

An Exploration of Future of Bioplastics and Their Physical, Chemical and Biological Characteristics

D. Pansuriya¹, D. S. Kaul¹*, P. Kodgire², A. Nema¹, and M. Mistry¹

¹ Civil Engineering Department, Pandit Deendayal Energy University, Gandhinagar 382426, India

² Chemical Engineering Department, Pandit Deendayal Energy University, Gandhinagar 382426, India

Received 06 July 2025; revised 09 October 2025; accepted 26 January 2026; published online 07 March 2026

ABSTRACT. Recently, petroleum-based plastic has become an integral part of human lives; however, its imperishable nature makes it the leading pollutant in solid waste, creating serious environmental problems. Inadequate plastic waste management increases the toxicity of landfills and causes air and marine pollution. Several initiatives have been started to overcome these challenges. Its replacement with biodegradable plastic is one of the upcoming solutions. This study is carried out to shed light on the past, present, and future research trends in the bioplastic arena. Such a study is important for bioplastic-related research to be made available at a single source with in-depth analysis. This study has used 3,802 publications extracted from the Web of Science core collection databases using various combinations of search strings. VOSviewer was used to analyzing this data. With the help of various analysis techniques available with VOSviewer, many types of analysis (e.g., predominantly used material, tested properties of bioplastic etc.) were carried out. Through this study, the development and various aspect of bioplastic been investigated.

Keywords: bioplastic manufacturing process, bioplastic properties, biopolymers, VOSviewer, application

1. Introduction

In recent years, polymers and their composites for plastic have received much attention and acceptance. They have become an integral part of human lives because of their wide range of applications due to various properties associated with them, such as good mechanical properties (flexibility, strength, heat resistant, insulating, flame retardant, corrosion resistance), lower production cost with much lighter in weight than metals and alloys (Prabhu and Prashantha, 2018a; Narancic and O'Connor, 2019). The petroleum-based single-use plastic poses an enormous environmental problem due to its poor degradability and disposal techniques. Burning or dumping plastic leads to pollution of air and soil. Lacking appropriate management techniques for plastic waste causes air and marine pollution through combustion with mixed waste and its transport through the river into the ocean. Due to their partial recycling and reuse, there is an immense amount of polymer waste in landfills. Plastic mixed with solid waste in landfills adds toxic compounds to solid waste, which otherwise have been converted into better quality compost. Sorting recyclable plastic from mixed solid waste is challenging and involves enormous costs. Also, some plastic resins are difficult to recycle (Chidambarampadmavathy et al., 2017). Incineration, pyrolysis, gasification, and energy recovery are the several tech-

niques used for plastic disposal and conversion to synthetic gas or fuel. These methods have their demerits and pose adverse environmental impacts (Hopewell et al., 2009). A few authors have projected that global municipal plastic waste generation could reach 300 million tons annually by 2030 and 380 million tons by 2060 (Lebreton and Andrady, 2019a). It is estimated that global daily solid waste generation will reach more than 6 million tons by 2025 (Hornweg et al., 2013; Lebreton and Andrady, 2019b). As per estimates, a fraction of 10% of plastics in the solid waste stream annually will generate over 200 million tons plastic waste by 2025 which is comparable to global plastic production of 2002 (Urbanek et al., 2017).

Microplastics in the environment create severe health issues when they enter the human body through biomagnification and bioaccumulation. The characteristic of plastics, like resistance to degradation in the natural environment for several decades (Urbanek et al., 2017; Abraham et al., 2021a), is a major cause of landfill, ocean, air pollution, and health hazards. Thus, the need for a material that can be easily biodegraded and poses less adverse impact on the environment at the end of life is warranted. Hence, the concept of bioplastic has come to light. Nowadays, numerous initiatives have been started towards manufacturing bioplastics to prevail over the problems with petroleum-based plastics.

According to European Bioplastics, bioplastic can be defined as a plastic material that is either biobased, biodegradable, or features both properties (Gill, 2014). Bioplastics are plastic derived from biomass or monomers derived from biomass and renewable raw materials (Memon et al., 2011; Lambert and Wag-

* Corresponding author. Tel.: +917923275453.
E-mail address: dayashankar.kaul@sot.pdpu.ac.in (D. S. Kaul).

ner, 2017). The following studies have stated that bioplastics contain renewable carbon, ranging from 20 to 100% (Civancik-Uslu et al., 2019; Abraham et al., 2021b). Bioplastics are distinguished into three categories such as (i) biobased biodegradable bioplastics (ii) fossil-based biodegradable bioplastics and (iii) biobased non-biodegradable plastic (Bátori et al., 2018). Bio-based plastics are defined by the origin of their raw materials and are produced wholly or partly from renewable biological sources such as plants, algae, or microorganisms; however, being bio-based does not necessarily imply biodegradability. In contrast, biodegradable plastics are defined by their end-of-life behavior, as they can be decomposed by microorganisms into natural substances such as water, carbon dioxide, and biomass under specific conditions. These plastics may be either biobased or fossil-based. Bio-based biodegradable bioplastics are made of polysaccharides, proteins, lipids, microorganisms, natural rubber, or synthesized from bioderived monomers. In contrast, fossil-based biodegradable bioplastic can be synthesized from fossil-based polyesters. “Drop-ins” fall under the category of biobased non-biodegradable bioplastics. The study also specified that one metric ton of bioplastics generates 0.8 to 3.2 times less carbon dioxide than petroleum-based plastics (Pilla, 2011a; Abraham et al., 2021a). European Bioplastics forecasted that the global production capacity of bioplastics will increase from 2.23 million tonnes in 2021 to 2.87 million tonnes in 2025.

Thus, several researchers are investigating an eco-friendly alternative to petroleum-based plastic from various renewable resources to eliminate the negative impact of petroleum-based plastic. It is important to know the present and future trends in the field of bioplastics. Study becomes important when several bioplastic-related pieces of research become available in a single place for detailed analysis, and the outcome reaches the research community for future research.

Bibliometric analysis is the statistical analysis that uses bibliographic data for the task. It helps to identify the past, present, and future trends, areas of research strength and weakness, and research gaps in the particular field of research. The map-based bibliometric tool allows the bibliometric data to be visualized, analysed, and interpreted. The tools available are Bibexcel, Biblioshiny, BiblioMaps, CitNetExplorer, SciMAT, CiteSpaceII, CoPalRed, IN-SPIRE, Leydesdorff’s software, Network Workbench Tool, Sci² Tool, Vantage Point, VOSviewer, etc. (Sangam et al., 2012). Bibliographic data can be extracted using various keywords relevant to the looked-for field of the study from the various databases. Subsequently, the software is used to perform a bibliometric analysis. Databases such as Web of Science, Scopus, Google Scholar, PubMed, Crossref, Dimensions, and various reference managers such as EndNote, RefWorks, Mendeley, etc. can be used. The data need to be extracted in the particular format which is supported by the software to be used, various file format that are supported by the different software are .txt, .csv, .ris, .gml, .clu, .vec, .net, .enw and .json etc.

VOSviewer and CiteSpace supported many databases and reference managers such as Web of Science, Scopus, Dimensions, Microsoft Academic, Crossref, RIS, CSV, etc. (Moral-Muñoz et al., 2020). Various bibliometric analysis techniques are

associated with each software. Though, some software is featured with some specific analysis techniques. VOSviewer and Bibexcel are associated with all the techniques. However, Bibexcel requires an external source to visualize networks’ graphical presentation (Bankar and Lihitkar, 2019). While referring to the various database compatible with VOSviewer software, the Web of Science database is a comprehensive database for the bibliometric analysis of the field.

Authors (Cobo et al., 2011) have differentiated the bibliographic coupling and co-citation analysis techniques. A bibliographic coupling is a fixed and permanent relation as it depends on the same reference cited by the two authors, countries, organizations, documents, and journals. While the co-citation analysis relies on two authors, journals, and references cited together. Additionally, by manually selecting the keywords of a particular group, one can analyse the desired topic of the field. A bibliometric analysis on bioplastics is necessary at this stage because the field is expanding rapidly, making it increasingly difficult to systematically navigate and synthesize the growing body of literature. Despite extensive research activity, comprehensive quantitative analyses that integrate publication trends and thematic evolution remain limited. In particular, thematic shifts cannot be adequately captured through narrative reviews alone. Given the dynamic and interdisciplinary nature of bioplastics research, data-driven bibliometric insights are increasingly required to support informed decision-making in research planning, policy formulation, and industrial development. Some studies have been carried out on bioplastic related themes using above bibliometric methodology (Nnolim and Nwodo, 2005; Akinpelu and Nchu, 2022). However, these works primarily focus on specific themes such as biodegradation mechanisms, individual biopolymers, or sustainability aspects and concentrated with citation, author and coauthor, counties, institutional and keyword analysis.

The present study has concentrated upon mostly technical aspects of the bioplastic with certain direction of focus. The main objective is to perform an analysis focusing on identifying various materials, manufacturing processes, tested properties of manufactured bioplastics, and their major application.

2. Methodology

The following criteria and methodologies adopted to perform the analysis are given below. Three main steps have been followed to carry out this study, viz., (1) planning of the analysis (2) Data query and processing and (3) analysis of data.

2.1. Planning of Analysis

The analysis is divided into four parts, as detailed in Figure 1, where research questions broadly to be addressed have been listed (refer to top left quadrant), along with inclusion (top right quadrant) and exclusion (bottom right) criteria for data mining. A process in the bottom left quadrant shows the quality control process adopted for quality control (e.g., the data obtained related to the search string). The step helped in acquiring relevant information from the database for the analysis.

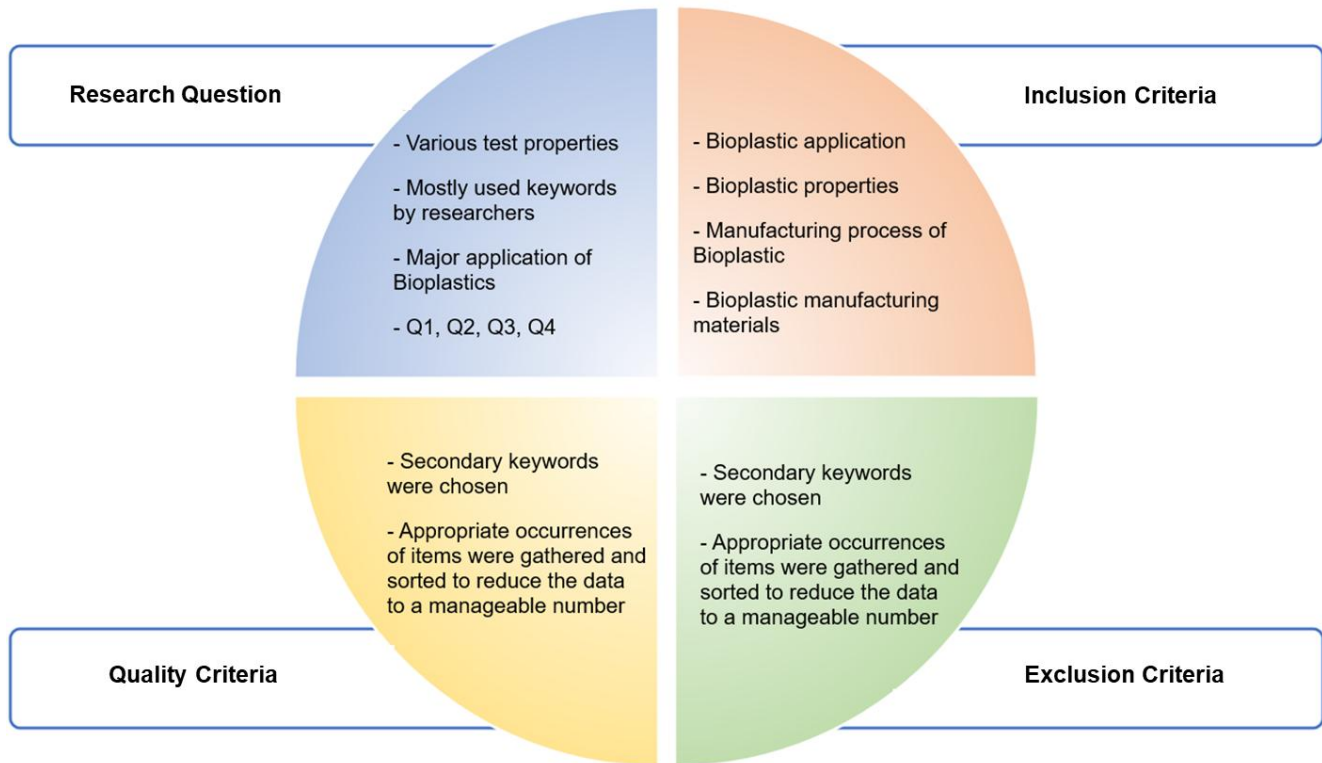


Figure 1. Methodology and planning adopted in the current study: Q1–Q4 represents key processes, impactful publications, commonly used materials, and the overall research landscape in bioplastics.

2.2. Data Query and Processing

The second step of the analysis is to extract the data. An appropriate selection of keywords to extract the data is crucial in such analysis. Hence, keeping the research questions in mind, the primary keywords were manually selected from the 85 literature published on bioplastics. These were then used to extract numerous publications from the Web of Science database. The publications and VOSviewer were used to extract secondary keywords (444 in number). The secondary keywords are reduced to 142 by following the criteria shown in Figures 1 and 2, respectively. These (142) keywords are then grouped into five categories, viz., (a) general bioplastic term, (b) manufacturing material, (c) bioplastic properties, (d) manufacturing process, and (f) bio-plastic application (refer to Figure 2). Using the Boolean operator “AND” and “OR” the numerous search strings were permuted from 142 keywords. These strings were used to extract the data in the .txt format from the database of the Web of Science core collection, which was refined by Language – English, Timespan – all years (1999 to 1st January 2021), Document types – all, Web of Science categories – all, Web of Science index – all.

2.3. Analysis of Data

The third step was to analyse the extracted data according to the research questions defined earlier (Figure 1). VOSviewer software (version 1.6.15) was used for the purpose. This software is featured to eliminate duplications in the data file and give

unique data results. Therefore, analysis was performed with merged results from all the search strings.

The VOSviewer software comprises five panels that allow us to visualise, adjust and perform actions on the currently active map. The software consists of three visualisations: Network visualisation, Overlay visualisation, and Density visualisation to analyse and interpret the map. It is well designed to analyse various data types from the respective data source. It presents an analysis in the form of maps, and a link can create connections between two items. Each link has strength and is represented by a positive numerical value.

When creating a network visualization, the strength of the relationship between two items is indicated by the thickness of the link. A thicker link suggests a stronger relationship, and vice versa. However, when using VOSviewer to generate a graph, it can only display a maximum of 10,000 lines in the graph. VOSviewer prioritizes showing stronger relations in the graph. All the items on the map are grouped into clusters, and an item can belong to any cluster. It’s important to note that there may be an item that does not belong to any cluster (VOSviewer: user manual). The number of items allowed in a cluster can be determined based on the user’s interest. The graph generated displays the number of clusters, several items, total links, and total link strength of the entire map. These graphs provide various types of data that can be extracted such as the name of the item, the total number of links, total link strength, and the cluster to which it belongs.

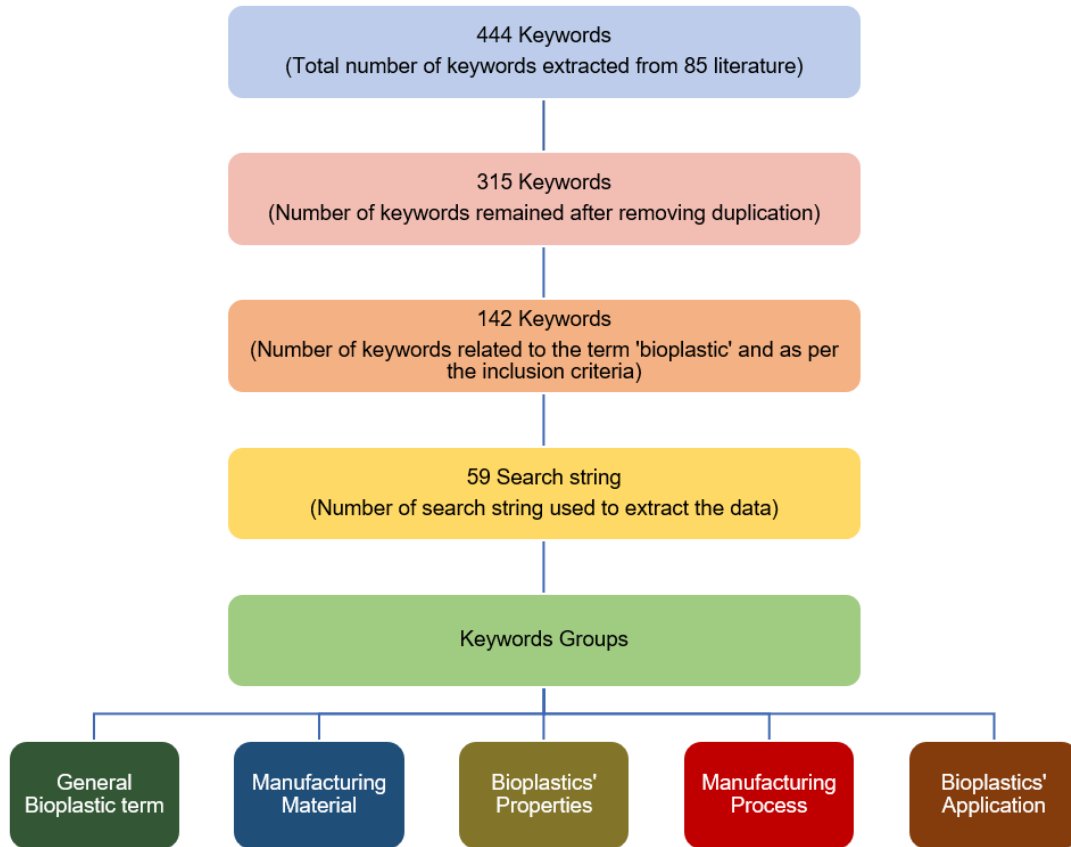


Figure 2. The methodology followed in selecting the keywords and extracting the data from Scopus.

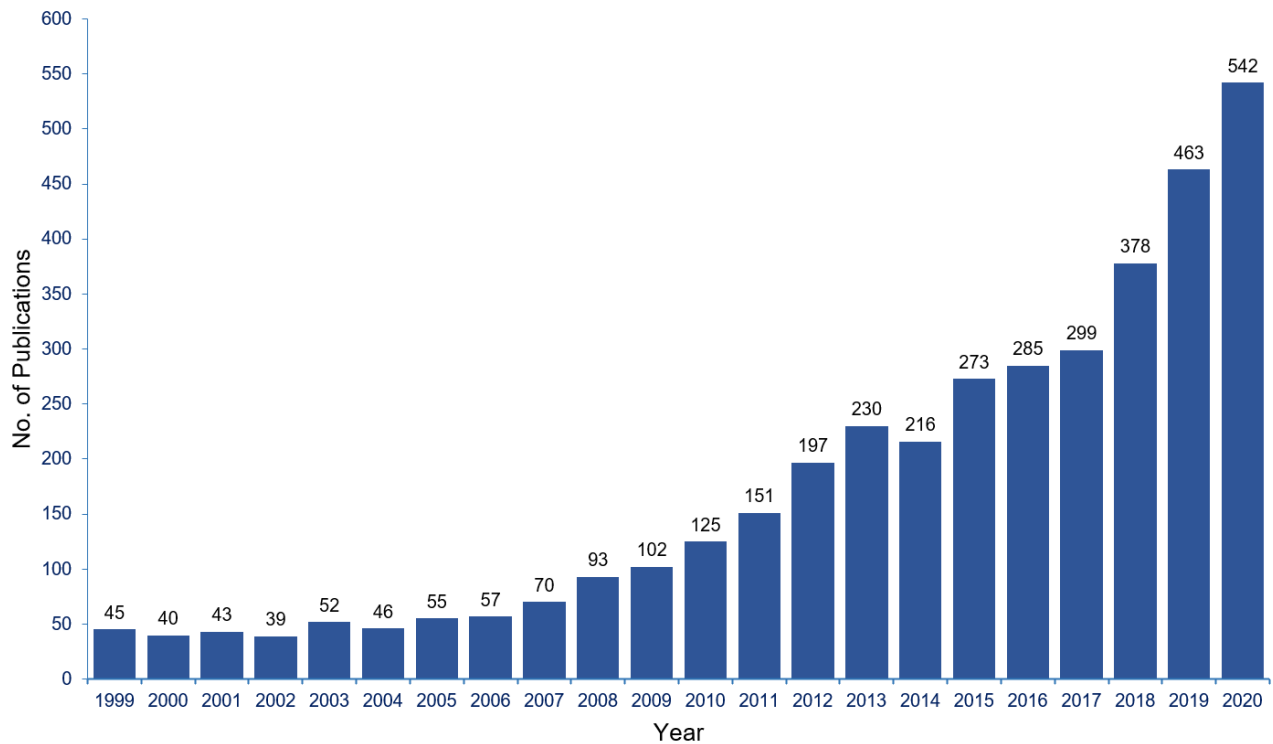


Figure 3. Growth of the bioplastics publications for the year 1999 ~ 2020.

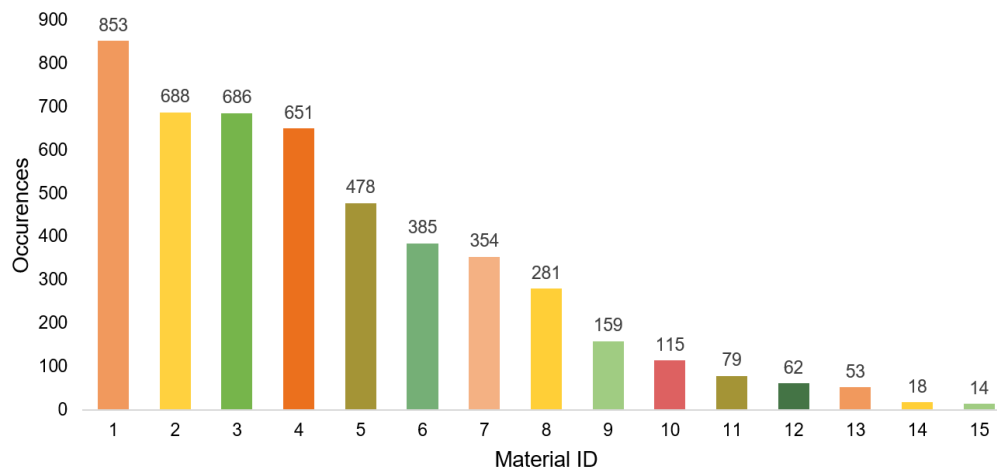


Figure 4. Materials used for manufacturing bioplastics.

3. Result and Discussion

This section has been divided into several subsections: bioplastic materials, bioplastic manufacturing process, bioplastic test properties, frequently used keywords in the field of bioplastic; and most productive publications in the field. The application of bioplastic, future perspectives and limitations are described in the last section. Overall, the research on bioplastics has increased substantially. Figure 3 shows the exponential growth of the study concerning bioplastics, from 45 in 1999 to 542 publications in 2020, indicating the subject matter's importance.

3.1. Bioplastics Material

Bio-based materials (viz., polysaccharides, proteins, lipids, biobased polyesters, microbial polymers, and synthesized biopolymers) with additives (viz., plasticizers, stabilizers, antimicrobial agents, antioxidant agents, flame retardants), etc., have been used to manufacture bioplastics. A minimum of one occurrence of keywords, one item per cluster, and a maximum of 10,000 lines were considered to identify the widely used materials for bioplastic manufacturing. Based on that, from the 12,446 keywords, 1,679 were manually selected related to manufacturing materials and bioplastics. Further, out of 1,679 keywords, 1,503 keywords showed a link between them. Thus, the bibliometric map of 1,503 keywords containing various materials used by researchers is provided in Figure S1 in Supplementary Information.

The diverse publications used different notations for the same material, e.g., polylactic acid was written as poly (lactic acid) or poly(lactic) acid or polylactic acid or polylacticacid (PLA). Thus, the total number of occurrences was taken as the summation of all different notations. Likewise, keywords related to various sources of starch, cellulose, materials used as a stabilizer, materials used as a plasticizer, sources of fibers, and proteins are covered under the head to starch, cellulose, stabilizers, plasticizers, fibers, and proteins, respectively. The total number of occurrences of respective materials shows how many times that material had been brought up in literature to manufacture the bioplastics. Figure 4 represents researcher's frequent-

ly used (top 15, ranked according to their occurrences) materials. The material id in the figure is as follows: 1: PLA (Polylactic acid); 2: Starch; 3: PHA (Polyhydroxyalkanoate); 4: PHB (Polyhydroxybutyrate); 5: Cellulose; 6: Stabilizers; 7: Plasticizer; 8: Fibers; 9: Proteins; 10: PHBV (Poly(3-hydroxybutyrate-co-3-hydroxy-valerate)); 11: PCL (Polycaprolactone); 12: Algae; 13: PVA (Polyvinyl alcohol); 14: Poly(ethylene glycol); 15: Polyhydroxy valerate. Analysis indicated that the bioplastics manufactured from polylactic acid are the most preferred, with the highest occurrences of 853, followed by starch and others (Figure 4).

Poly(lactic acid) ($C_3H_4O_2$)_n is an aliphatic thermoplastic polyester and non-toxic, compostable bioplastic manufactured by polymerizing lactic acid monomers ($C_3H_6O_3$) derived from the fermentation of starch. High molecular weight PLA (MW > 100,000 D) possesses mechanical strength with a tensile strength comparable to conventional plastics that is 50 ~ 70 MPa. The degradation of PLA is influenced by pH and UV light; the alkaline condition favors PLA degradation (Karamanlioglu et al. 2017). PLA can be easily processed through film extrusion, blow or injection molding, fire spinning, etc. (Tian et al., 2017a). The dominance of polylactic acid (PLA) in the literature reflects its technological maturity, commercial availability, and compatibility with conventional plastic processing techniques such as extrusion and injection molding. These attributes make PLA an attractive material for both academic research and industrial applications, particularly in packaging. The strong research focus on PLA also indicates an industry-driven preference for bioplastics that can be integrated into existing manufacturing infrastructure with minimal modification. In contrast, the increasing attention toward microbial biopolymers such as PHA and PHBV as well as cellulose-based reinforcements, suggests a growing research effort to address the limitations of PLA, including brittleness, cost, and end-of-life performance.

Starch is a biodegradable, cheap, renewable, and abundantly available natural biopolymer (Khan et al. 2017). Various starch sources are corn, rice, wheat, potato, cassava, tapioca, sago, barley, jicama, oats, banana, date, soy, olive, peas, sugar, sugar beet pulp etc. High glass transition temperature and melting temper-

ature of starch resist using starch itself as a bioplastic. However, blending with a plasticizer can increase the plasticity of starch (Khan et al., 2017). A few authors (Edgar et al., 2001a; Jiménez et al., 2012) stated that starch-based films become stronger, stiffer, and less flexible after several weeks of storage. Starch's retrogradation and moisture sensitivity are the major drawbacks but can be improved by blending with other biopolymers (Prabhu and Prashantha, 2018b).

PHA (Polyhydroxyalkanoate) is a microbial thermoplastic polyester of R-hydroxyalkanoic acid. For the industrial production of PHA, sucrose and glucose are widely used due to their lower cost (Urtuvia et al. 2014). PHA with 3 to 6 hydroxyl acids holds physical, chemical, and mechanical properties similar to conventional plastics (Devadas et al. 2021). It possesses a higher melting temperature of PHA 168 (Cooper et al., 2007a). Various bacteria derive PHB (Polyhydroxybutyrate) as an intracellular energy storage material. A biodegradable and biocompatible nature unveils application in the packaging and biomedical field (Yeo et al., 2018). PHB holds up to 70% crystallinity and has good gas barrier properties (Hamid et al., 2019). However, several drawbacks, such as thermal instability, poor mechanical properties, and high production cost, can be overcome by blending PHB with other biopolymers. A few authors (Tian et al., 2017b) suggested that mixing PHB with several monomers in different concentrations can regulate its thermal and mechanical properties.

Cellulose is the most abundant natural biopolymer found mainly as the structural component of plant cell walls (Ferreira et al., 2018). Cellulose is used in various forms such as cellulose acetate, carboxymethyl cellulose, cellulose ester, cellulose fibers, cellulose nanofiber, hemicellulose, lignocellulose, microcrystalline cellulose, nanocellulose, etc. Nanocellulose has a high specific surface area and has more hydroxyl groups and nanoscale morphology. It provides high strength, transiency, barrier property, low density, and low thermal expansion to bioplastics (Su et al., 2018). A few authors (Mohanty et al., 2000) have compared the biodegradability rate and strength of various cellulose forms which is provided below: Biodegradability rate: Hemicellulose > Accessible Crystalline Cellulose > Non crystalline Cellulose > Crystalline Cellulose > Lignin; Strength: Crystalline Cellulose > Non crystalline Cellulose + Hemicellulose + Lignin > Lignin.

The stabilizers used are antimicrobial, antifungal, antibacterial, antioxidant, and flame retardants. Oils (like canola oil, castor oil, cooking oil, cottonseed oil, crude palm oil, edible oil, essential oil, fish oil, jatropha oil, kernel oil, linseed oil, olive oil, palm oil, rapeseed oil, soybean oil, vegetable oil, waste cooking oil) and metal oxides or nanoparticles (such as copper nanoparticles, silicon dioxide (SiO₂), Titanium dioxide, TiO₂ nanoparticles, calcium silicates, metallic nanoparticles, montmorillonite, pd alloy nanoparticles, nanoclay, oxide nanoparticles, silicate nanocomposites, zinc oxide nanoparticle, zinc oxide (ZnO), etc., are being used. Chitosan has antibacterial properties that prevent the development of many fungi and bacteria on bioplastics' surfaces. A few authors suggested that the chitosan Zn⁺ and chitosan Ag⁺ complex have more antimicrobial properties than chitosan (Wang et al., 2004; Al-Tayyar et al., 2020a).

According to research done in (Cooper et al., 2007a), plasticizers' low molecular weight and non-volatile characteristics enhance bioplastics' flexibility. Plasticizers such as glycerol, sorbitol, chitosan, citric acid, and malic anhydride provide plasticity to bioplastics (Tian et al., 2017a). The study of (Cooper et al., 2007b) stated that the interaction of intermolecular hydrogen bonding could be reduced by blending glycerol with bioplastic, which offers cross linking and improves the flexibility of bioplastics. Chitosan has low oxygen permeability, good film formability, and nontoxicity (Farah et al., 2016). Because of its high antimicrobial activity, chitosan can also be used as an antimicrobial agent. A few authors (Farah et al., 2016) have found that sorbitol has increased the elongation with cellulose and chitosan and decreased the tensile strength.

Fibers reinforce bioplastics by enhancing strength and stiffness as they are lignocellulosic. The natural bio-fibers are leaf, bast, seed, and fruit. Carbon fiber, cellulose, nanofiber, wood fiber, and wool fiber are other fibers. The modulus of fiber increases with decreasing diameter of fiber (Mohanty et al., 2000). Other properties such as density, tensile strength, mechanical strength, electrical conductivity, and moisture content depend on the fiber's molecular structure and chemical composition. Sources of proteins are beans, cheese whey, cottonseed, gluten, keratin, silk, pea, rice, soy, whey, and by-products of the agri-food industries. It has much lower mechanical properties (Zhuang et al., 2013). However, it can be upgraded by chemical, enzymatic or physical protein treatments (Jiménez-Rosado et al., 2020). PHBV is a polyhydroxybutyrate (PHB) derivative with good moulding properties, low crystallinity, low melting temperature, and less brittleness (Abraham et al., 2021b). It has good mechanical properties and undergoes rapid enzymatic hydrolysis in sewage sludge, wastewater, and soil, but anaerobic hydrolysis is comparatively slow. Temperature, surface area, microbial density, composition, microbial infiltration, and enzyme percolation are several factors that influence the rate of degradation of PHBV (Wang et al., 2003). PCL (Polycaprolactone) is a thermoplastic polymer derived through the ring opening reaction of cyclic lactone monomer. PCL is a tough and semi-rigid material at room temperature, and the modulus lies between LDPE and HDPE (Mohanty et al., 2000). It provides good water, solvent, oil, and chlorine resistance (Flieger et al., 2003). According to the rheological study of PCL (Chavalitpanya and Phattanarudee, 2013), it has higher elasticity and viscosity than PLA.

Various types of algae have been used for bioplastics. A few authors (Tibbetts et al., 2015; Khoo et al., 2019; Koyande et al., 2019; Tang et al., 2020) have defined microalgae's bioactive composition as containing 12 ~ 48% lipids, 18 ~ 46% proteins, 18 ~ 46% carbohydrates, and 10 ~ 14% carotenoids. PVA (Polyvinyl alcohol) is a synthetic water-soluble polymer with good chemical resistance and biodegradability (Al-Tayyar et al., 2020b). It is a hydrolysed product with admirable strength and flexibility (Wang et al., 2003). PVA can resist oxygen permeation through bioplastic and has good mechanical, and thermal properties and transparency (Abdullah and Dong, 2019). Lower molecular weight PEG (Polyethylene glycol) improves elongation at break and softness while blending with other biopolymers (Pivsa-Art et al., 2016). PEG can increase the mobility of PLA. PHV (Poly-

Table 1. Summary Table on Advantages and Disadvantages of Various Bioplastics

Bioplastic Type	Advantages	Disadvantages
PLA	Renewable, versatile, well understood	Brittleness, low heat resistance, requires industrial composting
PHA/PHB/PHBV	Full biodegradability, biocompatible	High cost, variable mechanical properties
PBS/PBSA	Tough, biodegrades faster than PLA	Less available, processing adjustments needed
Starch/Cellulose	Cheap, abundant, biodegradable	Poor moisture and mechanical performance

hydroxyvalerate) is a copolymer of PHB. The PHV has better phys-icochemical properties, such as lower crystallinity degree and more flexibility than PHB (Simó-Cabrera et al., 2021). A brief summary of advantages and disadvantages of above materials is shown in Table 1.

3.2. Bioplastic Manufacturing Process

Bioplastics can be manufactured similarly to conventional plastics using extrusion, molding, casting, etc. A minimum of one number of occurrences, minimum of one item per cluster, and a maximum of 10,000 lines of the map were taken. Thus, from the 12,446 keywords, 33 keywords (combined, including commercial and laboratory scale manufacturing processes) were manually selected related to manufacturing processes and bioplastics. These 23 keywords were linked together and represented as the bibliometric map (Figure S2 in Supplementary Information), illustrating various manufacturing processes used in various publications. Each manufacturing process's occurrences represent how often the researchers have used that process to manufacture bioplastics.

Figure 5 shows the widely used processes to manufacture bioplastics. From the analysis, the extrusion process is mostly used as a manufacturing process in 74 kinds of literature, i.e., 52.9%, followed by an injection molding process (20.0%) and others. Most researchers have used compact-sized machinery or casting to manufacture bioplastics in a lab. The predominance of lights a strong emphasis on scalability and industrial relevance in bioplastics research. Extrusion is a well-established, cost-effective technique that allows efficient blending and compounding of biopolymers with additives, making it suitable for both laboratory and industrial production. The frequent use of injection molding further supports the trend toward process compatibility with existing polymer manufacturing systems. In contrast, casting-based approaches are primarily associated with laboratory-scale material development, indicating early-stage research or proof-of-concept studies.

3.3. Bioplastic Test Properties

After manufacturing bioplastics, various properties must be tested before bringing them to the commercial market. A minimum of one occurrence of all keywords, minimum of one item per cluster, and a maximum of 10,000 lines of the map were taken. Thus, from the 12,446 keywords, 280 keywords were selected manually related to properties and bioplastics. Of the 280 keywords, 240 keywords were linked. Hence created bibliometric map (Figure S3 in Supplementary Information) represents various properties of bioplastics that the researchers have test-

ed. Figure 6 below represents the researchers' most tested (top 10) properties of manufactured bioplastics. The properties' occurrences demonstrate how often that property has been tested earlier. Researchers tested mechanical properties the most, followed by degradation properties and several others. The mechanical properties dominate bioplastics testing, reflecting the necessity to benchmark strength, stiffness, and durability against conventional petroleum-based plastics, particularly for packaging and load-bearing applications. Degradation-related studies form the second most prominent category, underscoring growing regulatory pressure and environmental concern regarding end-of-life performance. Thermal, barrier, and rheological properties appear with moderate frequency, indicating their relevance in determining processing feasibility, shelf life, and suitability for food and biomedical applications. In contrast, properties such as optical, electrical, and long-term environmental performance are comparatively less investigated, likely due to their application-specific nature or the complexity and time-intensive requirements of such assessments. This uneven distribution of tested properties suggests that current research is primarily driven by short-term functional validation and process compatibility, while comprehensive evaluation under real-world service and environmental conditions remains limited. Addressing these under-explored property domains will be essential for expanding bioplastics into high-performance and long-duration applications.

3.4. Frequent Used Keywords in the Bioplastic Field

The co-occurrence analysis technique helps analyse the most frequently used keywords by authors. The network is created by taking a minimum of 2 occurrences of keywords, minimum of 1 item per cluster, and a maximum of 10,000 lines. Thus, of the 12,446 total keywords, 3,598 keywords meet the threshold, indicating that the remaining were used only once. Among them, the largest set of related keywords consists of 3,597 keywords. Accordingly, 3,597 keywords have a link with other keywords. The represented co-occurrence analysis map (Figure S4 in Supplementary Information) shows 23 clusters consisting of 3,597 items with 91,368 links (one item links with other items) and 133,158 total link strength (total of the how many times each item links with other items). From the network of co-occurrence analysis, "bioplastics" is the most frequently used keyword by authors, with the highest number of 726 occurrences. Figure 7 represents the top 10 most frequently used keywords in the bioplastics field. The most frequently occurring keywords are strongly centered on bioplastics, specific materials such as polylactic acid (PLA) and starch, and performance-related terms including mechanical properties and biodegradation. This pattern indicates that current research is primarily focused on improving the functional performance and

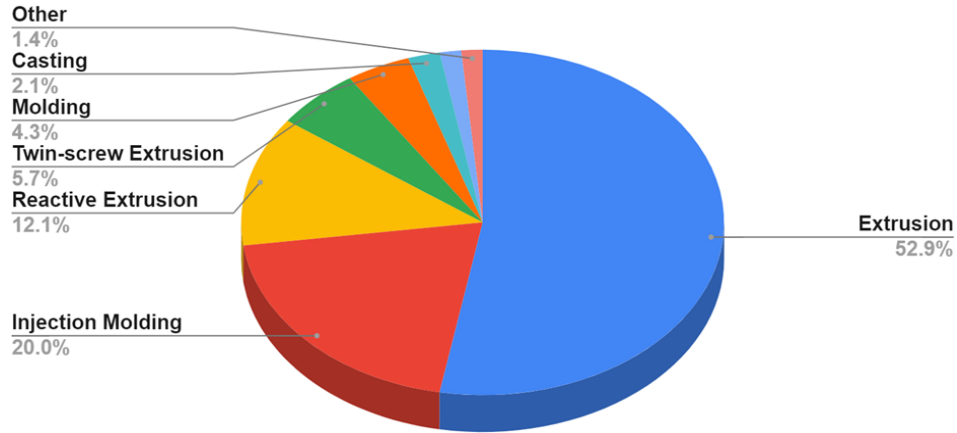


Figure 5. Bioplastics' manufacturing processes.

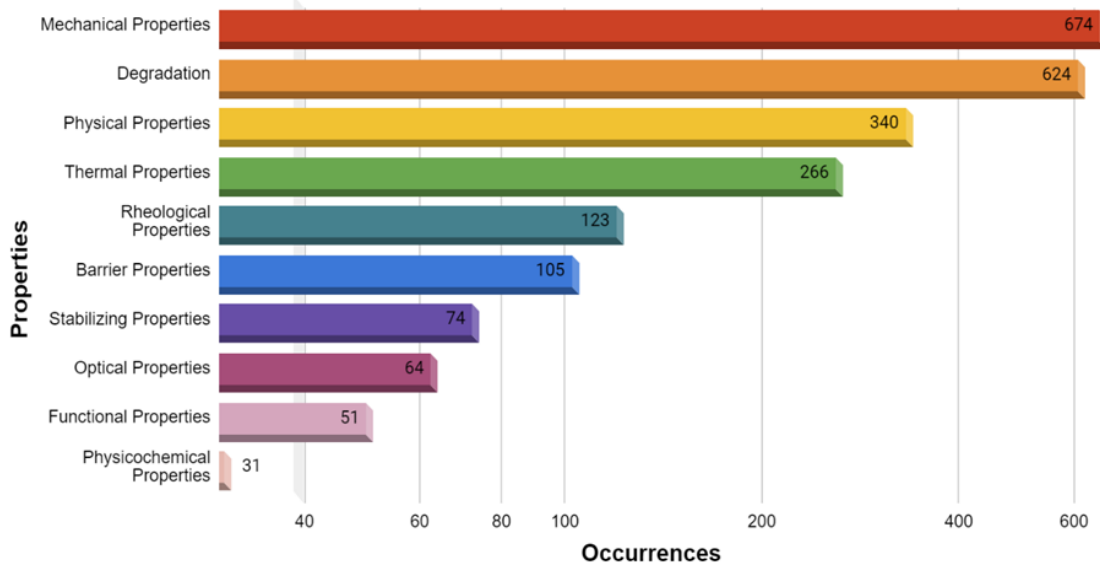


Figure 6. Bioplastics' tested for various properties.

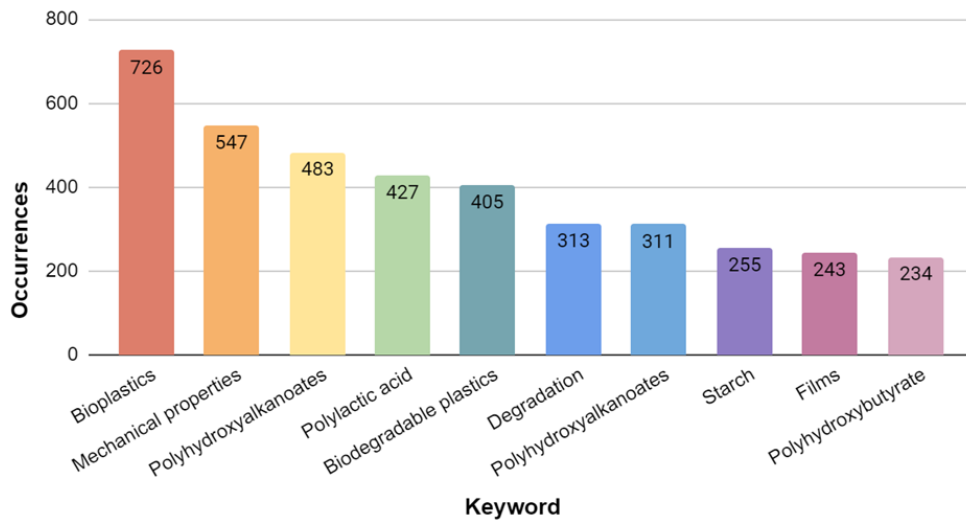
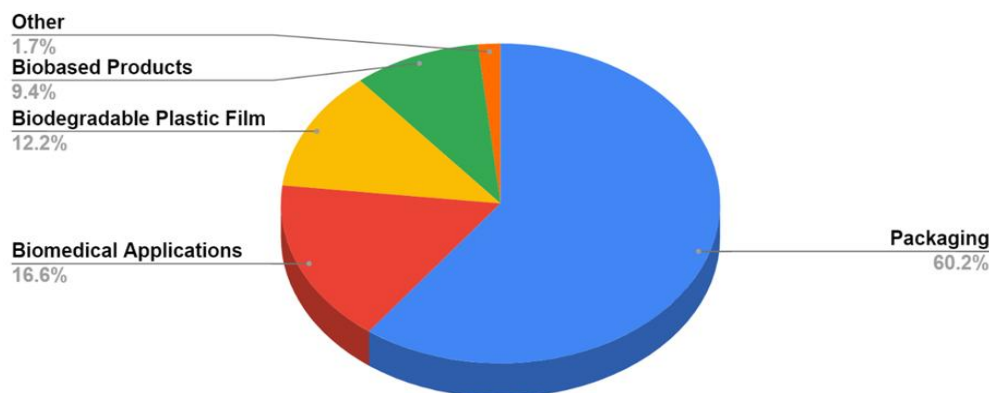


Figure 7. Frequently used keywords.

Table 2. Most Impactful Publications

Rank	Document title	Citations	Reference
1	Biofibres, biodegradable polymers, and biocomposites: An overview	1,993	(Mohanty et al., 2000)
2	An overview of the recent developments in polylactide (PLA) research	1,317	(Nampoothiri et al., 2010)
3	Sustainable biocomposites from renewable resources: Opportunities and challenges in the green materials world	1,288	(Siracusa et al., 2008a)
4	Biological degradation of plastics: A comprehensive review	873	(Shah et al., 2008)
5	Biodegradable polymers for food packaging: A review	868	(Siracusa et al., 2008b)
6	A microbial polyhydroxyalkanoates (PHA) based bio and materials industry	697	(Chen, 2009)
7	Biodegradable composites based on LignocellulosicFibers – An overview	690	(Satyanarayana et al., 2009)
8	Advances in cellulose ester performance and application	680	(Edgar et al., 2001b)
9	Surface modifications of natural fibers and performance of the resulting biocomposites: An overview	556	(Mohanty et al., 2001)
10	Thermoplastic films from plant proteins	505	(Reddy and Yang, 2013)

**Figure 8.** Frequently used keywords for major applications of bioplastics in various fields.

environmental compatibility of established bioplastic materials rather than exploratory polymer discovery. The prominence of application-related keywords, particularly those associated with packaging, reflects the dominant role of packaging as a driver for bioplastics research, largely influenced by regulatory pressure and high consumption volumes. Additionally, the frequent appearance of property- and process-related keywords suggests that researchers are emphasizing material optimization, processing feasibility, and end-of-life behavior to facilitate the transition of bioplastics from laboratory-scale development to industrial and commercial implementation.

Top keywords seem to provide only traditional knowledge, if we explore the large keywords at the periphery, it will help better visualize the new research that may pore into the field of new bioplastic research as in supplementary (Figure S4 in Supplementary Information).

3.4.1. Most Impactful Publications

To analyse the most impactful publication of the field, the citation analysis in the unit of documents can be used. The bibliometric network of this analysis represents the most cited documents in the particular field, and the link strength between two documents represents the number of times that two documents have been cited together. Here, the network was created by taking a minimum 70 number of document citations. Thus, of the 3,802 documents, 233 meet the threshold, and the largest set of

related documents consists of 191 documents. The bibliometric map (Figure S5 in Supplementary Information) consists of 20 clusters with 191 documents and 430 links. The most impactful publication in the field is “Biofibres, biodegradable polymers, and biocomposites: An overview,” with 1,993 citations authored by A. K. Mohanty, M. Misra, and G. Hinrichsen and published in the *Macromolecular Materials and Engineering* journal. Table 2 shows the top 10 impactful publications in the field. The most influential publications identified through the bibliometric analysis are predominantly qualitative and systematic reviews that focus on specific material classes, applications, or degradation mechanisms. For example, highly cited works by Mohanty et al. (2000a, 2001b), Siracusa et al. (2008a, 2008b), and Satyanarayana et al. (2009) emphasize biofibres, biocomposites, and packaging applications, while Nampoothiri et al. (2010) and Chen (2009) provide in-depth material-centric reviews on PLA and PHA, respectively. These studies consistently highlight PLA dominance, the importance of extrusion-compatible processing, and packaging as the leading application — findings that are strongly aligned with the trends revealed by our bibliometric results. While these qualitative reviews provide deep material-specific insights, they are limited in scope and temporal integration, often focusing on selected polymers or applications rather than the broader evolution of the field. In contrast, the bibliometric analysis captures research expansion dynamics across materials, processes, properties, and applications over decades. Notably, the bibliometric results indicate increasing attention toward mi-

icrobial biopolymers, cellulose-based reinforcements, and composite systems — emerging directions that are less emphasized in these narrative reviews. Thus, top publication does not captures the recent trend; for the recent trend, publication on the periphery should be explored rather as in Supplementary Information (Figure S5).

3.5. Applications of Bioplastics

Plastic is everywhere! Nowadays, the application of biodegradable plastics is warranted to reduce the use of single-use plastics. The bibliometric map of various applications of bioplastics was generated by co-occurrences analysis of all keywords by considering a minimum of one occurrence of a key word and manually selecting the keywords related to various applications of bioplastics. Thus, the bibliometric map (refer to Figure S6 in Supplementary Information) represents the various applications of bioplastics mentioned by the researchers in their publications. Each application's occurrence shows how many times that application has been mentioned in the various publications by the researchers. Figure 8 shows the major application of bioplastics in various fields. Bioplastics have been extensively used in food packaging and eco-friendly & sustainable packaging. According to (Pilla, 2011b), approximately 65% of the total bioplastics market is involved in the packaging industry. It has been widely used in biomedical applications in tissue engineering, orthopedic applications, biotechnological and clinical applications. Biodegradable plastic films are used as packaging and antimicrobial. Bio-based products include biodegradable bags, plastic bottles, beverage cups, and cutlery. Different application domains are associated with distinct types of bioplastics, reflecting variations in performance requirements and end-use conditions. Packaging applications predominantly utilize polylactic acid (PLA), starch-based plastics, and cellulose derivatives due to their ease of processing, cost-effectiveness, and acceptable mechanical and barrier properties for short-term use (Siracusa et al. 2008b; Farah et al., 2016; Prabhu and Prashantha, 2018a). In biomedical and clinical applications, materials such as PLA, PHA, and polycaprolactone (PCL) are more frequently employed because of their biocompatibility, controlled degradation behavior, and suitability for tissue engineering and drug delivery (Flieger et al., 2003; Chen, 2009; Yeo et al., 2018). Agricultural and composite applications often rely on starch- and cellulose-based bioplastics reinforced with natural fibers, where biodegradability and economic feasibility are prioritized over long-term durability (Mohanty et al., 2000; Satyanarayana et al., 2009). These trends demonstrate that bioplastics are not a uniform material class; rather, their selection is application-specific and driven by differences in chemical structure, mechanical performance, degradation behavior, and processing compatibility (Lambert and Wagner, 2017; Narancic and O'Connor, 2019). Thus, bioplastics can be a better alternative to petroleum-based plastics to reduce plastic pollution and landfill toxicity and replace conventional plastics in the upcoming years.

3.6. Future Perspective and Limitations

Several polymers have been investigated to produce bioplastic. Several properties govern their usage and non-usage.

Research is moving ahead, but a polymer possessing a few good properties fails on other metrics. The future should further investigate the wonder material possessing petroleum-based plastic properties, except biodegradability. Bibliometric trends indicate that future research in bioplastics should prioritize the development of multi-functional materials that combine mechanical performance, processability, and controlled biodegradability. Packaging applications are expected to remain the primary driver of bioplastics research due to regulatory pressure and high consumption volumes; however, expanding into multi-purpose and durable applications will require improvements in thermal stability, toughness, and moisture resistance. Emerging interest in bio-composites, reinforced bioplastics, and microbial polymers suggests promising pathways to overcome current material limitations. Additionally, greater emphasis on standardized degradation assessment and real-environment performance evaluation will be critical for advancing both scientific understanding and industrial adoption. The study has used only web of science data; standalone data from Scopus could provide additional insight.

4. Conclusion

The growth of the study concerning bioplastics has increased exponentially from 1999 to 2020. This study shows that polylactic acid is the most used material to manufacture bioplastics, and starch is the second most used material, followed by many others. The extrusion and molding processes are the most processes for manufacturing, followed by many others. The mechanical properties have been tested the most, and degradation is the second used test, followed by many others. The applications of bioplastics are widespread in the field of packaging and biomedical engineering. The bibliometric study of the data of 3,802 publications identified the most impactful, collaborative, and cited countries, institutions, authors, journals, and publications from 1999 to 1st January 2021. This information could provide insight to future researchers in choosing areas of their choice at places where focused research with the scientist of the field of research stakes a heavy claim on the future of the bioplastic.

Credit Author Statement. Dhrushi Pansuriya: Formal analysis, Investigation, Methodology, Roles/writing-original draft. Daya Kaul: Conceptualization, Methodology, Supervision, Writing-review and editing. Pravin Kodgire: Supervision, Methodology, Writing-review and editing. Akanksha Nema: Writing-review and editing. Mitali Mistry: Editing.

References

- Abdullah, Z.W. and Dong, Y. (2019). Biodegradable and water-resistant poly(vinyl)alcohol (PVA)/starch (ST)/glycerol (GL)/halloysite nanotube (HNT) nanocomposite films for sustainable food packaging. *Frontiers in Materials*, 6, 58. <https://doi.org/10.3389/fmats.2019.00058>
- Abraham, A., Park, H., Choi, O. and Sang, B.-I. (2021). Anaerobic codigestion of bioplastics as a sustainable mode of waste management with improved energy production—A review. *Bioresource Technology*, 322, 124537. <https://doi.org/10.1016/j.biortech.2020.124537>
- Akinpelu, E.A. and Nchu, F. (2022). A bibliometric analysis of research trends in biodegradation of plastics. *Polymers*, 14(13), 2642. <https://doi.org/10.3390/polym14132642>

- doi.org/10.3390/polym14132642
- Al-Tayyar, N.A., Youssef, A.M. and Al-Hindi, R. (2020). Antimicrobial food packaging based on sustainable Bio-based materials for reducing foodborne Pathogens: A review. *Food Chemistry*, 310, 125-915. <https://doi.org/10.1016/j.foodchem.2019.125915>
- Bankar, R.S. and Lihitkar, S.R. (2019). Science mapping and visualization tools used for bibliometric and scientometric studies: A comparative study. *Journal of Advancements in Library Sciences*, 6(1), 382-394. <https://doi.org/10.37591/joals.v6i1.1807>
- Bátori, V., Åkesson, D., Zamani, A., Taherzadeh, M.J. and Horváth, I.S. (2018). Anaerobic degradation of bioplastics: A review. *Waste Management*, 80, 406-413. <https://doi.org/10.1016/j.wasman.2018.09.040>
- Chavalitpanya, K. and Phattanarudee, S. (2013). Poly (lactic-acid)/polycaprolactone blends compatibilized with block copolymer. *Energy Procedia*, 34, 542-548. <https://doi.org/10.1016/j.egypro.2013.06.783>
- Chen, G.Q. (2009). A microbial polyhydroxyalkanoates (PHA) based bio-and materials industry. *Chemical Society Reviews*, 38(8), 2434-2446. <https://doi.org/10.1039/b812677c>
- Civancik-Uslu, D., Puig, R., Voigt, S., Walter, D. and Fullana-i-Palmer, P. (2019). Improving the production chain with LCA and eco-design: application to cosmetic packaging. *Resources, Conservation and Recycling*, 151, 104475. <https://doi.org/10.1016/j.resconrec.2019.104475>
- Cobo, M.J., López-Herrera, A.G., Herrera-Viedma, E. and Herrera, F. (2011). Science mapping software tools: Review, analysis, and cooperative study among tools. *Journal of the American Society for information Science and Technology*, 62(7), 1382-1402. <https://doi.org/10.1002/asi.21525>
- Cooper, D., Doucet, L. and Pratt, M. (2007). Understanding ‘appropriateness’ in multinational organizations. *Journal of Organizational Behavior: The International Journal of Industrial, Occupational and Organizational Psychology and Behavior*, 28(3), 303-325. <https://doi.org/10.1002/job.440>
- Devadas, V.V., Khoo, K.S., Chia, W.Y., Chew, K.W., Munawaroh, H.S.H., Lam, M.K., Lim, J.W., Ho, Y.-C., Lee, K.T. and Show, P.L. (2021). Algae biopolymer towards sustainable circular economy. *Bioresource Technology*, 325, 124702. <https://doi.org/10.1016/j.biortech.2021.12.4702>
- Edgar, K.J., Buchanan, C.M., Debenham, J.S., Rundquist, P.A., Seiler, B.D., Shelton, M.C. and Tindall, D. (2001). Advances in cellulose ester performance and application. *Progress in Polymer Science*, 26(9), 1605-1688. [https://doi.org/10.1016/S0079-6700\(01\)00027-2](https://doi.org/10.1016/S0079-6700(01)00027-2)
- Farah, S., Anderson, D.G. and Langer, R. (2016). Physical and mechanical properties of PLA, and their functions in widespread applications—A comprehensive review. *Advanced Drug Delivery Reviews*, 107, 367-392. <https://doi.org/10.1016/j.addr.2016.06.012>
- Ferreira, F., Pinheiro, I., Gouveia, R., Thim, G. and Lona, L. (2018). Functionalized cellulose nanocrystals as reinforcement in biodegradable polymer nanocomposites. *Polymer Composites*, 39, E9-E29. <https://doi.org/10.1002/pc.24583>
- Flieger, M., Kantorová, M., Prell, A., Řezanka, T. and Votruba, J. (2003). Biodegradable plastics from renewable sources. *Folia Microbiologica*, 48(1), 27-44. <https://doi.org/10.1007/BF02931273>
- Ghazizadeh, E., Hosseinkhani, S., Oskuee, R., Molaabasi, F. and Jaafari, M. (2018). Sequential or multiplex electrochemical detection of miRs based on the p19 function relative to three sandwiches of different structural hybrids on the liposomal sensor. *Materials Science and Engineering: C*, 92, 703-711. <https://doi.org/10.1016/j.msec.2018.07.006>
- Gill, M. (2014). Bioplastic: A better alternative to plastics. *International Journal of Research in Applied, Natural and Social Sciences*, 2(8), 113-118, ISSN(E): 2321-8851; ISSN(P): 2347-4580
- Hamid, S.S., Wakayama, M., Ichihara, K., Sakurai, K., Ashino, Y., Kadowaki, R., Soga, T. and Tomita, M. (2019). Metabolome profiling of various seaweed species discriminates between brown, red, and green algae. *Planta*, 249(6), 1921-1947. <https://doi.org/10.1007/s00425-019-03134-1>
- Hoorweg, D., Bhada-Tata, P. and Kennedy, C. (2013). Environment: Waste production must peak this century. *Nature*, 502(7473), 615-617. <https://doi.org/10.1038/502615a>
- Hopewell, J., Dvorak, R. and Kosior, E. (2009). Plastics recycling: challenges and opportunities. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 364(1526), 2115-2126. <https://doi.org/10.1098/rstb.2008.0311>
- Jiménez-Rosado, M., Bouroudian, E., Perez-Puyana, V., Guerrero, A. and Romero, A. (2020). Evaluation of different strengthening methods in the mechanical and functional properties of soy protein-based bioplastics. *Journal of Cleaner Production*, 262, 121517. <https://doi.org/10.1007/s11947-012-0835-4>
- Jimenez, A., Fabra, M.J., Talens, P. and Chiralt, A. (2012). Edible and biodegradable starch films: a review. *Food and Bioprocess Technology*, 5(6), 2058-2076. <https://doi.org/10.1016/j.jclepro.2020.12.1517>
- Karamanlioglu, M., Preziosi, R. and Robson, G.D. (2017). Abiotic and biotic environmental degradation of the bioplastic polymer poly (lactic acid): A review. *Polymer Degradation and Stability*, 137, 122-130. <https://doi.org/10.1016/j.polyimdegradstab.2017.01.009>
- Khan, B., Bilal Khan Niazi, M., Samin, G. and Jahan, Z. (2017). Thermoplastic starch: A possible biodegradable food packaging material—A review. *Journal of Food Process Engineering*, 40(3), e12447. <https://doi.org/10.1111/jfpe.12447>
- Khoo, K.S., Lee, S.Y., Ooi, C.W., Fu, X., Miao, X., Ling, T.C. and Show, P.L. (2019). Recent advances in biorefinery of astaxanthin from *Haematococcus pluvialis*. *Bioresource Technology*, 288, 121606. <https://doi.org/10.1016/j.biortech.2019.12.1606>
- Koyande, A.K., Chew, K.W., Rambabu, K., Tao, Y., Chu, D.T. and Show, P.L. (2019). Microalgae: A potential alternative to health supplementation for humans. *Food Science and Human Wellness*, 8(1), 16-24. <https://doi.org/10.1016/j.fshw.2019.03.001>
- Lambert S, Wagner M (2017) Environmental performance of bio-based and biodegradable plastics: The road ahead. *Chemical Society Reviews*, 46, 6855-6871. <https://doi.org/10.1039/C7CS00149E>
- Lebreton, L. and Andrady, A. (2019). Future scenarios of global plastic waste generation and disposal. *Palgrave Communications*, 5(1), 1-11. <https://doi.org/10.1057/s41599-018-0212-7>
- Mandáková, P., Virtová, M., Šíma, P., Beranová, M. and Slípka, J. (2003). Congenitally determined neurodegeneration “Lurcher” induces morphofunctional changes of thymus. *Folia Microbiologica*, 48(3), 394-398. <https://doi.org/10.1007/BF02931373>
- Memon, A., Ithisoponakul, S., Pramoonmak, S., lawsuriyonta, M., Leenoi, D. and Passadee, N. (2011). A development of laminating mulberry paper by biodegradable films. *Energy Procedia*, 9, 598-604. <https://doi.org/10.1016/j.egypro.2011.09.070>
- Mohanty, A., Misra, M. and Drzal, L.T. (2001). Surface modifications of natural fibers and performance of the resulting biocomposites: An overview. *Composite Interfaces*, 8(5), 313-343. <https://doi.org/10.1163/156855401753255422>
- Mohanty, A.K., Misra, M.A. and Hinrichsen, G.I. (2000). Biofibres, biodegradable polymers and biocomposites: An overview. *Macromolecular Materials and Engineering*, 276(1), 1-24. [https://doi.org/10.1002/\(SICI\)1439-2054\(20000301\)276:1<1:AID-AME1>3.0.CO;2-W](https://doi.org/10.1002/(SICI)1439-2054(20000301)276:1<1:AID-AME1>3.0.CO;2-W)
- Moral Muñoz, J.A., Herrera-Viedma, E., Santisteban Espejo, A.L. and Cobo Martín, M.J. (2020). Software tools for conducting bibliometric analysis in science: An up-to-date review. *Profesional de la Información*, 29(1), e290103. <https://doi.org/10.3145/epi.2020.ene.03>
- Nampoothiri, K.M., Nair, N.R. and John, R.P. (2010). An overview of the recent developments in polylactide (PLA) research. *Bioresource Technology*, 101(22), 8493-8501. <https://doi.org/10.1016/j.biortech.2010.05.092>
- Narancic, T. and O’Connor, K.E. (2019). Plastic waste as a global challenge: Are biodegradable plastics the answer to the plastic waste problem? *Microbiology*, 165(2), 129-137. <https://doi.org/10.1099/mic.0.000749>
- Niranjana Prabhu, T. and Prashantha, K. (2018). A review on present

- status and future challenges of starch-based polymer films and their composites in food packaging applications. *Polymer Composites*, 39(7), 2499-2522. <https://doi.org/10.1002/pc.24236>
- Nnolim, N.E. and Nwodo, U.U. (2025). Insight into global bio-based plastics development: A bibliometric analysis-aided assessment of the past decades' research exploit. *Sustainability*, 17(13), 5955. <https://doi.org/10.3390/su17135955>
- Pilla, S. (2011). Engineering applications of bioplastics and biocomposites-An overview. *Handbook of bioplastics and biocomposites engineering applications*, pp 1-15. <https://doi.org/10.1002/9781118203699.ch1>
- Pivsa-Art, W., Fujii, K., Nomura, K., Aso, Y., Ohara, H. and Yamane, H. (2016). The effect of poly (ethylene glycol) as plasticizer in blends of poly (lactic acid) and poly (butylene succinate). *Journal of Applied Polymer Science*, 133(8). <https://doi.org/10.1002/app.43044>
- Reddy, N. and Yang, Y. (2013). Thermoplastic films from plant proteins. *Journal of Applied Polymer Science*, 130(2), 729-738. <https://doi.org/10.1002/app.39481>
- Sangam, S.L. and Mogali, M.S.S. (2012). Mapping and visualization softwares tools: A review. In *Proceedings of the International Conference on Content Management in Networked Environment*, pp 1-9. ISBN: 978-93-82694-03-8.
- Satyanarayana, K.G., Arizaga, G.G. and Wypych, F. (2009). Biodegradable composites based on lignocellulosic fibers—An overview. *Progress in Polymer Science*, 34(9), 982-1021. <https://doi.org/10.1016/j.progpolymsci.2008.12.002>
- Shah, A.A., Hasan, F., Hameed, A. and Ahmed, S. (2008). Biological degradation of plastics: a comprehensive review. *Biotechnology Advances*, 26(3), 246-265. <https://doi.org/10.1016/j.biotechadv.2007.12.005>
- Simó-Cabrera, L., García-Chumillas, S., Hagagy, N., Saddiq, A., Tag, H., Selim, S., AbdElgawad, H., Arribas Agüero, A., Monzó Sánchez, F. and Cánovas, V. (2021). Haloarchaea as cell factories to produce bioplastics. *Marine Drugs*, 19(3), 159. <https://doi.org/10.3390/md19030159>
- Siracusa, V., Rocculi, P., Romani, S. and Dalla Rosa, M. (2008). Biodegradable polymers for food packaging: a review. *Trends in food science & technology*, 19(12), 634-643. <https://doi.org/10.1016/j.tifs.2008.07.003>
- Su, Y., Yang, B., Liu, J., Sun, B., Cao, C., Zou, X., Lutes, R. and He, Z. (2018). Prospects for replacement of some plastics in packaging with lignocellulose materials: A brief review. *BioResources*, 13(2), 4550-4576. <https://doi.org/10.15376/biores.13.2.Su>
- Tang, D.Y.Y., Khoo, K.S., Chew, K.W., Tao, Y., Ho, S.H. and Show, P.L. (2020). Potential utilization of bioproducts from microalgae for the quality enhancement of natural products. *Bioresource Technology*, 304, 122997. <https://doi.org/10.1016/j.biortech.2020.122997>
- Tian, H., Yan, J., Rajulu, A.V., Xiang, A. and Luo, X. (2017). Fabrication and properties of polyvinyl alcohol/starch blend films: Effect of composition and humidity. *International Journal of Biological Macromolecules*, 96, 518-523. <https://doi.org/10.1016/j.ijbiomac.2016.12.067>
- Tibbetts, S.M., Milley, J.E. and Lall, S.P. (2015). Chemical composition and nutritional properties of freshwater and marine microalgal biomass cultured in photobioreactors. *Journal of Applied Phycology*, 27(3), 1109-1119. <https://doi.org/10.1007/s10811-014-0428-x>
- Urbanek, A.K., Rymowicz, W., Strzelecki, M.C., Kociuba, W., Franczak, Ł. and Mirończuk, A.M. (2017). Isolation and characterization of Arctic microorganisms decomposing bioplastics. *AMB Express*, 7(1), 148. <https://doi.org/10.1186/s13568-017-0448-4>
- Urtuvia, V., Villegas, P., González, M. and Seeger, M. (2014). Bacterial production of the biodegradable plastics polyhydroxyalkanoates. *International Journal of Biological Macromolecules*, 70, 208-213. <https://doi.org/10.1016/j.ijbiomac.2014.06.001>
- Wang, X.L., Yang, K.K. and Wang, Y.Z. (2003). Properties of starch blends with biodegradable polymers. *Journal of Macromolecular Science, Part C: Polymer Reviews*, 43(3), 385-409. <https://doi.org/10.1016/j.carbpol.2003.11.007>
- Wang, X., Du, Y. and Liu, H. (2004). Preparation, characterization and antimicrobial activity of chitosan-Zn complex. *Carbohydrate Polymers*, 56(1), 21-26. <https://doi.org/10.1081/MC-120023911>
- Yeo, J.C.C., Muiruri, J.K., Thitsartam, W., Li, Z. and He, C. (2018). Recent advances in the development of biodegradable PHB-based toughening materials: Approaches, advantages and applications. *Materials Science and Engineering: C*, 92, 1092-1116. <https://doi.org/10.1016/j.msec.2017.11.006>
- Zhuang, H., Barth, M.M. and Cisneros-Zevallos, L. (2014). *Innovations in food packaging*, pp. 445-473, Elsevier. <https://doi.org/10.1016/B978-0-12-394601-0.00018>