

Development of Polyhydroxybutyrate (PHB) production articles: a bibliometric analysis (1990-2023)

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Abstract

Since the 1940s, the rise in plastic manufacturing has led to increasing plastic waste and environmental damage, driving the need for biodegradable plastics like polyhydroxybutyrate (PHB). PHB is sustainably produced through microbial fermentation using agricultural and industrial waste and is applied in packaging, agriculture, biomedicine, and 3D printing due to its biodegradability and biocompatibility. Advances from 1990 to 2023 include optimized genetic engineering in bacterial strains like *Cupriavidus necator*, low-cost feedstocks such as molasses, and scalable bioreactor designs for efficient large-scale production. Mixed microbial cultures in wastewater treatment plants exemplify innovations that combine PHB production with pollution mitigation. A bibliometric analysis of Science Direct highlights China's leading role in PHB research, evidenced by the highest publication and citation rates. This study enhances the literature by revealing significant trends and advancements in PHB development.

Keywords: *biodegradable, plastics, polyhydroxybutyrate, bibliometric.*

Data Availability: Research data is available upon request from the corresponding author.

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1. Introduction

In today's globalized world, humans will never be separated from plastic. Plastic consumption is increasing every year. The increase in plastic manufacturing since the 1940s illustrates a notable surge in plastic waste, culminating in a staggering global total of 230 million tonnes by 2009—accounting for approximately 8% of the world's oil production. Across the globe, plastic has emerged as an integral component of everyday life for humanity. Every item humans need is inseparable from plastic polymers, whether for food, electronics, vehicles, buildings, or others. Plastic pollution has become a severe problem in society, with plastic produced between 2004 and 2018 equivalent to plastic production in the previous half-century. Most of this plastic will end up in landfills and also directly discharged into the environment. As the plastics currently consumed are mainly derived from petroleum, the plastics industry cannot avoid issues related to fossil fuel depletion and climate change^[1]. In addition, plastics derived from fossil fuels have characteristics that are difficult to decompose in nature or the environment. The ability of fossil fuel plastics to decompose in nature is tens to hundreds of years; the decomposition of fossil fuel plastics will not disappear entirely but become microplastics and nanoplastics. Recent projections indicate that approximately 8 million tonnes of

plastic are introduced into the oceans annually from coastal nations, with forecasts predicting that this figure could potentially double by the year 2050^[2]. The accumulation of plastic waste poses numerous environmental issues and challenges, primarily as much of this waste ends up in landfills and natural surroundings. In recent years, a significant body of research has highlighted the prevalence of microplastics (MP) across diverse ecosystems, particularly focusing on aquatic environments such as oceans, rivers, estuaries, lakes, and even the pristine waters of the Arctic and its estuarine areas^[3-5].

In light of the profound long-term environmental consequences associated with the utilization of fossil fuel-based plastics, there is a growing demand for and production of biodegradable plastics. These eco-friendly alternatives are anticipated to find applications across multiple sectors, including agriculture, pharmaceuticals, cosmetics, and the food industry^[6]. In the last few decades, there has been much research in the development of new materials to deal with the environmental problems presented by fossil-based plastics, including the development of starch-based biodegradable plastics for the food and beverage packaging sector, but due to their properties that are still far from fossil-based plastics, the development of starch-based biodegradable

plastics is not very significant. Because of this, many new biodegradable plastic material developments have been presented by researchers around the world, including the development of Poly Lactic Acid (PLA), and the most recent and widely developed in the last ten years include polyhydroxyalkanoate (PHA) and polyhydroxybutyrate (PHB). In the global world, polyhydroxyalkanoate (PHA) production in 2018 was 29,000 tonnes and increased in 2023 to about 37,000 tonnes^[7]. Hydroxybutyrate (PHB), just like PHA biopolymers, can be obtained from microbial fermentation. Based on a compound annual growth rate (CAGR) of 11.2% and a prediction of the PHB market in 2024 of \$98 million^[8]. While the advancement of innovative biodegradable plastic materials, including PLA, PHA, and PHB, is substantial, substantial backing from governments, corporations, and individuals globally is essential to foster the production of high-quality, cost-effective biodegradable plastics. This support is crucial for replacing fossil fuel-based plastics, ultimately mitigating both immediate and long-term environmental issues associated with their use. In this regard, scientific research and bibliometric analyses can offer critical insights to inform more effective policies aimed at promoting the development of biodegradable plastics as alternatives to these environmentally detrimental fossil-based options.

Several researchers have conducted bibliometric studies on plastic pollution and specific plastic waste treatment strategies, such as thermochemical conversion, recycling through pyrolysis, and biodegradation^[9-14]. However, to the authors' knowledge, no bibliometric study has systematically analyzed the development of biodegradable polyhydroxybutyrate (PHB) plastics. This highlights the need for a comprehensive bibliometric study to explore the research trends, gaps, and global progress in developing PHB biodegradable materials.

This study aims to focus on the development and production of polyhydroxybutyrate (PHB) biodegradable plastics by providing insights into their scientific evolution. A thorough bibliometric review was conducted using the ScienceDirect database from 1990–2023, employing quantitative methods for performance analysis and scientific mapping. The analysis includes key aspects such as research trends, author contributions, institutional and national outputs, as well as citation patterns. The study leverages the VOSviewer application to visualize and evaluate collaborative networks, knowledge clusters, and thematic developments in PHB research.

By emphasizing the scientific and technological advancements in the production of PHB materials, this research aspires to provide a roadmap for future studies and foster informed, collaborative efforts in enhancing the quality and sustainability of biodegradable plastic production. The findings are expected to guide stakeholders in academia, industry, and policymaking toward innovative solutions for global plastic pollution.

2. Materials and Methods

Bibliometric analysis is a quantitative study of an article or topic about a bibliographic survey that provides

an overview of a particular field of research, which can be classified by research article, author, and journal^[15]. In this study, the authors relied on the database from Science Direct to collect publication articles related to the development of polyhydroxybutyrate (PHB) plastic biodegradable materials. Science Direct is an open-access digital platform that provides access to publications from Elsevier, one of the world's leading academic publishers of scientific content^[16]. The author started this research on 12 March 2024, where this article focuses on international journals related to the development of PHB plastic biodegradable materials in the period 1990 to 2023. The keywords that the author used in searching for articles for this bibliometric study were "Production" and "Polyhydroxybutyrate" to show the development of new biodegradable plastic polyhydroxybutyrate PHB in the world from 1990 to 2023. The author found many articles from Science Direct about developing production of polyhydroxybutyrate as a new material to replace fossil-based plastics, which were then analyzed using the VOS Viewer application. To export article metadata from ScienceDirect, use the Export or Download Citations options and select formats such as Txt. or BibTeX for bibliometric purposes. The exported data can be directly used in tools like VOSviewer without manual conversion. If a .txt format is required, the file can be opened in a text editor and saved with a .txt extension. This process facilitates bibliographic data analysis to support research visualization and mapping^[17]. The matrix used by the author in creating this bibliometric article is the author of the article, the affiliation of the article publisher, the country of the article publisher, the impact of the journal that published the article, and the year of writing the article. The master data from Science Direct covers several disciplines, including science, engineering, social sciences, and humanities. Based on the source with the keyword "polyhydroxybutyrate production" in Science Direct, 4,577 scientific articles were obtained.

Bibliometric analysis, in general, is widely used to obtain comprehensive data or knowledge about a researcher and its structure, themes, topics, and terminology^[18]. The mapping method used in bibliometric articles is the VOSviewer application^[19-22] for mapping and data analysis carried out by the author using the VOSviewer version 1.6.15 application after the data from Science Direct is downloaded. VOS viewer helps build and visualize bibliometric and network articles, citations, co-authorship, and publication databases^[23]. VOSviewer, a widely used software for visualizing bibliometric networks, can be freely downloaded from its official website VOSviewer. The website provides different versions of the software to accommodate various operating systems, including Windows, macOS, and Linux^[24]. This bibliometric technique will identify emerging topics, research limitations, and core journals in the research field to produce comprehensive and well-structured data. The bibliometric results of biodegradable production polyhydroxybutyrate (PHB) plastic development articles are increasing from year to year, which reflects the concern about the environmental threat of fossil-based plastics so the need for the development of new materials as a substitute for fossil-based plastics.

VOSviewer is widely used to visualize and explore bibliometric networks, such as relationships between authors, keywords, or citations. A key step in this analysis involves

importing data from text files (.txt) extracted from scientific databases like ScienceDirect. These text files typically contain bibliographic information in a format compatible with VOSviewer, including metadata such as author names, article titles, affiliations, keywords, and inter-entity relationships. The text file is uploaded into VOSviewer using the API and DOI columns, allowing seamless integration of the .txt format. The software processes this data to generate a relational matrix, such as co-occurrence or co-citation networks, which are then visualized as maps or network diagrams to provide meaningful insights^[23]. For this study, comprehensive analyses were conducted using co-authorship, co-occurrence, citation, and bibliographic coupling techniques. Units of analysis included authors, organizations, countries, sources, and documents, enabling a detailed exploration of bibliometric patterns within VOSviewer”.

3. Results and Discussion

3.1 Data source

Data sources from science-direct data-based bibliometric data related to developing polyhydroxybutyrate (PHB) plastic degradable materials from 1990 to 2023 are shown in Table 1. ScienceDirect was selected for this bibliometric analysis due to its reputation as a leading database providing high-quality scientific articles across disciplines, particularly in biochemistry, materials science, chemical engineering, and environmental science. Its reliable data consistency and well-organized metadata enable efficient filtering by document type, field, or keywords, ensuring^[26]. A total of 4,577 articles with the keyword “polyhydroxybutyrate production” originated from 1990 to 2023. Four thousand five hundred seventy-seven articles cover a variety of document types, including research papers of 2,074 articles, followed by 1,055 review articles, 112 encyclopedia articles, 863 book chapters, and 61 conference abstract articles. Based on the publication title, 346 articles were related to biosource technology, followed by 191 articles from the International Journal of Biological Macromolecules, 96 articles related to the science of total environment, 84 articles titled Water research, and 82 articles titled Biotechnology. In addition, the subject of the article is displayed on Science Direct, where biochemistry, genetics, and molecular biology have 1,234 articles, followed by material science with 947 articles, chemical engineering with 1,101 articles, environmental science with 807 articles, and immunology and microbiology by 648 articles and in the last five years interval with environmental issues caused by fossil-based plastics in nature resulted in an increasing number of publications of articles related to biodegradable polyhydroxy butyrate (PHB) plastic materials as shown by 1,143 research articles produced over the last five years, followed by 781 review articles, and 547 book chapters. The documents produced over the last five years illustrate the wide-ranging scientific inquiry within the realm of polyhydroxybutyrate (PHB) biodegradable plastics. They also reflect the various methodologies and viewpoints presented by researchers and experts in this domain, which play a crucial role in the development of novel eco-friendly plastic materials intended to replace fossil fuel-derived plastics.

Table 1. Information from Science Direct about development articles of polyhydroxybutyrate interval 1990-2023.

Description	Result
General information	
Time Interval	1990-2023
Source	Science Direct
Documents Articles	4,577
Article Type	
Review Articles	1,055
Research Articles	2,074
Encyclopedia	112
Book Chapters	863
Conference Abstracts	61
Book Reviews	3
Case Reports	3
Conference Info	1
Correspondence	2
Data-Articles	3
Discussion	11
Editorials	20
Errata	3
Mini-Reviews	11
News	1
Patent Reports	2
Short Communications	60
Others	292
Subject Areas	
Biochemistry, Genetics, and Molecular Biology	1,234
Material Science	1,101
Chemical Engineering	947
Environmental Science	807
Immunology and Microbiology	648
Chemistry	573
Agricultural and Biological Sciences	438
Energy	400
Engineering	256
Earth and Planetary Sciences	127

From year to year, research related to the development of polyhydroxybutyrate plastic biodegradable materials continues to increase from 1990 to 2023 in Science Direct, where the peak occurred in the last five years, as shown in Figure 1. Where the development of articles related to the production of polyhydroxybutyrate (PHB) has increased since 2018 reaching 256 articles, 2019 reached 312 articles, 2020 reached 339 articles, 2021 reached 537 articles, 2022 reached the highest at 622 articles, and 2023 reached 578 articles. There was a decline in publications in 2023 compared to 2022 regarding polyhydroxybutyrate (PHB) production. Several factors contributed to this decrease. Technical challenges such as high production costs, low yields, complex technologies, and difficulties in downstream processing have hindered progress in PHB research. Additionally, a shift in research focus to more promising or industry-relevant areas has reduced interest in PHB production. Funding limitations for bioplastics research also constrained the number of studies published. Lastly, the lingering effects of the COVID-19 pandemic up to 2022 likely disrupted research and publication activities, collectively explaining the decline in PHB-related

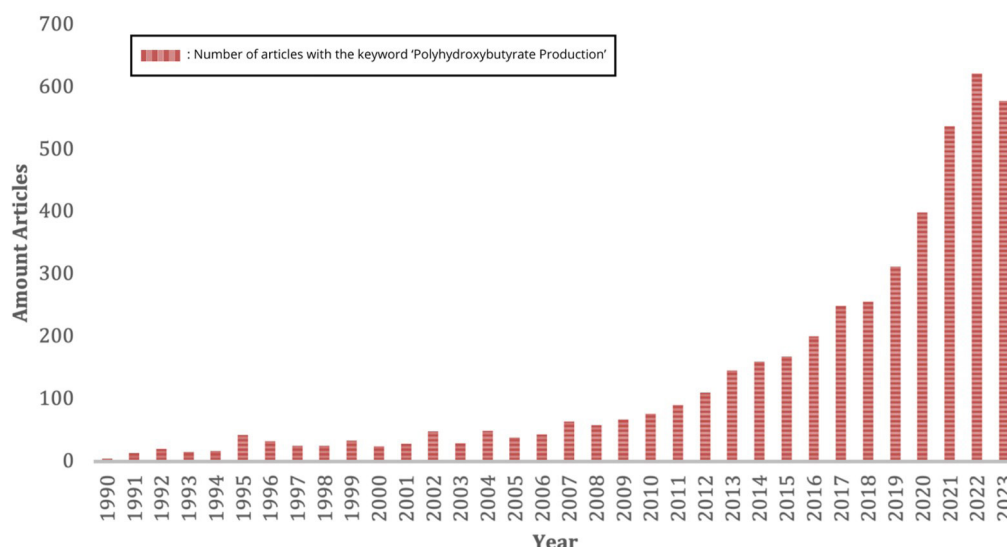


Figure 1. Publication articles trends production of polyhydroxybutyrate from 1992-2023.

publications in 2023^[27]. According to research conducted by Yeo et al.^[28], the contributions of researchers, biologists, and engineers in advancing polyhydroxybutyrate (PHB) are crucial for enhancing its industrial acceptance and popularity. Key emerging areas associated with PHB development encompass the establishment of cost-efficient fermentation methods aimed at reducing production expenses, thereby rendering PHBs more economically viable than conventional petroleum-based plastics. Additionally, there is a focus on designing recycling and reuse strategies for all PHB products prior to commercialization, conducting comprehensive life cycle assessments of these materials, and improving the overall mechanical and thermal properties of PHBs^[29].

Based on articles related to the production of Polyhydroxybutyrate (PHB), the most published subject areas are biochemistry, genetics, and molecular biology with 1,234 articles, followed by material science with 1,101 articles, chemical engineering with 947 articles, environmental science with 807 articles, immunology and microbiology with 648 articles, chemistry with 436 articles, energy with 400 articles, engineering with 256 articles, and earth and planetary science with 127 articles. These subject areas are shown in Figure 2.

This study aims to deliver a bibliographic overview, with the insights gleaned from this article poised to stimulate increased research into polyhydroxybutyrate (PHB) biodegradable plastics as a gradual substitute for fossil fuel-derived plastics, ultimately helping to mitigate the environmental impacts associated with them. The evolution of keywords and research trends can serve as a valuable reference for scholars seeking to explore new topics and avenues within related fields, thereby enhancing stakeholder investment and fostering policy support^[30]. Feedback and suggestions on this article have a good purpose in limiting future innovations in polyhydroxybutyrate (PHB), which is cheap and has characteristics equivalent to fossil-based plastics. The ultimate goal of PHB research is for PHB to

become a competitive composite to replace petroleum-based polymers^[28,29].

The analysis results in Figure 3 show that ten relevant journals published on polyhydroxybutyrate (PHB) production development in the period 1990-2023. The VOSviewer map provides a detailed visualization of research clusters based on bibliometric data, categorized by distinct colors. The red cluster focuses on applied biotechnology topics such as bioplastic production, polymer degradation, and engineering, as indicated by key nodes like *Elsevier Ebooks*. The green cluster represents metabolic and synthetic biotechnology, with journals like *Metabolic Engineering* and *Current Opinion in Biotechnology* highlighting advancements in biological process optimization. The light blue cluster relates to environmental management, including waste management and pollution studies, evident in journals such as *Waste Management* and *Environmental Pollution*. The dark blue cluster emphasizes aquatic systems, particularly aquaculture and algal research, as seen in *Algal Research*. The yellow cluster highlights renewable energy and green biotechnology, addressing topics like sustainable fuel production. The light green cluster is dedicated to soil biology and biochemistry, represented by *Soil Biology & Biochemistry*. The brown cluster focuses on plant physiology and agricultural biotechnology, while the pink cluster delves into microbiology and molecular engineering, illustrated by *FEBS Letters*^[31]. Where Elsevier book contributed the most, namely (401) documents published related to PHB, followed by Biosource Technology (271) documents, International Journal of biological molecular (133) (documents, journal of Biotechnology (79) documents, Current Opinion in biotechnology (77) documents, water research (52) documents, metabolic engineering (48) documents, new biotechnology (42) documents, science of total environment (40) documents, and international journal of hydrogen (40). To generate such a map using VOSviewer, bibliographic data is prepared from Science Direct databases in formats Txt. The analysis type is selected co-authorship and co-

occurrence of keywords, followed by setting thresholds for publication or keyword frequency. Clustering is refined by adjusting resolution and minimum cluster size, and node sizes are determined based on frequency or link strength. The resulting visualization highlights research interconnections and trends, providing valuable insights for bibliometric analysis in the scientific domain^[32]. This data reflects that the development of innovation or research on the production of polyhydroxybutyrate (PHB) plastic biodegradable materials is still very much in demand by experts and researchers, as seen from the number of documents published in the Scopus reputable journal, which is relatively high. In conducting bibliometric analysis, a detailed description is needed related to which journals publish these topics and the scope of the journals that publish them^[33].

Table 2 shows the number of citations in journals that discuss the topic of Polyhydroxybutyrate (PHB) in the period 1990-2023. The number of citations generated shows enthusiasm for the topic of polyhydroxybutyrate research, shown by the top 10 journals with the most citations in science directly related to this topic, where the highest is in the journal *bioresource technology* with 18,490 citations, followed by *progress in polymer science* with 9,244 citations, *international journal of biological molecular* with 5,629 citations, *current opinion in biotechnology* with 4,460 citations, *journal of biotechnology* with 4,423 citations, *biotechnology advances* with 4,317 citations, *biomaterials* with 4,226 citations, *water research* with 4,192 citations, *trends in food science and technology* with 3,744 citations, and *metabolic engineering* with 3,321 citations. The increasing citations also indicate the importance and development of innovation related to polyhydroxybutyrate (PHB) research today, and many research topics are being developed related to polyhydroxybutyrate (PHB) research. *Bioresource Technology* is one of the journals with the most articles and citations related to PHB production, where several articles focus on genetic engineering with examples of “Cost-effective production of bioplastic polyhydroxybutyrate via introducing heterogeneous constitutive promoter and elevating acetyl-Coenzyme A pool of rapidly growing cyanobacteria”^[34] and “Utilizing microalgal hydrolysate from dairy wastewater-grown *Chlorella sorokiniana* SU-1 as a sustainable feedstock for polyhydroxybutyrate and β -carotene production by engineered *Rhodotorula glutinis* #100-29”^[35]. In addition, some articles that are widely

discussed in bioresource technology are on media optimization, such as “Impact of added nutrients in tequila vinasse on the production of hydrogen and polyhydroxybutyrate through photofermentation utilizing *Rhodospseudomonas pseudopalustris*”^[36] and “A closed-loop biorefinery strategy for the production of polyhydroxybutyrate (PHB) utilizes sugars extracted from carob pods as the exclusive raw material, while also implementing downstream processing that incorporates lignin, a co-product of the process”^[37]. The data in Table 2 were obtained through bibliometric analysis using the ScienceDirect database, covering publications from 1990 to 2023. The clustering and visualization were done using VOSviewer software, which allows the identification of relationships between publications and the number of citations they receive. The collection process uses citation analysis and extracted while still a table before finishing with a diagram image of the relationship between citations^[38].

3.2 Authors, affiliation, and country

Figure 4 illustrates the network of authors, affiliations, and publishing countries of articles related to polyhydroxybutyrate (PHB). This data includes the name of the author or authors, the affiliation of the article, and the country that published it. The data in Figure 4 were obtained through bibliometric analysis using VOSviewer software. Data was initially collected from the ScienceDirect database by keyword search of ‘Polyhydroxybutyrate Production’ and metadata analysis of publications, using author criteria to see the relationship and data matrix between authors in this study.

Based on the polyhydroxy butyrate (PHB) analysis matrix based on authors or authors of articles, the five authors who most often write articles with the theme of PHB production are Guoqiang Chen with (29) articles, followed by Shashi Kant Bhatia (22) articles, maria a.m. reis with (20) articles, yung hun yang with (19) articles, and ranjna sirohi with (16) articles. Guoqiang Chen, over the past five years, has published three articles related to PHB. In addition, some prominent names, such as Guoqiang Chen, Armando J. Domb, and Saeed Karbaschi, are at the center of the large cluster, indicating that they are central figures in the research on this topic. In 2019, he wrote an Encyclopedia related to polyhydroxyalkanoates/polyhydroxy butyrate, and in 2020, he wrote about “Rewiring Carbon Flux in *Escherichia coli* Using a Bifunctional Molecular Switch”. In 2022, he also wrote about “Engineering *Halomonas bluephagenesis* via Small Regulatory RNAs”^[39,40]. Guo-Qiang Chen is one of the consistent authors, and he must have published articles related to PHB every year from 2000 to 2022. His articles on PHB are mostly research articles related to genetic engineering to produce polyhydroxybutyrate (PHB). Furthermore, analysis based on the affiliation of the organization publishing polyhydroxybutyrate (PHB) particles is shown in Table 3. Where the most affiliation is from Tsinghua University with (47) PHB-related article documents, followed by the Chinese Academy of Science (40) documents; French National Center for Scientific with (33) documents; Delf University of Technology with (32) documents; Universidade Nova de Lisboa with (26) documents, Konkuk University with (25) documents, Technical University of Denmark with (24) documents, University of Queensland with (22) documents, Redede

Table 2. Amount of Citation on Journals with PHB Topic Interval 1990-2023.

Journals	Citations
Source	
Bioresource Technology	18,490
Progress in Polymer Science	9,244
International Journal of Biological Molecular	5,629
Current Opinion on Biotechnology	4,460
Journal of Biotechnology	4,423
Biotechnology Advances	4,317
Biomaterials	4,226
Water Research	4,192
Trends in Food Science and Technology	3,744
Metabolic Engineering	3,321

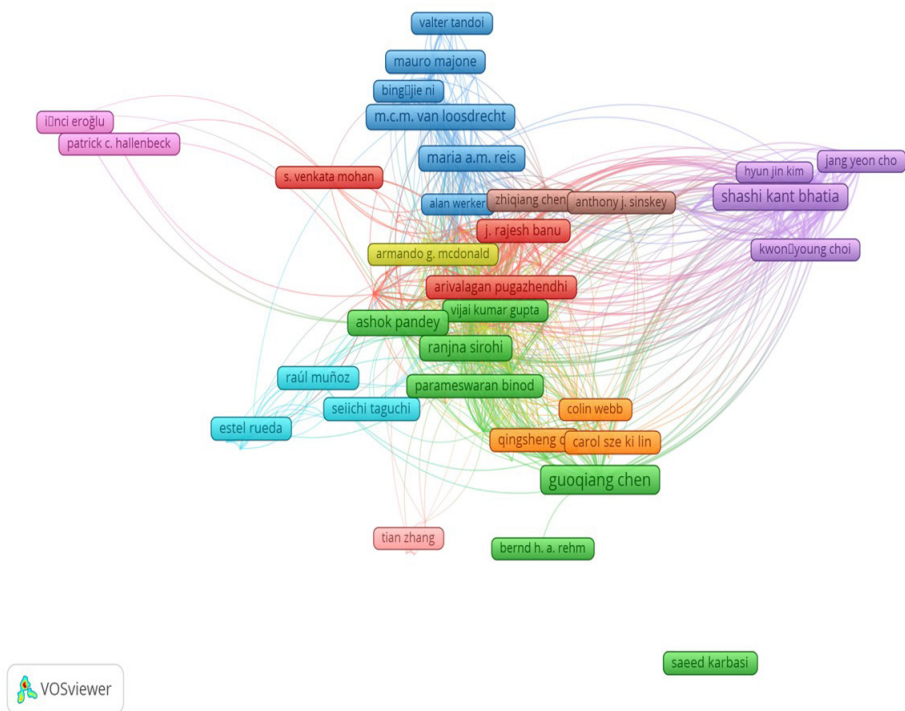


Figure 4. Analysis Matrix of Authors by Articles PHB interval 1990-2023.

Table 3. Total Articles of PHB by Affiliation Interval 1990-2023.

Organization	Documents
Affiliation	
Tsinghua University	47
Chinese Academy of Sciences	40
French National Center for Scientific	33
Delf University of Technology	32
Universidade Nova de Lisboa	26
Konkuk University	25
Technical University of Denmark	24
University of Queensland	22
Redede quimica e tecnologia	21
Academy of Scientific and Innovation	20

quimica e tecnologia with (21) documents, and Academy of Scientific and Innovation with (20) documents. This shows that both universities and research institutes around the world in Asia (China and Korea), Europe (Netherlands, Portugal, France, Denmark), and Australia are very interested in research and development related to polyhydroxybutyrate (PHB) biodegradable plastic materials.

The data in Figure 5 was obtained through bibliometric analysis using VOSviewer software. The process began with collecting bibliographic data from the ScienceDirect database using the keyword ‘Polyhydroxybutyrate’ for the period 1990–2023. Metadata was extracted using the ‘citation’ and ‘authors’ criteria in the VOSViewer application. data analysis based on the highest number of citations to 20 authors of polyhydroxybutyrate (PHB) articles in the interval period 1990 to 2023 showed that the author from China, Quoqiang Chen, got the most citations with 2698 citations, followed by

Luc Averous with 2607 citations, and Van Loosdrecht with 2500 citations. The citation data on the author shows that Quangqiang Chen also produces the most publications and the most citations, which shows that the quality of research and articles related to polyhydroxybutyrate (PHB) published by Quoqiang Chen is of high quality so that many other researchers refer to Quoqiang Chen’s research. Although the number of articles is slight, many citations indicate the excellent quality of the article, whereas if there are many articles by an author but few citations, it can be said that the quality of the article is not good or the topic is not attractive.

Based on Figure 6, it is found that Tsinghua University holds the top 3 most affiliations from China with 47 articles related to the development and research of PHB. The Chinese Academy of Science follows this with 40 articles, and the French National Scientific with 33 articles related to PHB from 1990 to 2023. In line with the number of articles, Tsinghua University is also an affiliate of PHB production research and development articles with the most citations, namely 3,275 citations, followed by the Delf University of Technology with 3,111 citations, and the National Institute for Interdisciplinary Science and Technology with 2,573 citations. This shows that Tsinghua University is not only productive in PHB research and development articles, but its articles are also of good quality, with the most citations from 1990 to 2023. Some articles from Tsinghua University include “controlling cell volume for Efficient PHB Production by Halomonas”, “polyhydroxyalkanoate/polyhydroxy butyrate” and “Unsterile and Continous Production of Polyhydroxybutyrate by Halomonas TD01”^[29,41,42].

Furthermore, related to the analysis of countries that published polyhydroxy butyrate (PHB) articles, where there

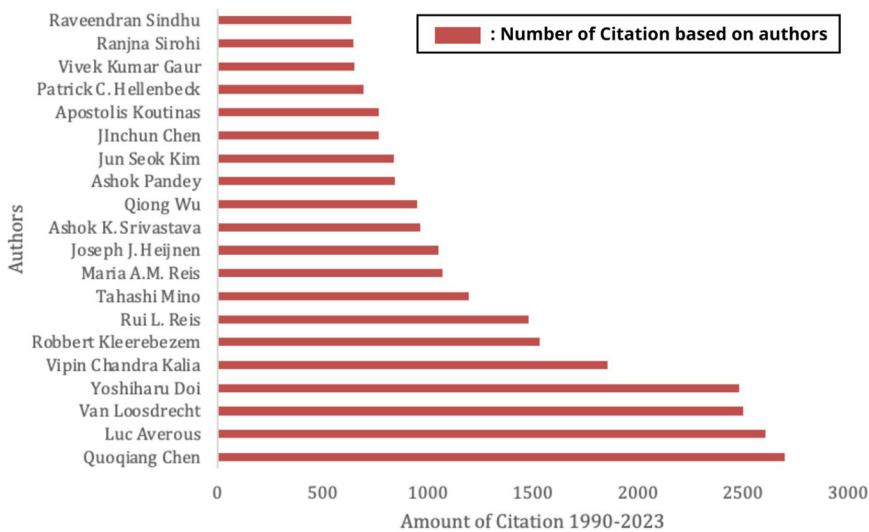


Figure 5. Analysis citation of top 20 authors PHB interval 1990-2023.

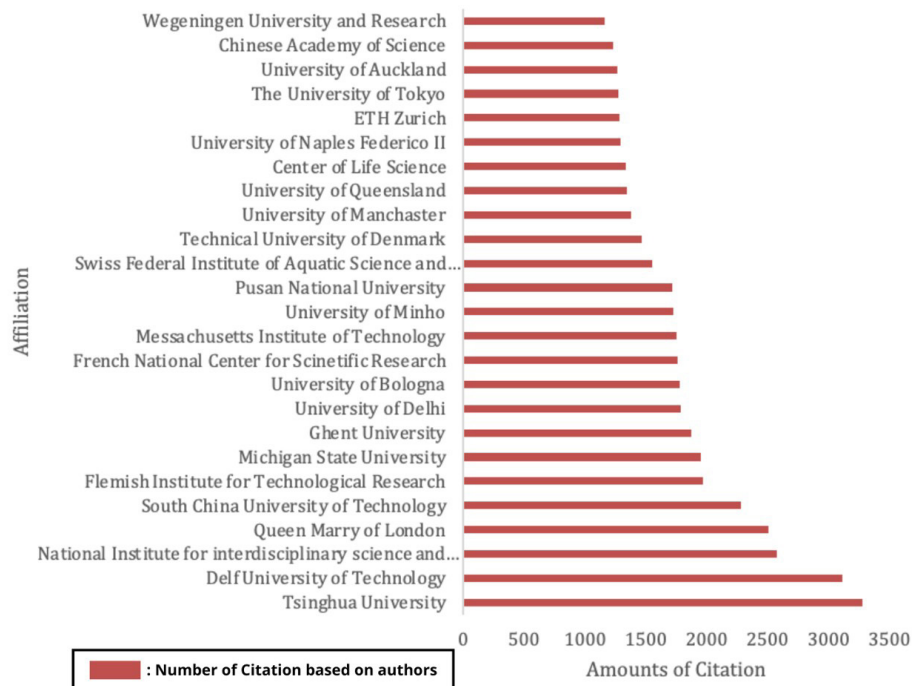


Figure 6. Data Affiliations and Amounts of Citation PHB Interval 1990-2023.

are top 10 countries that published the most articles related to this, according to Figure 5. and the most are China with (350) articles, followed by the USA with (335) articles, India with (316) articles, UK with (144) articles, South Korea with (140) articles, Germany with (118) articles, Spain with (113) articles, Italy with (101) articles, Japan with (92) articles. This data shows that the understanding of PHB research is widespread worldwide, starting from mainland Europe, America, and Asia. All countries in the top 10 most published countries are developed countries with very high technological development of new materials

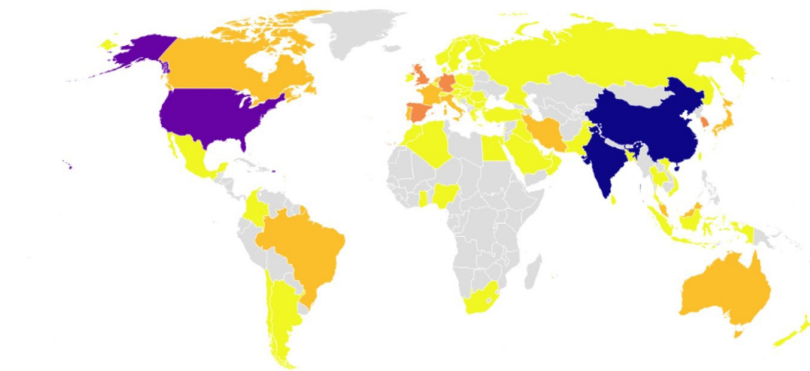
or biomaterials. This indicates that the state, through its government, supports research related to new materials, both polyhydroxybutyrate (PHB) and other materials.

Based on data analysis using the VOSviewer application, the database from Science Direct shows and reveals that China, USA, and India are three countries that are concerned about research on polyhydroxybutyrate (PHB) biodegradable plastic materials, shown by clustering in VOSviewer. The three countries dominate in terms of publication documents and citations, indicating that research related to PHB is more focused in these countries. This trend reflects their

significant investment in the development of biodegradable materials, with India, China, and the USA leading the way in both the volume of research conducted and the international recognition of their findings. The clustering also highlights the prominent role these nations play in advancing the science and application of PHB, particularly in industries such as packaging, medicine, and environmental sustainability^[43]. For example, in 2023, the articles published by China on PHB reached 132 articles and the highest number of citations, namely 785 citations; in second place was India with 102 articles, and the number of citations reached 598. This is in line with data from VOSviewer, which indicates that these two countries are very focused on research related to this PHB. For example, some articles published by these two countries are “Concurrent generation of polyhydroxybutyrate and biogas from paper mill sludge utilizing a sodium citrate-mediated disperser to facilitate phase separation during pretreatment” written by Preethi et al.^[44] with the country

of affiliation is India. In addition, Preethi also wrote another article in 2023 titled “Augmentation in polyhydroxybutyrate and biogas production from waste activated sludge via mild sonication-assisted thermo-Fenton disintegration”^[45]. For China there are many articles related to process engineering and microorganisms in PHB research, where there are using N, N-dimethylamide/LiCl solvent in the PHB extraction system and obtained high PHB purity results, that there is also research related to PHB characteristics using a rare isolate, namely Actinomycetes Aquabacterium sp A7-Y^[46,47]. In Figure 7a, the color intensity indicates the number of publications for each country over the period 1990–2023. Light yellow indicates countries with fewer publications (5 documents), while dark purple indicates countries with the highest number of publications (up to 352 documents). In this case, China appears dominant with dark purple (350 articles), followed by the United States (335 articles) and India (316 articles).

Amount of Documents by Countries Produced "Production PHB Articles"



Created with Datawrapper

7.(a)



7.(b)

Figure 7. (a) Analysis of Country Publish Articles PHB Interval 1990–2023; (b) Matriks Country by VOS Viewer.

Meanwhile, in Figure 7b, the visualization matrix uses the size and brightness of the nodes to show the number of publications and the level of connectivity between countries. Larger and brighter nodes, such as those of China, the United States, and India, indicate their leading role in PHB research both in terms of the number of publications and influence in the global collaboration network. The lines between countries show the collaboration that occurs in research, with the United States appearing to have greater connectivity than China and India^[48].

Based on Figure 8, data analysis of countries producing polyhydroxy butyrate (PHB) articles, it shows that the USA, China, India, and the UK are the top 4 countries with the most citations for PHB articles where these four countries show support regulations from the government, researchers, academics who support regulations for the creation of new materials, especially in the field of biodegradable plastics (PHB) so that the amount and quality of research produced from these four countries is very high quality and the number of documents indicates that research innovation in these four countries is significantly developed.

During the 1990s to early 2000s, the main focus of research on polyhydroxyalkanoate (PHB) production was on identifying microorganisms that could efficiently produce PHBs through fermentation. Research during this period highlighted microbes such as *Ralstonia eutropha* and *Cupriavidus necator*, which are capable of producing PHBs from diverse carbon sources, including agricultural waste and simple feedstocks such as glucose^[49]. The main merit of this research is the increased in-depth understanding of biotechnology and PHB-producing microorganisms, which paves the way for more efficient production processes. However, although significant progress was made in terms of understanding microorganisms, a major obstacle during this time was the still very high production cost, which

hindered the widespread commercialization of PHBs as biotechnology-based products^[50].

Entering the 2010s, the research focus turned to the use of renewable and cheaper feedstocks, such as lignocellulosic waste, vegetable oils, and other biomass, to lower the production cost of PHBs. In addition, advances in genetic engineering technology opened up new opportunities with the genetic modification of microorganisms to increase PHB production yields^[51]. The advantages of this approach are the significant reduction in production costs thanks to the use of cheap feedstocks as well as the potential for higher yield increases through genetic engineering. However, the challenges lie in the complexity of genetic engineering techniques that require time and large investments to achieve optimal results, as well as strict regulatory constraints regarding the use of genetically modified organisms on an industrial scale^[52]. In this decade, steps towards reducing production costs have begun to show great potential in the commercial application of PHBs, although the road to widespread implementation still requires overcoming several technical and economic barriers^[53].

4. Current and Future Trends

The author would like to shed light on future polyhydroxybutyrate (PHB) developments in this subchapter. These trends are analyzed based on the keywords of the principal authors in the research period 1990 to 2023. These keywords were used in titles, abstracts, and publication keywords. The keywords represent how popular and desirable the field is for research^[54,55]. The most influential keywords on the development of polyhydroxybutyrate (PHB) production are shown in Figure 9.

From the Word Cloud data, it is obtained that the word with the highest frequency appearing in the keyword is "Engineering," meaning that researchers are researching

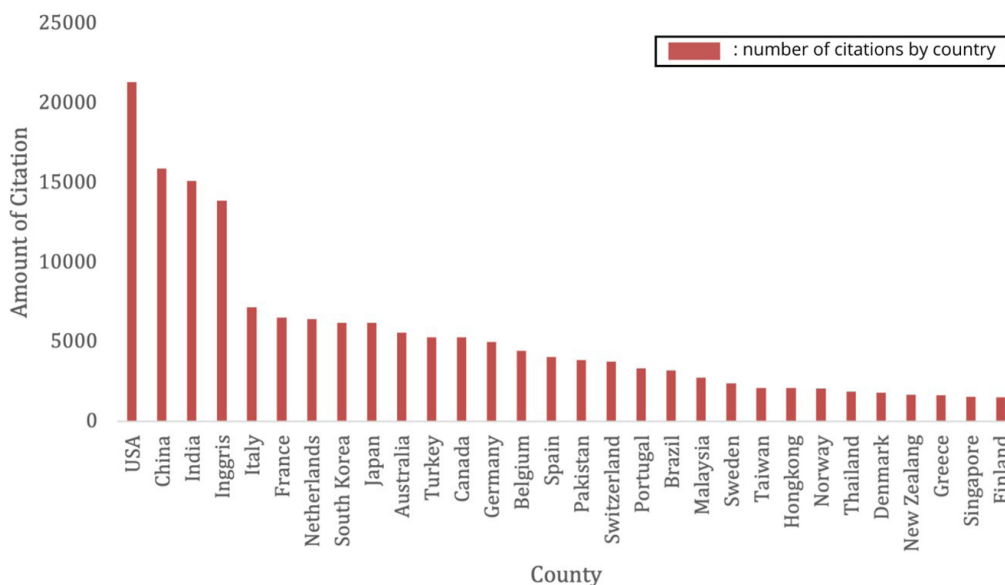


Figure 8. Top 30 Analysis Data Citation based on County Interval 1990-2023.

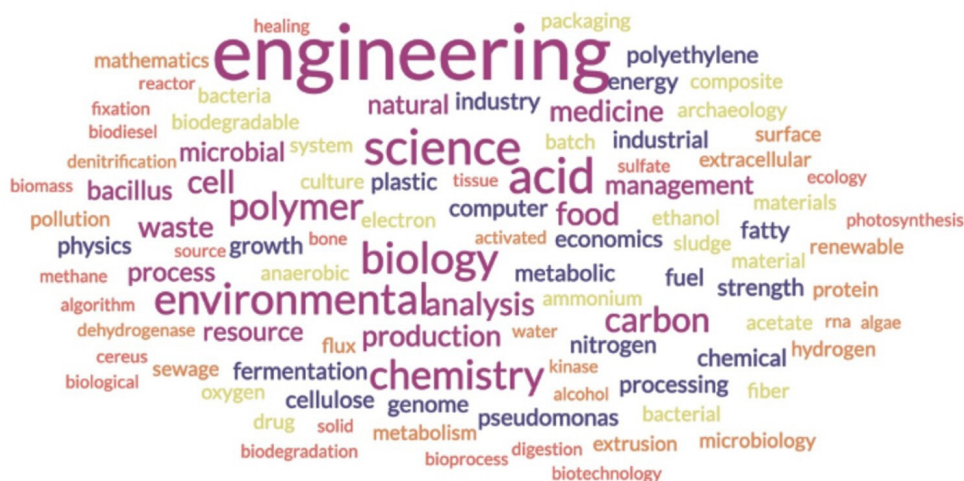


Figure 9. Word Cloud from Keywords Production Polyhydroxybutyrate.

the development of PHB production in terms of engineering or process engineering. In addition, the keywords that often appear are “Science,” “Environmental,” “Biology,” “Carbon,” and “Acid”. This means that the development of PHB production is related to engineering carbon sources that influence the environment.

Figure 10 illustrates the keywords over time, and the researchers developed these keywords into 6 clusters. Cluster 1 is colored Green, where this cluster of keywords revolves around biological systems related to microorganism genes, metabolic engineering, and microorganism metabolism. This shows that the development of this green cluster is more towards genetic engineering of microorganisms as an example in the research of Meng et al. in 2022, wherein the production of PHB, the cloning of propylene in-house L72T was expressed into *Escherichia coli*^[56]. In addition, there is also an increase in PHB production by distributing metabolic flux in recombinant *Escherichia coli*^[57].

Cluster 2 is in blue, where this cluster has repeated keywords in engineering, bioplastics, biotechnology, and production economics. In this cluster, the most visible relationship is the relationship to increase production efficiency by biotechnology to increase production yields and reduce production costs. This is shown in several articles in the last five years that show how to reduce PHB production costs. One illustration involves the utilization of crude glycerol for polyhydroxybutyrate (PHB) synthesis through the genetic modification of *Rhodotorula glutinis*. In this context, glycerol, which is a by-product of sugar manufacturing, serves as a substrate for the production of PHB^[58]. Additionally, there is research on polyhydroxybutyrate (PHB) production utilizing molasses and tap water without the need for sterilization, employing *Priestia* sp. YH4. This study highlights the use of inexpensive carbon sources to lower production expenses, emphasizing that omitting sterilization further contributes to cost reduction^[59].

Cluster 3 is red, repeating keywords polymer chemistry, Polymer Science, Polylactic Acid, strength, and Crystalline. In cluster 3, the relationship that is very visible from the

repeated keywords of the authors is related to the characteristics of PHB biopolymers formed by many words such as thermoplastic, biocomposite, crystallinity, and mechanical properties. Based on research from Sookswat et al. 2023. This research is based on PHB production by utilizing glycerol to determine the thermal properties of PHB films. This study shows the development of PHB production technology based on physical and chemical properties, and it shows that PHB is resistant to heat 90-175 °C^[60].

Cluster 4 is yellow, with keywords most related to chemical reactions; in this cluster, the keywords that often appear are chemical and fermentation reactions. Where there are words bioreactor, COD, Chemistry, hydrogen, and nitrogen, based on these keywords, the cluster has a relationship between keywords related to the parameters of the PHB production process. An example is a study related to the impact of carbon-to-nitrogen ratio and pH on the microbial prevalence and microbial polyhydroxybutyrate production levels using a mixed microbial starter culture in 2022, where this study discusses growth conditions to optimize PHB production, which is influenced by the ratio of carbon and nitrogen sources and PH^[61]. Furthermore, additional research has examined the impact of growth conditions on the molecular weight of Poly-3-hydroxybutyrate synthesized by *Azotobacter chroococcum* 7B. where this research shows the Effect of pH, aeration, and temperature on the PHB production process^[62].

Cluster 5, which is purple, and Cluster 6, which is orange, show keywords that are related to loose or distant, where these keywords are not related to PHB directly, such as cluster 5, there are fructose, sucrose, fermentation, biodiesel, and biofuel. This is probably because the keywords in cluster 5 can also be related to research with other topics, such as biodiesel and biofuels, such as sucrose and fructose, which can be hydrolyzed into biodiesel, bioethanol, and other energy sources. Cluster 6, colored orange, is likely related to data science because the keywords that appear on the World Wide Web are related to data science. Cluster 6 is the most distantly related to PHB production.

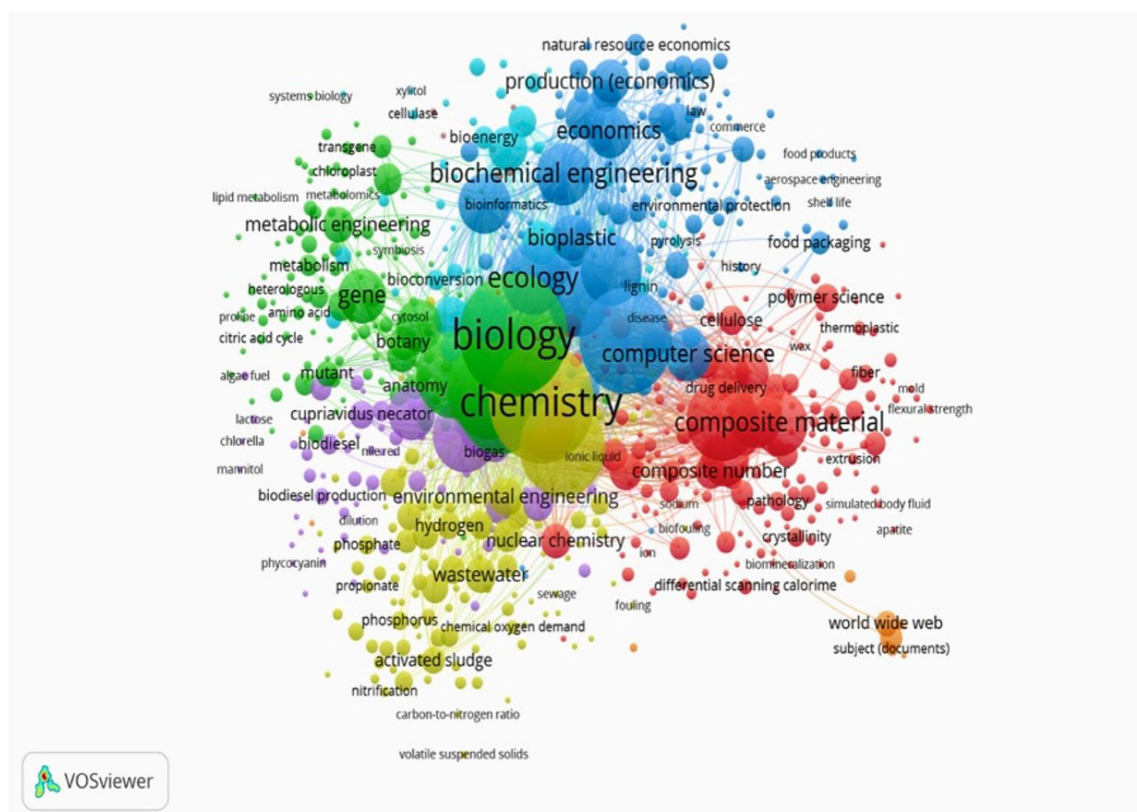


Figure 10. Clustering keywords over time about PHB.

From 1990 to 2023, several fields emerged as implications of biodegradable materials research, including polyhydroxybutyrate (PHB) plastics. Based on the data from these keywords, it can be seen that the researchers are pushing for further research related to genetic engineering, increasing PHB extraction, and using waste as a source of PHB culture nutrients to produce PHB with a high yield value and low price so that it will have a competitive value against fossil-based plastics^[63].

5. Conclusion

This study provides in-depth insights into the research trends on polyhydroxybutyrate (PHB) as a biodegradable plastic material that serves as a potential alternative to fossil-based plastics from 1990 to 2023. Using the ScienceDirect database and the VOSviewer application, our analysis reveals that research on PHB has experienced rapid growth since the early 2010s, with a significant surge between 2017 and 2023, reaching 300-600 publications per year. This growing interest highlights the increasing importance of PHB research, which serves as a foundation for policymakers, academics, and industries in developing sustainable regulations and eco-friendly materials.

Our subject area analysis indicates that the fields of biochemistry, genetics, and molecular biology have the highest number of publications, totaling 1,234 articles, including research papers and reviews. Elsevier Book is one of the main publishers in this domain, with 401 publications

over 32 years. However, citation trends show that Biosource Technology holds the highest number of citations, with 18,490 citations over 23 years. Among researchers, Quioqiang Chen stands out as the most prolific author, with 29 publications and the highest number of citations (2,698). Tsinghua University is identified as the leading institution in PHB research, contributing 47 publications and receiving 3,275 citations. Geographically, China has the highest number of publications (350 articles), while the United States ranks first in citations, with 21,324 citations over the same period.

Emerging research trends indicate that the most frequently occurring keywords include “biology,” “engineering,” and “composite materials”. This reflects a growing focus on the biological engineering of microorganisms to enhance PHB production, aiming to develop composite PHB materials with superior properties and higher yields.

Given these findings, PHB research holds great potential for fostering sustainable and environmentally friendly material innovations. To accelerate its development and application, further collaboration between academia, industry, and policymakers is essential.

6. Author's Contribution

- **Conceptualization** – Kharis Yohan Abidin; Abdullah.
- **Data curation** – Kharis Yohan Abidin.
- **Formal analysis** – Kharis Yohan Abidin; Yeyen Nurhamiyah; Dewi Nandyawati.

- **Funding acquisition** – Kharis Yohan Abidin.
- **Investigation** – Yeyen Nurhamiyah; Abdullah.
- **Methodology** – Hadiyanto; Istadi.
- **Project administration** – Kharis Yohan Abidin.
- **Resources** – Kharis Yohan Abidin; Hadiyanto; Istadi.
- **Software** – Kharis Yohan Abidin; Hadiyanto; Istadi.
- **Supervision** – Abdullah.
- **Validation** – Abdullah.
- **Visualization** – Abdullah.
- **Writing – original draft** – Kharis Yohan Abidin; Yeyen Nurhamiyah; Dewi Nandyawati.
- **Writing – review & editing** – Kharis Yohan Abidin; Yeyen Nurhamiyah; Dewi Nandyawati.

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8. References

1. Bhatia, S. K., Otari, S. V., Jeon, J.-M., Gurav, R., Choi, Y.-K., Bhatia, R. K., Pugazhendhi, A., Kumar, V., Banu, J. R., Yoon, J.-J., Choi, K.-Y., & Yang, Y.-H. (2021). Biowaste to bioplastic (polyhydroxyalkanoates): conversion technologies, strategies, challenges, and perspective. *Bioresource Technology*, 326, 124733. <http://doi.org/10.1016/j.biortech.2021.124733>. PMID:33494006.
2. Rinanda, R., Sun, Y., Chang, K., Sulastri, R., Cui, X., Cheng, Z., Yan, B., & Chen, G. (2023). Plastic waste management: a bibliometric analysis (1992–2022). *Sustainability*, 15(24), 16840. <http://doi.org/10.3390/su152416840>.
3. Bellasi, A., Binda, G., Pozzi, A., Galafassi, S., Volta, P., & Bettinetti, R. (2020). Microplastic contamination in freshwater environments: a review, focusing on interactions with sediments and benthic organisms. *Environments*, 7(4), 30. <http://doi.org/10.3390/environments7040030>.
4. Li, C., Busquets, R., & Campos, L. C. (2020). Assessment of microplastics in freshwater systems: a review. *The Science of the Total Environment*, 707, 135578. <http://doi.org/10.1016/j.scitotenv.2019.135578>. PMID:31784176.
5. Xu, S., Ma, J., Ji, R., Pan, K., & Miao, A.-J. (2020). Microplastics in aquatic environments: occurrence, accumulation, and biological effects. *The Science of the Total Environment*, 703, 134699. <http://doi.org/10.1016/j.scitotenv.2019.134699>. PMID:31726297.
6. Patil, T. D., Ghosh, S., Agarwal, A., Patel, S. K. S., Tripathi, A. D., Mahato, D. K., Kumar, P., Slama, P., Pavlik, A., & Haque, S. (2024). Production, optimization, scale-up, and characterization of polyhydroxyalkanoate copolymers utilizing dairy processing waste. *Scientific Reports*, 14(1), 1620. <http://doi.org/10.1038/s41598-024-52098-0>. PMID:38238404.
7. Cardozo, J. R. G., Bucheli, R. V., Pareja, N. M., Villadiego, O. S. R., Londoño, G. A. C., & Martínez, A. L. M. (2020). Fed-batch production and characterization of polyhydroxybutyrate by *Bacillus megaterium* LVN01 from residual glycerol. *Dyna*, 87(214), 111–120. <http://doi.org/10.15446/dyna.v87n214.83523>.
8. Lee, J., Park, H. J., Moon, M., Lee, J.-S., & Min, K. (2021). Recent progress and challenges in microbial polyhydroxybutyrate (PHB) production from CO₂ as sustainable feedstock: a state-of-the-art review. *Bioresource Technology*, 339, 125616. <http://doi.org/10.1016/j.biortech.2021.125616>. PMID:34304096.
9. Kasavan, S., Yusoff, S., Fakri, M. F. R., & Siron, R. (2021). Plastic pollution in water ecosystems: a bibliometric analysis from 2000 to 2020. *Journal of Cleaner Production*, 313, 127946. <http://doi.org/10.1016/j.jclepro.2021.127946>.
10. Khatun, R., Xiang, H., Yang, Y., Wang, J., & Yildiz, G. (2021). Bibliometric analysis of research trends on the thermochemical conversion of plastics during 1990–2020. *Journal of Cleaner Production*, 317, 128373. <http://doi.org/10.1016/j.jclepro.2021.128373>.
11. Armenise, S., SyieLuing, W., Ramírez-Velásquez, J. M., Launay, F., Wuebben, D., Ngadi, N., Rams, J., & Muñoz, M. (2021). Plastic waste recycling via pyrolysis: A bibliometric survey and literature review. *Journal of Analytical and Applied Pyrolysis*, 158(2), 105265. <http://doi.org/10.1016/j.jaap.2021.105265>.
12. Akinpelu, E. A., & Nchu, F. (2022). A bibliometric analysis of research trends in biodegradation of plastics. *Polymers*, 14(13), 2642. <http://doi.org/10.3390/polym14132642>. PMID:35808687.
13. Yang, S.-S., Wu, W.-M., Pang, J.-W., He, L., Ding, M.-Q., Li, M.-X., Zhao, Y.-L., Sun, H.-J., Xing, D.-F., Ren, N.-Q., Yang, J., Criddle, C. S., & Ding, J. (2023). Bibliometric analysis of publications on biodegradation of plastics: Explosively emerging research over 70 years. *Journal of Cleaner Production*, 428, 139423. <http://doi.org/10.1016/j.jclepro.2023.139423>.
14. Nabgan, W., Ikram, M., Alhassan, M., Owgi, A. H. K., Van Tran, T., Parashuram, L., Nordin, A. H., Djellabi, R., Jalil, A. A., Medina, F., & Nordin, M. L. (2023). Bibliometric analysis and an overview of the application of non-precious materials for pyrolysis reaction of plastic waste. *Arabian Journal of Chemistry*, 16(6), 104717. <http://doi.org/10.1016/j.arabjc.2023.104717>.
15. Japri, N. F., Majid, Z. A., Ghoshal, S. K., Danial, W. H., See, H. H., & Othman, M. Z. (2024). On the versatility of graphene-cellulose composites: An overview and bibliometric assessment. *Carbohydrate Polymers*, 337(1), 121969. <http://doi.org/10.1016/j.carbpol.2024.121969>. PMID:38710542.
16. Buele, I., & Guerra, T. (2021). Bibliometric analysis of scientific production on tax evasion in sciencedirect, years 2010 to 2019. *Journal of Legal, Ethical and Regulatory*, 24(2), 627. Retrieved in 2024, October 12, from <https://www.abacademies.org/articles/bibliometric-analysis-of-scientific-production-on-tax-evasion-in-sciencedirect-years-2010-to-2019-10427.html>
17. Lim, W. M., Kumar, S., & Donthu, N. (2024). How to combine and clean bibliometric data and use bibliometric tools synergistically: guidelines using metaverse research. *Journal of Business Research*, 182, 114760. <http://doi.org/10.1016/j.jbusres.2024.114760>.
18. Van Eck, N. J. (2023). *Methodological advances in bibliometric mapping and science* (Doctoral thesis). Erasmus Universiteit Rotterdam, Rotterdam, The Netherlands.
19. Van Eck, N. J., & Waltman, L. (2007). Bibliometric mapping of the computational intelligence field. *International Journal of Uncertainty, Fuzziness and Knowledge-based Systems*, 15(5), 625–645. <http://doi.org/10.1142/S02184885070004911>.
20. Van Eck, N. J., Waltman, L., Noyons, E. C. M., & Buter, R. K. (2010). Automatic term identification for bibliometric mapping. *Scientometrics*, 82(3), 581–596. <http://doi.org/10.1007/s11192-010-0173-0>. PMID:20234767.
21. Van Eck, N. J., & Waltman, L. (2013). *Manual for VOSviewer version 1.5.4*. Leiden: Univeriteit Leiden, Erasmus Universiteit Rotterdam. Retrieved in 2024, March 22, from https://www.vosviewer.com/documentation/Manual_VOSviewer_1.5.4.pdf
22. Waaijer, C. J. F., Van Bochove, C. A., & Van Eck, N. J. (2011). On the map: Nature and Science editorials. *Scientometrics*,

- 86(1), 99-112. <http://doi.org/10.1007/s11192-010-0205-9>. PMID:21212822.
23. Luing, W. S., Ren, M. G., Nyakuma, B. B., Ngadi, N., Yinn, W. K., Muñoz Hernández, M., Armenise, S., & Tung, C. C. (2022). Upcycling plastic waste to carbon nanomaterials: a bibliometric analysis (2000-2019). *Clean Technologies and Environmental Policy*, 24(3), 739-759. <http://doi.org/10.1007/s10098-021-02267-w>.
24. Arruda, H., Silva, E. R., Lessa, M., Proença, D., Jr., & Bartholo, R. (2022). VOSviewer and Bibliometrix. *Journal of the Medical Library Association: JMLA*, 110(3), 392-395. <http://doi.org/10.5195/jmla.2022.1434>. PMID:36589296.
25. Kirby, A. (2023). Exploratory bibliometrics: Using VOSviewer as a preliminary research tool. *Publications*, 11(1), 10. <http://doi.org/10.3390/publications11010010>.
26. Yudhanto, S., & Asmiyanto, T. (2021). Metadata research development: a bibliometric study on Science Direct. *Library Philosophy and Practice*, 5059, 1-11. Retrieved in 2024, October 12, from <https://digitalcommons.unl.edu/libphilprac/5059>
27. Jaffur, B. N., Kumar, G., & Khadoo, P. (2024). Production and functionalization strategies for superior polyhydroxybutyrate blend performance. *International Journal of Biological Macromolecules*, 278(Pt 3), 134907. <http://doi.org/10.1016/j.ijbiomac.2024.134907>. PMID:39173809.
28. Yeo, J. C. C., Muiruri, J. K., Thitsartarn, W., Li, Z., & He, C. (2018). Recent advances in developing biodegradable PHB-based toughening materials: approaches, advantages, and applications. *Materials Science and Engineering C*, 92, 1092-1116. <http://doi.org/10.1016/j.msec.2017.11.006>. PMID:30184731.
29. Jiang, X.-R., Yao, Z.-H., & Chen, G.-Q. (2017). Controlling cell volume for efficient PHB production by *Halomonas*. *Metabolic Engineering*, 44, 30-37. <http://doi.org/10.1016/j.ymben.2017.09.004>. PMID:28918285.
30. Chang, K., Tao, J., Fang, C., Li, J., Zhou, W., Wang, X., Yan, B., Zeng, D., & Chen, G. (2022). Evolution of research topics on the Tibetan Plateau environment and ecology from 2000 to 2020: a paper mining. *Environmental Science and Pollution Research International*, 29(9), 12933-12947. <http://doi.org/10.1007/s11356-021-17149-3>. PMID:35034301.
31. Rochman, S., Rustaman, N., Ramalis, T. R., Amri, K., Zukmadini, A. Y., Ismail, I., & Putra, A. H. (2024). How bibliometric analysis using VOSviewer based on artificial intelligence data (using ResearchRabbit Data): Explore research trends in hydrology content. *ASEAN Journal of Science and Engineering*, 4(2), 251-294. <http://doi.org/10.17509/ajse.v4i2.71567>.
32. Marzi, G., Balzano, M., Caputo, A., & Pellegrini, M. M. (2024). Guidelines for bibliometric-systematic literature reviews: 10 steps to combine analysis, synthesis, and theory development. *International Journal of Management Reviews*, 27(1), 81-103. <http://doi.org/10.1111/ijmr.12381>.
33. Swain, D. K. (2013). Journal bibliometric analysis: a case study on Internet Research. *Library Philosophy and Practice*, 985, 1-22. Retrieved in 2024, October 12, from <https://digitalcommons.unl.edu/libphilprac/985>
34. Lee, S. Y., Lee, J. S., & Sim, S. J. (2024). Cost-effective production of bioplastic polyhydroxybutyrate via introducing heterogeneous constitutive promoter and elevating acetyl-Coenzyme A pool of rapidly growing cyanobacteria. *Bioresource Technology*, 394, 130297. <http://doi.org/10.1016/j.biortech.2023.130297>. PMID:38185449.
35. Kusmayadi, A., Huang, C.-Y., Leong, Y. K., Yen, H.-W., Lee, D.-J., & Chang, J.-S. (2023). Utilizing microalgal hydrolysate from dairy wastewater-grown *Chlorella sorokiniana* SU-1 as a sustainable feedstock for polyhydroxybutyrate and β -carotene production by engineered *Rhodotorula glutinis* #100-29. *Bioresource Technology*, 384, 129277. <http://doi.org/10.1016/j.biortech.2023.129277>. PMID:37290703.
36. Franco-León, J. J., Arriola-Guevara, E., Suárez-Hernández, L. A., Toriz, G., Guatemala-Morales, G., & Corona-González, R. I. (2021). Influence of supplemented nutrients in tequila vinasses for hydrogen and polyhydroxybutyrate production by photofermentation with *Rhodospseudomonas pseudopalustris*. *Bioresource Technology*, 329, 124865. <http://doi.org/10.1016/j.biortech.2021.124865>. PMID:33639381.
37. Manikandan, N. A., Pakshirajan, K., & Pugazhenth, G. (2020). A closed-loop biorefinery approach for polyhydroxybutyrate (PHB) production using sugars from carob pods as the sole raw material and downstream processing using the co-product lignin. *Bioresource Technology*, 307, 123247. <http://doi.org/10.1016/j.biortech.2020.123247>. PMID:32234592.
38. McAllister, J. T., III, Lennertz, L. L., & Mojica, Z. A. (2021). Mapping a discipline: a guide to using VOSviewer for bibliometric and visual analysis. *Science & Technology Libraries*, 41(3), 319-348. <http://doi.org/10.1080/0194262X.2021.1991547>.
39. Hou, J., Gao, C., Guo, L., Nielsen, J., Ding, Q., Tang, W., Hu, G., Chen, X., & Liu, L. (2020). Rewiring carbon flux in *Escherichia coli* using a bifunctional molecular switch. *Metabolic Engineering*, 61, 47-57. <http://doi.org/10.1016/j.ymben.2020.05.004>. PMID:32416271.
40. Wang, L.-J., Jiang, X.-R., Hou, J., Wang, C.-H., & Chen, G.-Q. (2022). Engineering *Halomonas bluephagenesis* via small regulatory RNAs. *Metabolic Engineering*, 73, 58-69. <http://doi.org/10.1016/j.ymben.2022.06.005>. PMID:35738548.
41. Wang, Y., Dao, J., & Chen, G.-Q. (2019). *Polyhydroxyalkanoate/polyhydroxybutyrate*. In M. Moo-Young (Ed.), *Comprehensive biotechnology* (3rd ed., Vol. 3, pp. 244-257). Amsterdam: Elsevier. <http://doi.org/10.1016/B978-0-444-64046-8.00163-4>.
42. Tan, D., Xue, Y.-S., Aibaidula, G., & Chen, G.-Q. (2011). Unsterile and continuous production of polyhydroxybutyrate by *Halomonas TD01*. *Bioresource Technology*, 102(17), 8130-8136. <http://doi.org/10.1016/j.biortech.2011.05.068>. PMID:21680179.
43. Nayanathara Thathsarani Pilapitiya, P. G. C., & Ratnayake, A. S. (2024). The world of plastic waste: a review. *Cleaner Materials*, 11, 100220. <http://doi.org/10.1016/j.clema.2024.100220>.
44. Preethi, B., Rajesh Banu, J., & Gunasekaran, M. (2023). Simultaneous production of polyhydroxybutyrate and biogas from paper mill sludge through sodium citrate-mediated disperser-induced phase-separated pretreatment. *Journal of Water Process Engineering*, 56, 104544. <http://doi.org/10.1016/j.jwpe.2023.104544>.
45. Preethi, Rajesh Banu, J., Kumar, G., & Gunasekaran, M. (2023). Augmentation in polyhydroxybutyrate and biogas production from waste-activated sludge through mild sonication-induced thermo-Fenton disinfection. *Bioresource Technology*, 369, 128376. <http://doi.org/10.1016/j.biortech.2022.128376>. PMID:36414138.
46. Liu, J., Zhang, H., Jiang, X., Tremblay, P.-L., & Zhang, T. (2023). An efficient and reusable N-dimethylacetamide/LiCl solvent system for extracting high-purity polyhydroxybutyrate from bacterial biomass. *Biochemical Engineering Journal*, 192, 108812. <http://doi.org/10.1016/j.bej.2023.108812>.
47. Feng, L., Yan, J., Jiang, Z., Chen, X., Li, Z., Liu, J., Qian, X., Liu, Z., Liu, G., Liu, C., Wang, Y., Hu, G., Dong, W., & Cui, Z. (2023). Characterization of polyhydroxybutyrate (PHB) synthesized by newly isolated rare actinomycetes *Aquabacterium* sp. A7-Y. *International Journal of Biological Macromolecules*, 232, 123366. <http://doi.org/10.1016/j.ijbiomac.2023.123366>. PMID:36693609.
48. Ren, D., Marusich, L. R., O'Donovan, J., Bakdash, J. Z., Schaffer, J. A., Cassenti, D. N., Kase, S. E., Roy, H. E., Lin,

- W., & Höllerer, T. (2019). Understanding node-link and matrix visualizations of networks: a large-scale online experiment. *Network Science*, 7(2), 242–264. <http://doi.org/10.1017/nws.2019.6>.
49. Nygaard, D., Yashchuk, O., & Hermida, É. B. (2021). PHA granule formation and degradation by *Cupriavidus necator* under different nutritional conditions. *Journal of Basic Microbiology*, 61(9), 825–834. <http://doi.org/10.1002/jobm.202100184>. PMID:34342882.
50. Dalton, B., Bhagabati, P., De Micco, J., Padamati, R. B., & O'Connor, K. (2022). A review on biological synthesis of the biodegradable polymers polyhydroxyalkanoates and the development of multiple applications. *Catalysts*, 12(3), 319. <http://doi.org/10.3390/catal12030319>.
51. Sirohi, R., Pandey, J. P., Gaur, V. K., Gnansounou, E., & Sindhu, R. (2020). Critical overview of biomass feedstocks as sustainable substrates for the production of polyhydroxybutyrate (PHB). *Bioresource Technology*, 311, 123536. <http://doi.org/10.1016/j.biortech.2020.123536>. PMID:32448640.
52. Nath, S. (2024). Biotechnology and biofuels: paving the way towards a sustainable and equitable energy for the future. *Discovery Energy*, 4(1), 8. <http://doi.org/10.1007/s43937-024-00032-w>.
53. Sharma, K., Malik, K., Chaudhary, S., Kumar, S., Dhull, N., & Sujeta. (2022). Polyhydroxybutyrates (PHBs): an eco-friendly alternative to petroleum-based plastics for diminution of their detrimental effects on the environment. *International Journal of Agricultural and Applied Sciences*, 3(2), 8–18. <http://doi.org/10.52804/ijaas2022.322>.
54. Miao, C., Humphrey, R. H., & Qian, S. (2017). A meta-analysis of emotional intelligence effects on job satisfaction mediated by job resources and a test of moderators. *Personality and Individual Differences*, 116, 281–288. <http://doi.org/10.1016/j.paid.2017.04.031>.
55. Zheng, K., & Wang, X. (2019). Publications on the association between cognitive function and pain from 2000 to 2018: A bibliometric analysis using Citespace. *Medical Science Monitor*, 25, 8940–8951. <http://doi.org/10.12659/MSM.917742>. PMID:31762442.
56. Meng, D., Miao, C., Liu, Y., Wang, F., Chen, L., Huang, Z., Fan, X., Gu, P., & Li, Q. (2022). Metabolic engineering for the biosynthesis of poly(3-hydroxybutyrate-co-3-hydroxyvalerate) from glucose and propionic acid in recombinant *Escherichia coli*. *Bioresource Technology*, 348, 126786. <http://doi.org/10.1016/j.biortech.2022.126786>. PMID:35114368.
57. Lin, Z., Zhang, Y., Yuan, Q., Liu, Q., Li, Y., Wang, Z., Ma, H., Chen, T., & Zhao, X. (2015). Metabolic engineering of *Escherichia coli* for poly(3-hydroxybutyrate) production via threonine bypass. *Microbial Cell Factories*, 14(1), 185. <http://doi.org/10.1186/s12934-015-0369-3>. PMID:26589676.
58. Aristya, G. R., Lin, Y.-J., Chang, J.-S., Chang, J.-J., & Yen, H.-W. (2022). Polyhydroxybutyrate (PHB) production from crude glycerol by genetic engineering of *Rhodotorula glutinis*. *Bioresource Technology Reports*, 18, 101048. <http://doi.org/10.1016/j.biteb.2022.101048>.
59. Jung, H. J., Kim, S. H., Shin, N., Oh, S.-J., Hwang, J. H., Kim, H. J., Kim, Y.-H., Bhatia, S. K., Jeon, J.-M., Yoon, J.-J., & Yang, Y.-H. (2023). Polyhydroxybutyrate (PHB) production from sugar cane molasses and tap water without sterilization using novel strain, *Priestia sp.* YH4. *International Journal of Biological Macromolecules*, 250, 126152. <http://doi.org/10.1016/j.ijbiomac.2023.126152>. PMID:37558031.
60. Sooksawat, T., Attapong, M., Saengsakun, W., Siripornadulsil, S., & Siripornadulsil, W. (2023). Optimization of polyhydroxybutyrate (PHB) production by *Priestia megaterium* ASL11 and glycerol and thermoplastic properties of PHB-based films. *Biocatalysis and Agricultural Biotechnology*, 54, 102951. <http://doi.org/10.1016/j.bcab.2023.102951>.
61. Zhou, W., Colpa, D. I., Geurkink, B., Euverink, G.-J. W., & Krooneman, J. (2022). The impact of carbon to nitrogen ratios and pH on the microbial prevalence and polyhydroxybutyrate production levels using a mixed microbial starter culture. *The Science of the Total Environment*, 811, 152341. <http://doi.org/10.1016/j.scitotenv.2021.152341>. PMID:34921889.
62. Myshkina, V. L., Nikolaeva, D. A., Makhina, T. K., Bonartsev, A. P., & Bonartseva, G. A. (2008). Effect of growth conditions on the molecular weight of Poly-3-hydroxybutyrate produced by *Azotobacter chroococcum* 7B. *Applied Biochemistry and Microbiology*, 44(5), 482–486. <http://doi.org/10.1134/S0003683808050050>. PMID:18822772.
63. Costa, J. A. V., Moreira, J. B., Lucas, B. F., Braga, V. S., Cassuriaga, A. P. A., & Morais, M. G. (2018). Recent advances and future perspectives of PHB production by cyanobacteria. *Industrial Biotechnology*, 14(5), 240–256. <http://doi.org/10.1089/ind.2018.0017>.

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