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Review

Recent approaches for enhanced production of microbial polyhydroxybutyrate: Preparation of biocomposites and applications

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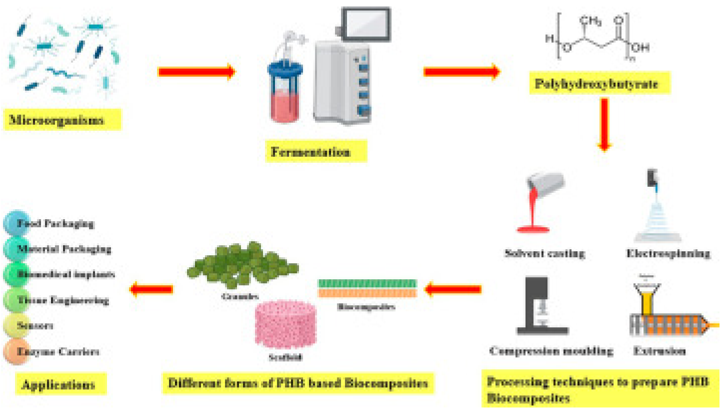
Highlights

- Polyhydroxybutyrate production from biomass feedstock and microbial genetic modification
- Processing techniques for the fabrication of polyhydroxybutyrate based polymer composites
- Biodegradability studies of polymer composites

Abstract

In modern decades, an increase in environmental awareness has attracted the keen interest of researchers to investigate eco-sustainable, recyclable materials to minimize reliance on petroleum-based polymeric compounds. Poly (3-hydroxybutyrate) is amorphous, linear, and biodegradable bacterial polyesters that belong to the polyhydroxyalkanoates family with enormous applications in many fields. The present review provides comprehensive information on polyhydroxybutyrate production from different biomass feedstock. Various studies on PHB production by genetically engineered bacterial cells and optimization of parameters have been discussed. Recent technological innovation in processing polyhydroxybutyrate-based biocomposite through the different process has also been examined. Besides this, the potential applications of the derived competent biocomposites in the other fields have been depicted.

Graphical abstract



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Introduction

In the contemporary world, life would be scarcely imagined without the use of polymers or petroleum-derived synthetic polymers. Plastics are extensively used to prepare packaging materials, institutional products, electrical and electronics materials, industrial, machinery, and construction. Subsequently, there is a tremendous increase in global solid waste generation due to the gradual accumulation of durable polymers. The traditionally used monomers for the extensive preparation of polymers are primarily based on ethylene and propylene products obtained as functional derivatives from fossil hydrocarbons. Synthetic polymers are highly durable and long-lasting; thus, even after their destruction, invisible remnants of the polymers remain in the ecosystem, impeding the sustainable development of marine life. None of these polymers are degradable under ordinary conditions and hence, require certain treatment before their disposal. Myriad of artificial methods [1] such as mechanical crushing, grinding, pyrolysis, incineration, catalytic decomposition, and fluidized bed oxidation employed for their destruction.

According to a survey conducted in 2015 [2], about 6300 million metric tons (Mt) of plastic waste was generated. Of which, 9% of waste was recycled, 12% was incinerated, and 79% was accumulated in the natural environment. With the help of the modelling approach, if the production rate of plastic continued with the same trend, then around 12,000 Mt of plastic waste will be generated in the natural environment by 2050 [2,3].

According to a research undertaken by the Association of Plastics Manufacturers in Europe in 2018, Asia is the world's leading producer of plastics, accounting for 51% of total plastics produced worldwide. In Asia, China and Japan have a market share of 30% and 4% respectively. Canada, Mexico, and the United States of the NAFTA countries cover the rest of the manufacturing of the world (Fig. 1) [4].

The manuscript is focused on the biosynthesis of PHB biopolymer by microbial cells grown on different substrates. Several conditions for the growth of microorganisms such as feedstock biomass, fermentation cycle, and type of strain, and its genetic modification have been discussed for PHB production. The degradation studies for PHB biocomposites reinforced with other synthetic and natural polymers have also been described. In addition, techniques for the preparation of PHB-based biocomposites were discussed with improved thermal and mechanical performance. Finally, the work on the PHB biocomposite has been summed up in innovative ideas in the form of patents.

Section snippets

Biodegradable polymers - a step towards the betterment of the environment

Biodegradable plastics have been extensively documented, but significant progress has recently been made in their production. The term "biodegradable plastics" implies the polymer can undergo microbial, enzymatic, and compost degradation to produce carbon dioxide, water, inorganic compounds, and biomass determined by standard protocols.

The biodegradation rate depends on the temperature, pH, and humidity of the environment. The degradation rate can further be complemented from the catabolic …

Microbial production of polyhydroxybutyrate

The PHB accumulation in a bacterial cell is a lifesaving response to bacterial cells' stress conditions. Such conditions for microbes can be provided in vitro by restricting nutritional supplements during their growth. The microbial fermentation with substrates such as agro-based by-products, industrial products, polysaccharides, and hydrolysed materials can be used to produce PHB [3,21,22]. Reports of the utilization of softwood hydrolysate as a carbon source have also been mentioned for PHB …

Biodegradation effect on polyhydroxybutyrate biocomposites

PHB is biodegradable under changing ecological conditions as compared to other synthetic polymers. The commercially available PHB usually has many constraints, such as low impact strength, poor flexibility, and difficulty in blending with other polymers without losing its functionality [61]. The polymer can be converted into its original constituents like carbon dioxide, water, and energy by degradation carried out by various microbes [5]. These microorganisms secrete extracellular enzymes such …

Processing techniques for preparation of PHB biocomposites

Natural PHB has favourable characteristics, with an exceptionally high crystallinity of up to 70%, which therefore ascribe to its superior mechanical properties. This characteristic is indicative of the presence of small, regularly-oriented units within a single sequential structure within the molecule [83]. The crystallization rate within the cell depends on the speed of spontaneous nucleation within the granule [9,84]. PHB biopolymer can be present at ambient temperature in crystal lattice …

Applications of PHB nanocomposites

According to the market report of European bioplastics (2018), the production of bioplastics represents approximately 1% of the 335 million tons of plastics produced annually. Bioplastic production worldwide has increased from 2.11 million tons (2018) to about 2.62 million tons in 2023 [143]. The companies like DuPont, BASF, Union Carbide, Cargill-Dow Polymers, Monsanto, Mitsui and Eastman Chemical, and Bayer are known to produce biodegradable plastics [5,10]. Many companies specifically …

Patent trends on PHB nanocomposites

For the past few decades, many research works are going on for the development of PHB nanocomposite. Several researchers have combined PHB together with other polymers and have patented their noble work. Biodegradable polymer blends suitable for use in coating, packaging, or drug delivery can be fabricated by using polyhydroxybutyrate, optionally combined with other additional biodegradable polymer or non-biodegradable polymers. PHB blended with BIOMAX polymer had better strength and elongation …

Conclusion

Many microorganisms have been reported for PHB production, however, the maximum yield from *Cupravidus* spp. was reported. The production depends on the substrate and other parameters utilized. When nitrogen was limited in the medium, the consequence was enhanced in several instances. Recombinant strains like *E. coli* and *Halomonas* were developed, resulting in higher PHB in comparison with the wild. Genetic modification can be used for enhancing the efficiency of microbial strains to solve many …

Abbreviations

PHB
: polyhydroxybutyrate …

OMMT
: organo-modified montmorillonite …

NC
: nanocellulose …

CNF
: cellulose nanofibrils …

Tm
: melting temperature …

T_{m1}
: melting temperature determined at first run …

T_{m2}
: melting temperature determined at second run …

YB
: Young's modulus (E) …

TM

tensile modulus …

EB(ε_b)

elongation at break …

TS(σ_b)

tensile strength …

FS

flexure strength …

CNC

cellulose nanocrystals …

PLA

poly(lactic acid) …

ATBC

acetyl tributyl citrate …

PHBV

poly(3-hydroxybutyrate-co-hydroxyvalerate) …

PCL

poly(ε-caprolactone) …

PBSA

poly(butylene succinate-*co*-adipate) …

ELO

…

…

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this manuscript. …

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> *Citation Excerpt :*
>
> …Moreover, HOB can accumulate PHB of 80–90% cell volume in the low-concentration nutrient state, while most other bacteria accumulate PHB only 40–50% of the cell volume (Ishizaki et al., 2001; Yu, 2018). Moreover, the concentration of PHB produced by HOB can be up to 0.4–58.5 g/L, which is far higher than that reported in other bacteria (0.3–1.2 g/L) (Anjana et al., 2021). In recent years, in order to obtain a higher yield of PHAs, researchers have conducted a series of studies on its production under different conditions.…

Sustainable biobased composites for advanced applications: recent trends and future opportunities – A critical review

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