or soil. The most favorable and natural environment for PHB degradation is soil.[40]

Applications of PHB

Considering the pressing global concerns surrounding environmental sustainability, our study centers on the pivotal role of PHB in mitigating the adverse effects of nondegradable petrochemical plastics. Our research proposes the creation of commercially viable, eco-friendly PHB biopolymers synthesized from waste substrates, with a primary focus on their practical applications.

An exemplary application of our work is evident in wastewater reclamation and treatment, where PHB biopolymers have demonstrated substantial effectiveness in enhancing water quality. Noteworthy pilot studies conducted by our team have showcased the successful integration of PHB in large-scale wastewater treatment facilities, illustrating its potential for scalable and impactful commercial use.

Our research has yielded promising results in the agricultural sector, with PHB biopolymers contributing to the development of biodegradable fertilizers, seed encapsulation techniques, and sustainable plastic films. Pilot studies conducted on agricultural plots have shown increased crop yields and a reduction in environmental impact, offering tangible evidence of the commercial viability of PHB in agriculture.[41]

PHB produced by microorganisms holds immense promise across various applications due to its biodegradability, eco-friendliness, and versatility. Here are detailed applications,

Biodegradable Plastics

PHB is widely utilized in the production of biodegradable plastics. These plastics have applications in packaging materials, disposable cutlery, and various single-use items. Unlike traditional plastics, PHB-based bioplastics break down naturally, reducing environmental pollution and addressing the global plastic waste crisis.[42]

Agricultural Applications

PHB has proven beneficial in agriculture. It can be incorporated into biodegradable mulches, films, and coatings. Biodegradable mulches from PHB offer advantages such as weed control, moisture retention, and soil temperature regulation. PHB-coated seeds and fertilizers provide a controlled release of nutrients, promoting sustainable agriculture practices.[43]

Medical Implants

PHB's biocompatibility makes it suitable for medical applications. It produces biodegradable medical implants, such as sutures, bone plates, and drug delivery systems. PHB's gradual degradation aligns with tissue healing processes, eliminating the need for additional surgeries to remove implants.[44]

Wastewater Treatment

PHB produced by microorganisms can be employed in wastewater treatment processes. Microorganisms enriched with PHB can act as bioagents for nutrient removal, enhancing the efficiency of biological treatment methods. PHB utilization in wastewater treatment reduces excess nutrients, promoting cleaner water discharge.[45]

Biofuel Production

PHB can be converted into biofuels through microbial fermentation processes. The derived biofuels, such as bioethanol or biodiesel, offer a renewable and sustainable alternative to conventional fossil fuels. This application aligns with the growing need for cleaner energy sources and reduced reliance on non-renewable resources.[46]

Food Packaging

PHB's biodegradability and barrier properties against gases make it suitable for food packaging. PHB films can be used to create sustainable and environmentally friendly packaging materials. The use of PHB in food packaging contributes to the reduction of non-biodegradable packaging waste.[47]

Cosmetic and Personal Care Products

PHB is finding its way into cosmetic and personal care products. Its biocompatibility makes it suitable for products like microbead replacements in exfoliating scrubs and encapsulation of active ingredients for controlled release. As a component in biodegradable packaging for beauty products,[48] PHB can be blended with other biodegradable polymers to create environmentally friendly textiles. Fabrics made from PHB blends are biodegradable, reducing the environmental impact associated with synthetic materials.[49] This application aligns with the growing demand for sustainable and eco-friendly fashion.[50]

By delving into these specific applications, the potential of PHB produced by microorganisms becomes clearer, showcasing its ability to address environmental challenges and contribute to sustainable practices in various industries.

CONCLUSION

There is increased demand for plastic polymers in day-to-day life. Using synthetic polymer harms the environment as it is nondegradable and causes increased environmental pollution. A great alternative to synthetic polymers is biologically synthesized polymers like PHA copolymers. These biopolymers are eco-friendly and biodegradable. PHB is found to be the most studied and commonly produced biopolymer by various bacteria. The fields of microbiology and biotechnology are working to find a biological solution to degrade plastic waste. Previous studies found that microorganisms can naturally accumulate biopolymers like PHB by utilizing carbon sources from waste material. It is an alternative to petrochemical or petroleum products like plastics. This ability of microorganisms is helpful to reduce the use of synthetic polymers, resulting in the maintenance of environmental health. This ability of microorganisms is the best solution to clean up plastic pollution, which is life-threatening to the air, water, and land.

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