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FILAMENTOS BIODEGRADÁVEIS PARA IMPRESSÃO 3D: UMA REVISÃO BIBLIOMÉTRICA DE MATERIAIS, TENDÊNCIAS E PERSPETIVAS DE SUSTENTABILIDADE

BIODEGRADABLE FILAMENTS FOR 3D PRINTING: A BIBLIOMETRIC REVIEW OF MATERIALS, TRENDS, AND SUSTAINABILITY PERSPECTIVES

FILAMENTOS BIODEGRADABLES PARA IMPRESIÓN 3D: UNA REVISIÓN BIBLIOMÉTRICA DE MATERIALES, TENDENCIAS Y PERSPECTIVAS DE SOSTENIBILIDAD

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RESUMO

Introdução: A crescente preocupação com a sustentabilidade tem estimulado a investigação de polímeros biodegradáveis para aplicações em impressão 3D. Apesar do seu uso generalizado, os termoplásticos convencionais suscitam preocupações ambientais devido à sua elevada resistência à degradação ambiental.

Objetivo: Explorar a literatura existente sobre polímeros biodegradáveis utilizados na produção de filamentos para impressão 3D, com enfoque nas suas propriedades, condições de processamento e comportamento de biodegradação.

Métodos: Foi realizada uma análise bibliométrica com base em estudos publicados nas bases de dados Scopus e Web of Science, com o intuito de obter uma visão aprofundada sobre o desenvolvimento e as tendências nesta área. A análise foi efetuada com recurso ao software VOSviewer e ao pacote Bibliometrix em R, permitindo identificar tendências de investigação, principais autores e tópicos relevantes. Foi também aplicada a metodologia PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses), assegurando uma seleção sistemática e transparente dos estudos.

Resultados: Os resultados revelam que os principais tópicos de investigação são o ácido polilático (PLA), os compósitos e as propriedades mecânicas, refletindo esforços no sentido da melhoria dos materiais biodegradáveis. Entre as palavras-chave mais utilizadas destacam-se impressão 3D, fabrico aditivo e sustentabilidade, enquanto temas como economia circular e avaliação do ciclo de vida têm ganho crescente de atenção. Os autores mais relevantes nesta área no período (2022-2024) e artigos em análise incluem Mansingh B., Patti A., Raghunathan V. e Subramani R. Verifica-se também um interesse crescente em biopolímeros alternativos, como os poli-hidroxialcanoatos (PHB), bem como na utilização de resíduos para a produção de filamentos ecológicos.

Conclusão: Estes resultados salientam o papel dos filamentos biodegradáveis na promoção de uma impressão 3D mais sustentável. O estudo fornece uma visão abrangente do estado atual da investigação e destaca o potencial dos materiais biodegradáveis para impulsionar tecnologias de fabrico aditivo mais sustentável.

Palavras-chave: filamentos biodegradáveis; impressão 3D; polímeros biodegradáveis; biodegradação; sustentabilidade

ABSTRACT

Introduction: The growing concern with sustainability has stimulated research into biodegradable polymers for 3D printing applications. Despite their widespread use, conventional thermoplastics raise environmental problems due to their high resistance to environmental degradation.

Objective: To explore the existing literature on biodegradable polymers used in filament production for 3D printing, focusing on their properties, processing conditions, and biodegradation behavior.

Methods: A bibliometric analysis was conducted using studies published in the Scopus and Web of Science databases to gain insights into the development and trends in this field. The analysis was performed using VOSviewer and the Bibliometrix package in R, allowing for the identification of research trends, key contributors, and relevant topics. The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology was also applied to ensure a systematic and transparent selection of studies.

Results: The results reveal that the main research topics are polylactic acid (PLA), composites, and mechanical properties, reflecting efforts to improve biodegradable materials. Among the most frequently used keywords are 3D printing, additive manufacturing, and sustainability, whilst topics such as the circular economy and life-cycle assessment are gaining increasing attention. The most prominent authors in this field during the period (2022–2024) and the articles under review include Mansingh B., Patti A., Raghunathan V., and Subramani R. There is also growing interest in alternative biopolymers, such as polyhydroxyalkanoates (PHB), as well as in the use of waste for the production of eco-friendly filaments.

Conclusion: These findings highlight the role of biodegradable filaments in promoting more sustainable 3D printing. The study provides a comprehensive overview of the current state of research and highlights the potential of biodegradable materials to drive more sustainable additive manufacturing technologies.

Keywords: biodegradable filaments; 3D printing; biodegradable polymers; biodegradation; biodegradation

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RESUMEN

Introducción: La creciente preocupación por la sostenibilidad ha impulsado la investigación de polímeros biodegradables para aplicaciones en impresión 3D. A pesar de su uso generalizado, los termoplásticos convencionales generan preocupaciones medioambientales debido a su alta resistencia a la degradación en el entorno.
Objetivo: Explorar la literatura existente sobre los polímeros biodegradables utilizados en la producción de filamentos para impresión 3D, centrándose en sus propiedades, condiciones de procesamiento y comportamiento de biodegradación.
Métodos: Se realizó un análisis bibliométrico utilizando estudios publicados en las bases de datos Scopus y Web of Science, con el fin de obtener una visión detallada sobre el desarrollo y las tendencias en este campo. El análisis se llevó a cabo mediante el software VOSviewer y el paquete Bibliometrix en R, lo que permitió identificar tendencias de investigación, autores clave y temas relevantes. También se aplicó la metodología PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) para garantizar una selección sistemática y transparente de los estudios.
Resultados: Los resultados revelan que los principales temas de investigación son el ácido poliláctico (PLA), los compuestos y las propiedades mecánicas, lo que refleja los esfuerzos por mejorar los materiales biodegradables. Entre las palabras clave más utilizadas destacan la impresión 3D, la fabricación aditiva y la sostenibilidad, mientras que temas como la economía circular y la evaluación del ciclo de vida están ganando cada vez más atención. Entre los autores más relevantes en este ámbito durante el periodo (2022-2024) y los artículos analizados se encuentran Mansingh B., Patti A., Raghunathan V. y Subramani R. También se observa un interés creciente por los biopolímeros alternativos, como los polihidroxialcanoatos (PHB), así como por el uso de residuos para la producción de filamentos ecológicos.
Conclusión: Estos resultados ponen de relieve el papel de los filamentos biodegradables en la promoción de una impresión 3D más sostenible. El estudio ofrece una visión global del estado actual de la investigación y destaca el potencial de los materiales biodegradables para impulsar tecnologías de fabricación aditiva más sostenibles.

Palabras clave: filamentos biodegradables; impresión 3D; polímeros biodegradables; biodegradación; sostenibilidad

INTRODUCTION

3D printing, also known as additive manufacturing, has become a promising technology across various fields. However, the growing demand for sustainable printing materials raises environmental concerns, particularly regarding the disposal of conventional polymers. In this context, biodegradable filaments may be an excellent option and are gaining attention as a more environmentally friendly alternative (Bher et al., 2022).

Bio-based biodegradable plastics can be recycled or incinerated similarly to conventional plastics. However, they are not widely recycled because they are considered contaminants in the current recycling system (Khalid et al., 2022). These materials are primarily designed to break down under specific conditions, usually in controlled environments such as industrial composting facilities (Polman et al., 2021). Unless specifically engineered to biodegrade in particular environments, such as water or soil, they will either not degrade or degrade very slowly under such conditions (Andanje et al., 2023).

Despite technological advances, uncertainties remain regarding the actual biodegradability of these materials. Many filaments labelled “biodegradable” may contain only a fraction of sustainable components, often mixed with synthetic polymers that hinder complete decomposition. Therefore, this study aims to investigate whether 100% biodegradable filaments are currently available on the market and, if not, what percentage of biodegradable material is present in their composition.

In addition to the technical analysis of the materials, a bibliometric study will be conducted to assess the current state of the art regarding biodegradable filaments for 3D printing. This approach will help identify the quantity and type of existing publications and the leading researchers and institutions involved, and map out research trends and gaps in the scientific literature. The goal is to contribute to a better understanding of these materials' viability and environmental impact, providing a foundation for future research and innovation in the field.

1. LITERATURE REVIEW

1.1. Creating a more sustainable future

Sustainability is key to balancing economic development, environmental preservation, and social well-being. It refers to the ability to meet present needs without compromising future generations' resources and living conditions. In ecological terms, sustainability is directly linked to preserving ecosystems, reducing pollutant emissions, and the conscious use of natural resources. Practices such as recycling, using renewable energy, and water conservation contribute to the planet's sustainability (Maynard et al., 2020; Hajek et al., 2023).

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One of the most significant sustainability challenges is polymer management, a material widely used in modern society (Helm et al., 2023). Petroleum-based and highly durable plastics cause substantial environmental impacts when improperly discarded. Plastic pollution affects marine life, contaminates soil, and can take hundreds of years to decompose. To mitigate these impacts, it is essential to adopt practices such as polymer recycling, developing biodegradable polymers, and implementing public policies that support the circular economy (Prata et al., 2019; Kumar et al., 2024). The search for more sustainable materials and raising awareness about responsible consumption also play a key role in reducing the environmental impact of plastics (Kumar et al., 2024).

Raising public awareness and the commitment of governments, companies, and individuals are crucial to achieving a more sustainable future. Small daily actions, such as separating recyclable waste, consuming responsibly, and supporting ecological initiatives, can make a big difference in preserving the environment and improving the quality of life. Investing in sustainability is a necessity and a collective responsibility to ensure a healthier and more balanced planet for future generations (Damico et al., 2022; Helm et al., 2023).

1.2. Biodegradation of polymers

Polymer biodegradation is the process by which polymers are broken down by microorganisms and environmental factors (Bher et al., 2022). A combination of internal and external factors influences this process. Internal factors are related to the chemical composition of the polymer itself, such as its molecular weight, chemical structure, and the presence of additives or modifiers, all of which can significantly affect the polymer’s susceptibility to degradation. As for external factors, environmental conditions such as temperature, humidity, and the presence of specific microorganisms or enzymes capable of metabolizing the polymer are critical in determining the degradation process. These internal and external elements play a crucial role in influencing the rate and extent of polymer biodegradation. Biodegradability reduces global waste by aiding the breakdown of collected materials (La Fuente et al., 2023; Dananjaya et al., 2024).

Polymer biodegradation occurs when microorganisms and other environmental factors deteriorate the material. This process is influenced by internal factors, such as the chemical composition of the polymer, and external ones, including temperature, humidity, and the presence of microorganisms (Folino et al., 2020; Bher et al., 2022). Biodegradation occurs in several stages, typically following the sequence: deterioration, biological fragmentation, assimilation, and mineralization. During deterioration, the polymer undergoes physical changes, while in the biological fragmentation stage, microorganisms break the polymer into smaller molecules. Mineralization is the final stage, in which the organic material is converted into minerals, thus completing the degradation cycle (Silva et al., 2023).

1.2.1. Types of biodegradation

There are three main types of biodegradation, which vary depending on the environment in which they occur, influencing both the speed and the outcomes of the process. These include soil biodegradation, compost biodegradation, and aquatic system biodegradation. In each of these cases, microorganisms act on bioplastics, breaking them down into simpler substances, thereby contributing to environmental preservation (Andanje et al., 2023). Table I presents the main types of biodegradation and the factors that influence them.

Table 1 - Different types of bioplastic biodegradation and their main influencing factors

Type of Biodegradation	Description
Soil Biodegradation	Occurs when bioplastics are discarded directly into the soil, where microorganisms such as bacteria and fungi promote their decomposition. These organisms produce enzymes that break down the polymer chains, using bioplastic as a carbon and energy source. The process is influenced by temperature, humidity, and soil composition (Folino et al., 2020; Qin et al., 2021).
Compost Biodegradation	It takes place under controlled composting conditions in the presence of oxygen, heat, and moisture. Microorganisms convert the bioplastic into carbon dioxide, water, and humus, a nutrient-rich material that can be used to fertilize the soil. This method helps reduce solid waste and supports environmental sustainability (Bandini et al., 2020; Folino et al., 2020).
Aquatic Biodegradation	Occurs when bioplastics come into contact with aquatic environments such as rivers, lakes, or oceans. Aquatic microorganisms adhere to the surface of the bioplastic and release enzymes that break down its structure. The degradation rate in water is generally slower than in soil or compost and depends on factors such as water temperature, dissolved oxygen, and nutrient availability. Incomplete degradation may form microplastics and nanoplastics, impacting aquatic ecosystems (Phosri et al., 2022; Andanje et al., 2023).

1.3. Biodegradable polymers

Biodegradable polymers can offer a solution to the current plastic waste crisis, as they naturally degrade in the environment without the need for human intervention. Their primary purpose is to reduce pollution and promote sustainability. These polymers present several advantages, especially their ability to naturally break down over time (Manfra et al., 2021; Andanje et al., 2023).

Biodegradable filaments are a sustainable alternative to traditional plastics for 3D printing, as they are designed to decompose naturally without leaving harmful residues (Khilji et al., 2023). These filaments can be made from natural polymers such as cellulose

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and starch, synthetic biopolymers that retain good mechanical strength and print quality (Morales et al., 2021; Cakir Yigit & Karagoz, 2023).

Some of these materials are compostable, breaking down quickly under suitable conditions, while others degrade more slowly but eventually decompose in the environment. Their use helps reduce the environmental impact of additive manufacturing, making 3D printing a more sustainable option for various applications (Andanje et al., 2023).

Additionally, recycling strategies for biodegradable polymers such as PLA have been proposed to further reduce environmental impacts. Guimarães et al. (2026) demonstrated the feasibility of converting 3D printing waste into new filaments using a custom-designed extrusion system, highlighting the potential of distributed recycling in additive manufacturing. Thermal processing techniques may also alter the semicrystalline structure of polymers (Guimarães et al., 2025a).

Table II presents some examples of biodegradable polymers, highlighting their main characteristics and applications.

Table 2 - Biodegradable polymer filaments are used in 3D printers and their main practical applications

Biodegradable Polymers	Polymeriz method	Ext. temp. (˚C)	Properties	Characteristics	Functions	Technology Applied	References
PLA (Polylactic Acid)	Condensation polymerization, lactide ring-opening	160–222	High strength and toughness	Biodegradable, produced from renewable sources (corn, sugarcane). Good processability for 3D printing, but limited mechanical and thermal resistance. Degrades better under industrial composting conditions.	Packaging, medical devices, 3D printing.	FDM, SLS	(Raj et al., 2018; Dananjaya et al., 2024)
PHA (Polyhydroxy alkanoates)	Bacterial fermentation	160	High stiffness, UV stability	Produced by bacteria, with biodegradability in soil and water. High cost and variability in properties hinder large-scale adoption. Copolymers like PHBV are more flexible.	Packaging, medical devices.	FDM, SLS, BJ	(Mehrpouya et al., 2021; Dananjaya et al., 2024)
PCL (Polycaprolac tone)	Ring-opening polymerization	Until 120	High strength, biocompati bility	Semicrystalline, flexible polymer with good chemical resistance. Slow biodegradation, suitable for biomedical applications. Easy to process but has limited mechanical strength.	Biomedical implants, controlled drug release.	FDM, SLA	(Gharibshahian et al., 2023; Popescu et al., 2023; Dananjaya et al., 2024)
PBS (Polybutylene Succinate)	Polycondensati on	160–200	Strong barrier properties	Good mechanical and thermal resistance. Biodegradable in natural environments and industrial composting. High production cost compared to petroleum-based plastics.	Packaging, disposable utensils.	FDM, SLS	(Dönitz et al., 2023; Dananjaya et al., 2024)
PGA (Polyglycolic Acid)	Condensation and ring-opening polymerization	220	Excellent gas barrier, high strength	High mechanical strength and biodegradable. Mainly used in the biomedical industry. High moisture absorption and high cost limit applications.	Absorbable sutures, biomedical.	FDM, SLA	(Kundak & Bilisik, 2023; Dananjaya et al., 2024)
PBAT (Polybutylene Adipate-co-Terephthalat e)	Condensation polymerization	140–170	Biodegrada bilit, flexibility	Flexible, has good mechanical properties, and is used in bags and agricultural films. Although biodegradable, it contains petroleum-derived terephthalic acid. Degrades better under industrial composting.	Shopping bags, garbage bags, cutlery, and mulch film.	FDM, BJ	(Sciancalepore et al., 2022; Ulbrich et al., 2022; Dananjaya et al., 2024)

Note: FDM - Fused Deposition Modelling; SLS – Selective Laser Sintering; SLA – Stereolithography; BJ – Binder Jetting.

1.4. 3D Printers for biodegradable filaments

Most 3D printers available on the market are compatible with biodegradable filaments, such as the polymers listed in Table II. As shown, most of these polymers have printing temperatures that fall within the operational range of commonly available 3D printers, typically between 140°C and 250°C, which aligns with the specifications of most conventional equipment (Ceylan Engin et al., 2024). However, specific printer characteristics can influence the quality of prints using biodegradable filaments. These printers must operate within an appropriate temperature range for the nozzle and the build plate, ensuring proper fusion and adhesion without compromising material integrity (Haryńska et al., 2021; Dananjaya et al., 2024). The build platform surface

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should offer good adhesion, reducing the need for high bed temperatures. Adequate ventilation systems help prevent warping and improve surface finish. At the same time, stainless steel or hardened steel nozzles are recommended for filaments with natural additives such as wood or bamboo, which also possess biodegradable properties (Tlegenov et al., 2018; Andanje et al., 2023). An efficient cooling system is also essential to ensure proper finish and avoid deformation (Saleh et al., 2021). Features such as filament runout sensors and remote monitoring tools reduce material waste, making printing more sustainable (Kazhymurat et al., 2022).

2. METHODS

2.1. Data

This study applies a bibliometric approach to analyze the impact of research trends and collaborations on developing biodegradable filaments, polymeric materials, and 3D printing of biodegradable materials. Using the Scopus and Web of Science databases, relevant studies were identified and analyzed with VOSviewer (1.6.18) and Bibliometrix R, enabling the visualization of research trends and interconnections. These tools facilitate bibliometric mapping, even for extensive datasets (Aria & Cuccurullo, 2017; Van & Waltman, 2018). A bibliometric analysis was conducted to identify the most relevant and recent studies, ensuring a solid theoretical foundation.

2.2. Type of Study

The bibliometric analysis process, used by Guimarães et al. (2025b), follows a structured sequence: definition of research objectives, database selection, data filtering and collection, application of bibliometric analysis using specialized software and interpretation of results. The flowchart, as illustrated in Figure 1, visually represents this methodology, detailing each step, from data acquisition to identifying key authors and research trends.

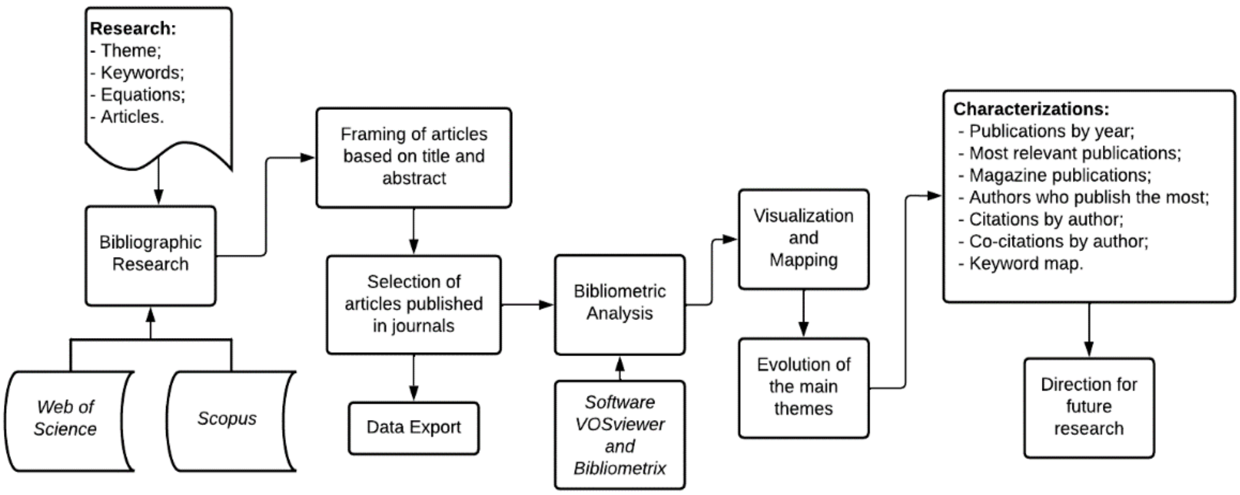

Figure 1 - Flowchart of the methodology used for research and bibliometric analysis (Guimarães et al., 2025c)

As previously mentioned, the study used Scopus and Web of Science as primary databases, selecting relevant keywords to compile a comprehensive dataset, as illustrated in Table III. Bibliometric analysis was conducted using VOSviewer and Bibliometrix R in R Studio, with a methodological flowchart adapted from Donthu et al. (2021). Furthermore, the PRISMA-ScR framework (Tricco et al., 2018) was integrated to ensure a systematic review process.

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Table 3 - The PRISMA-ScR flowchart bibliometric analysis procedure

Step 1 - Defining the aims and scope of the bibliometric study						
Comprehensive overview of research trends, productivity, and collaborations to identify progress and data in biodegradable filaments, biodegradable polymeric materials, and 3D printing of biodegradable materials, assessing their maturity level. RQ1. How is scientific productivity progressing in the field of biodegradable filaments, biodegradable polymeric materials, and 3D printing of biodegradable materials? RQ2. How is the research collaboration network structured in this field? RQ3. What are the emerging research trends in this area?						
Step 2 - Choosing the techniques for bibliometric analysis						
Scientific databases: Web of Science and Scopus (2022-2024); **Bibliometric mapping software:** VOSviewer and Bibliometrix						
Step 3 - Collecting the data for bibliometric analysis **Keywords (*Web of Science*)**						
Search 1	**TS="3D printing"** OR TS="Additive manufacturing" OR TS="Material extrusion" OR TS="Fused deposition modeling" OR TS="FDM"	AND	**TS="Biodegradable filament"** OR TS="Biodegradable polymer filament" OR TS="Biodegradable 3D printing filament" OR TS="Poly(lactic acid)" OR TS="PLA" OR TS="Polyhydroxyalkanoates" OR TS="PHA" OR TS="Polycaprolactone" OR TS="PCL" OR TS="Starch-based filament" OR TS="Natural fiber composite filament" OR TS="Renewable polymer filament" OR TS="Biofilament"	AND	**TS="Sustainability"** OR TS="Circular economy" OR TS="Environmental impact" OR TS="Waste reduction" OR TS="Polymer recycling" OR TS="Green materials" OR TS="Eco-friendly materials" OR TS="Life cycle assessment" OR TS="LCA"	**Results** **175**
Keywords (*Scopus*)						
Search 1	**TITLE-ABS-KEY "3D printing"** OR "Additive manufacturing" OR "Material extrusion" OR "Fused deposition modeling" OR "FDM"	AND	**TITLE-ABS-KEY "Biodegradable filament"** OR "Biodegradable polymer filament" OR "Biodegradable 3D printing filament" OR "Poly(lactic acid)" OR "PLA" OR "Polyhydroxyalkanoates" OR "PHA" OR "Polycaprolactone" OR "PCL" OR "Starch-based filament" OR "Natural fiber composite filament" OR "Renewable polymer filament" OR "Biofilament"	AND	**TITLE-ABS-KEY "Sustainability"** OR "Circular economy" OR "Environmental impact" OR "Waste reduction" OR "Polymer recycling" OR "Green materials" OR "Eco-friendly materials" OR "Life cycle assessment" OR "LCA"	**Results** **187**
Step 4 - PRISMA-ScR flow diagram					**WoS**	**Scopus**
Identification	Registration of all fields obtained by the search in the database. Total articles identified.				175 362	187
Screening	Total articles after applying the inclusion and exclusion criteria.				208	
Eligibility	Deletion of duplicate articles Deletion of articles manually by title, abstract and keywords.				154 141	
Included	Included in the analysis.				67	
Overall	Final sample.				**67**	
Step 5 - Running the bibliometric analysis						
Performance analysis	Summarizing the performance of prolific research indicators such as number of publications and citations; and publication rate by journal, research area, author, affiliation and country.					
Scientific mapping	Visualization of intellectual structure using citation and co-authorship analysis and research themes and topics using co-citation analysis, bibliographic coupling and co-occurrence analysis.					
Step 6 - Suggestions and implications for future investigations						
Step 7 - Conclusions						

This bibliometric analysis followed a structured seven-step methodology to ensure a systematic and transparent review process. Initially, the objectives and scope of the study were clearly defined, focusing on the use of biodegradable filaments in 3D printing. Bibliometric analysis techniques were then selected using VOSviewer and the Bibliometrix R package. Using refined keyword combinations, data were collected from two large databases Web of Science and Scopus. In Scopus, 187 documents were initially

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retrieved, and in Web of Science, 175, of which 67 articles were selected after applying inclusion criteria based on title, abstract, and relevance of keywords. These articles were further assessed using the PRISMA-ScR flow diagram, which helped ensure methodological rigor and traceability throughout the selection process. The analysis focused on identifying the most relevant publications, authors, keywords and research areas. The approach not only reinforced the contribution of this study to understanding developments in sustainable 3D printing but also guided future investigations by highlighting emerging themes and existing research gaps.

3. RESULTS

3.1. Bibliometric analysis

This section provides a bibliometric analysis of the impact of research developments in biodegradable filaments, biodegradable polymeric materials, and 3D printing of biodegradable materials. Key research trends and influential contributors were identified through co-citation mapping, co-occurrence analysis, and citation metrics. The study is based on 67 selected articles, offering data on the evolution and academic relevance of this field.

3.1.1. Annual scientific production vs. average citations per year

Figure 2 shows the evolution of annual scientific production and the average number of citations per article between 2022 and the end of 2024. A gradual increase in the number of publications is observed from 2022 to 2024, reaching a peak in 2024 with more than 30 articles. In contrast, the average number of citations per article shows a decreasing trend; this decline is consistent with the time required for the most recent articles to be cited, reflecting the temporal impact on the accumulation of citations.

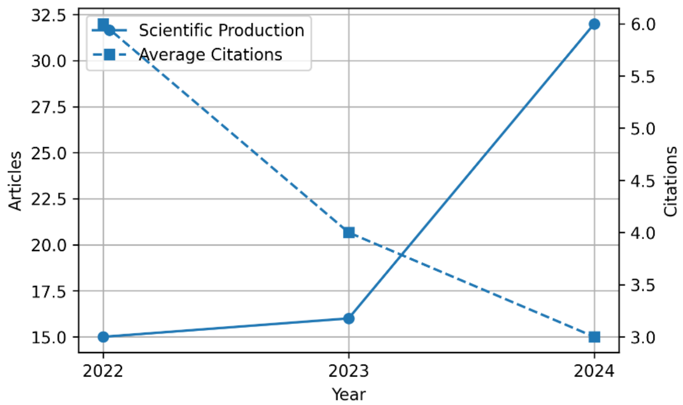

Figure 2 - Evolution of annual scientific production and average citations per year from 2022 to 2024

3.1.2. Distribution of the most cited publications by countries

This subsection examines the distribution of scientific production by country. Figure 3 illustrates that India and Italy are the leading contributors, with more than 21 documents published. Other countries with significant scientific output (6 to 20 documents) include the United States, China, Australia, and the United Kingdom. Several other nations, such as Brazil, Turkey, Saudi Arabia, and South Korea, are also active in the field, contributing between 1 and 5 documents. This global distribution highlights the widespread research interest in biodegradable filaments and 3D printing technologies.

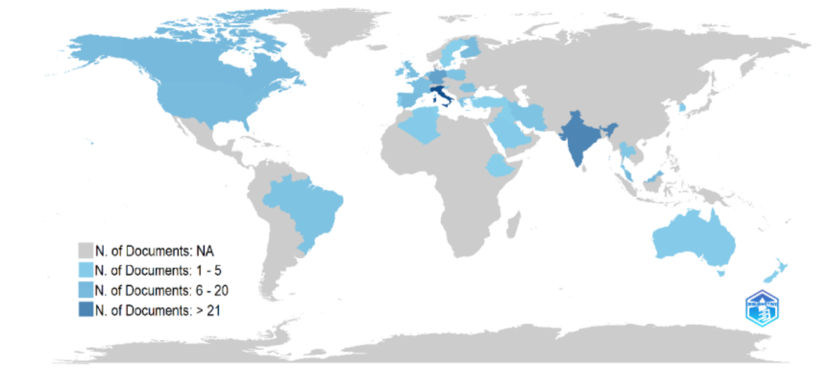

Figure 3 - Geographical distribution of scientific production by country

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3.1.3. Type of journal

Regarding the main journals publishing on biodegradable filaments for use in 3D printers, Figure 4 shows that the journal Polymers leads with the largest number of articles published on the topic, surpassing 17 publications. This is followed by Lecture Notes in Mechanical Engineering, with about nine articles, and Applied Chemical Engineering and The International Journal of Advanced Manufacturing Technology, each with about five articles.

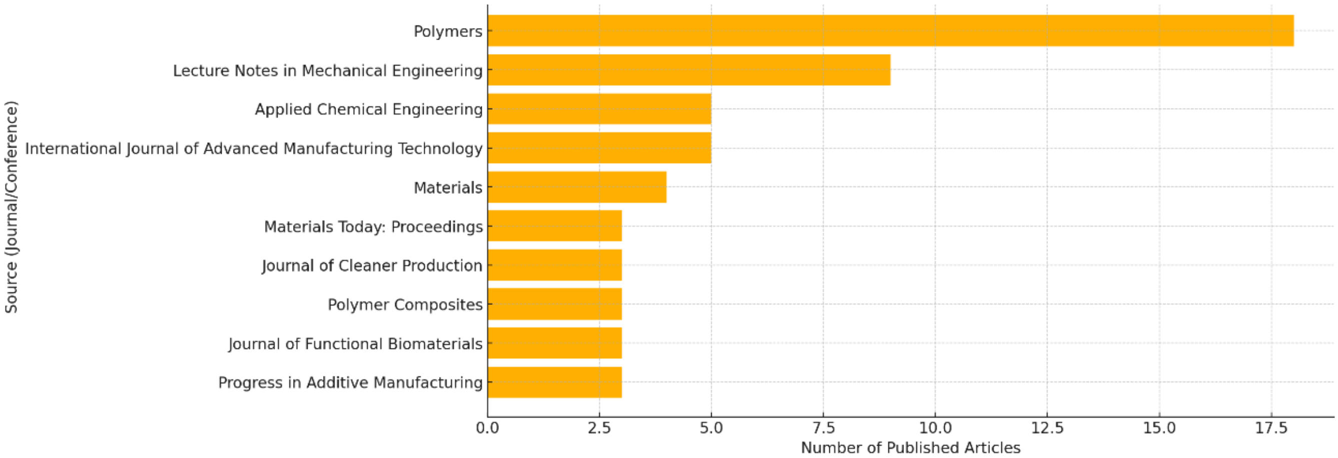

Figure 4 - Top journals publishing on biodegradable filaments for 3D printing

Other relevant journals include Materials, Materials Today: Proceedings, Journal of Cleaner Production, Polymer Composites, Journal of Functional Biomaterials, and Progress in Additive Manufacturing, all contributing between 3 and 4 articles each.
This distribution highlights the interdisciplinary nature of the topic, involving materials science, chemical engineering, biomaterials, and sustainable manufacturing. It also reflects a strong presence in journals focusing on polymers and emerging manufacturing technologies.

3.1.4. Most relevant publications in the last few years and most relevant authors

This subsection highlights the most influential articles published recently on biodegradable filaments for 3D printing. The selection was based on citation analysis, as summarised in Table IV, ensuring that the studies reviewed align with the present work's scope and objectives.

Table 4 - Ranking of the most influential articles on biodegradable filaments for additive manufacturing

Ranking	Author	Title	Year	Citation
1	Krapež Tomec & Kariž (2022)	Use of wood in additive manufacturing: review and future prospects.	2022	54
2	Manoj & Ch (2022)	Biodegradable filament for three-dimensional printing process: a review.	2022	43
3	Cañado et al. (2022)	3D printing to enable the reuse of marine plastic waste with reduced environmental impacts.	2022	41
4	Fico et al. (2022)	Sustainable polymer composites manufacturing through 3D printing technologies by using recycled polymer and filler.	2022	39
5	Subramani et al. (2024)	Exploring the use of biodegradable polymer materials in sustainable 3D printing.	2024	37
6	Raghunathan et al. (2024)	Development of fiber-reinforced polylactic acid filaments using untreated/silane-treated fibers for additive manufacturing.	2024	34
7	Mansingh et al. (2022)	Comprehensive characterization of raw and treated pineapple leaf fiber/polylactic acid green composites manufactured by 3D printing technique.	2022	29
8	Choe et al. (2022)	Biodegradation of 3D-printed biodegradable/non-biodegradable plastic blends.	2022	27
9	Patti et al. (2022)	Recovery of waste material from biobags: 3D printing process and thermo-mechanical characteristics in comparison to virgin and composite matrices.	2022	25
10	Mansingh et al. (2023)	Characterization and performance of additive manufactured novel bio-waste polylactic acid eco-friendly composites.	2023	22
11	Sasse et al. (2022)	Investigation of recycled and coextruded PLA filament for additive manufacturing.	2022	20
12	Palaniyappan et al. (2024)	Preparation and performance evaluation of 3D printed poly lactic acid composites reinforced with silane functionalized walnut shell for food packaging applications.	2024	18
13	Abdulrhman et al. (2022)	Routes towards manufacturing biodegradable electronics with polycaprolactone (PCL) via direct light writing and electroless plating.	2022	18
14	Żur-Pińska et al. (2023)	Smart and sustainable: exploring the future of PHAS biopolymers for 3D printing in tissue engineering.	2023	17
15	Pecorini et al. (2022)	Additive manufacturing of poly(3-hydroxybutyrate-co-3-hydroxyvalerate)/poly(d,l-lactide-co-glycolide) biphasic scaffolds for bone tissue regeneration.	2022	17

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The publication with the highest number of citations is by Krapež Tomec & Kariž (2022), which reviews the use of wood in additive manufacturing, demonstrating growing interest in renewable, bio-based materials (Polymers, 54 citations). This is followed by the review by Manoj & Ch (2022), focused explicitly on biodegradable filaments for 3D printing (Engineered Science, 43 citations), and Cañado et al. (2022), who discuss the reuse of marine plastic waste through 3D printing to reduce environmental impacts (Journal of Industrial Ecology, 41 citations).

Other highly cited studies include the development of sustainable polymer composites using recycled fillers (Fico et al., 2022), exploration of biodegradable polymer materials (Subramani et al., 2024), and reinforced PLA filaments with natural fibres (Raghunathan et al., 2024). These works reflect key trends such as material circularity, fiber reinforcement, and biopolymer-based functionality for additive manufacturing.

Together, these articles underscore the increasing scientific and industrial relevance of biodegradable materials in the context of sustainable 3D printing. The growing citation numbers indicate that the research community actively engages with these developments, particularly in waste valorization, composite formulation, and environmentally friendly manufacturing techniques.

3.1.5. Analysis and thematic perspective of the authors who published the most

The growing concern with sustainability has encouraged the development of biodegradable filaments for 3D printing. Polylactic acid (PLA) is the most widely studied material, often combined with natural fibers such as pineapple leaf, walnut shell, or other biodegradable polymers like PHB to improve strength and degradability. Mansingh et al. (2023) and Raghunathan et al. (2024) show that the chemical treatment of natural fibers enhances matrix–fiber adhesion, improving the performance of the composites. Subramani et al. (2024) and Fico et al. (2022) highlight the role of the circular economy, promoting the use of natural and industrial waste as fillers in sustainable filaments. Beltrán et al. (2021) and Patti et al. (2022) demonstrate that PLA can be recycled after use while maintaining acceptable properties, reinforcing its reuse potential.

There is also growing interest in alternatives to PLA, such as polyhydroxyalkanoates (PHA), which offer good biocompatibility and are suitable for biomedical applications, as discussed by Żur-Pińska et al. (2023). Choe et al. (2022) analyze mixtures of biodegradable and non-biodegradable polymers, concluding that not all are compostable, with the PLA/PHB combination performing best. Patti et al. (2022) further explore the reuse of biodegradable biobag waste for 3D printing applications, confirming its suitability when compared to virgin PLA and composite blends. In addition, Fico et al. (2022) review polymer composites in FFF technology and emphasize integrating recycled materials and natural fibers to improve mechanical performance and sustainability.

Life cycle assessment (LCA) is increasingly applied to evaluate environmental performance. Cañado et al. (2022) demonstrate that the reuse of marine plastic waste in 3D printing significantly lowers carbon emissions, especially when using biodegradable polymers like PHB. Patti et al. (2022) also show that recycled PLA reduces environmental impact while maintaining sufficient mechanical properties for low-demand applications.

Overall, these studies confirm that biodegradable filaments are a promising solution, offering both strong technical properties and environmental benefits. They support the shift towards circular and bio-based manufacturing systems and provide a solid foundation for future research into renewable, recyclable, and sustainable materials for 3D printing.

3.1.6. Keyword co-occurrences analysis

Co-occurrence analysis was performed using VOSviewer, considering only keywords that appeared at least five times. Of the 540 keywords analyzed, 24 met this limit and were included in the map. Figure 5 shows how these keywords are connected based on their joint appearance in articles, allowing for the identification of key topics and search trends.

Terms such as “3D printing”, “additive manufacturing”, “PLA”, “polylactic acid”, “composites”, “mechanical properties”, and “sustainability” stand out for their strong links with other keywords, reflecting the topics most frequently addressed in this field. There is also growing interest in sustainability-related issues such as “biodegradation”, “circular economy”, “waste”, and “fused filament manufacturing”.

The colour scale in the graph represents the average year of publication: shades of blue and purple refer to older studies (before 2023), while shades of green and yellow correspond to more recent ones (after 2023). This shows that sustainability and material reuse topics have gained more prominence in recent research.

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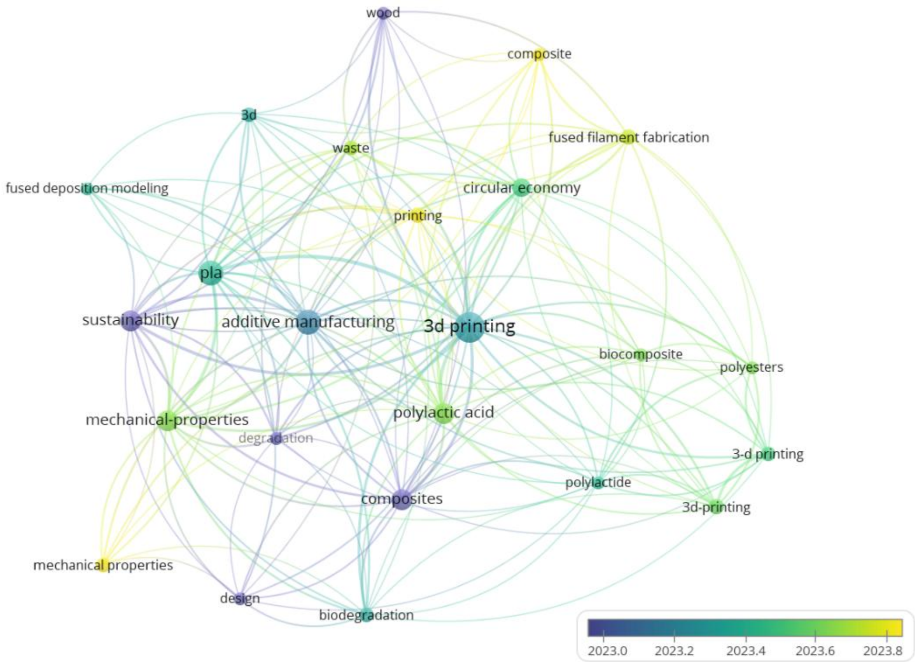

Figure 5 - Keyword co-occurrence map in biodegradable 3D printing research

The thematic map in Figure 6, generated through keyword co-occurrence analysis by the Bibliometrix R package software, shows that the most developed and central research topics in biodegradable materials for 3D printing are PLA, composites, and mechanical properties, classified as Driving Themes. They represent the core of current research, demonstrating technical maturity and strong links with other areas. The circular economy and plasticizers appear as Core Themes, which means they are relevant but still under development. Meanwhile, wood, DSC, and natural fibers fall into Emerging or Declining Themes, indicating growing or underexplored areas. Finally, subjects such as scanning electron microscopy, polymer chemistry, and environmental impact are categorized as niche topics, which are technically developed but less integrated into the main research domain.

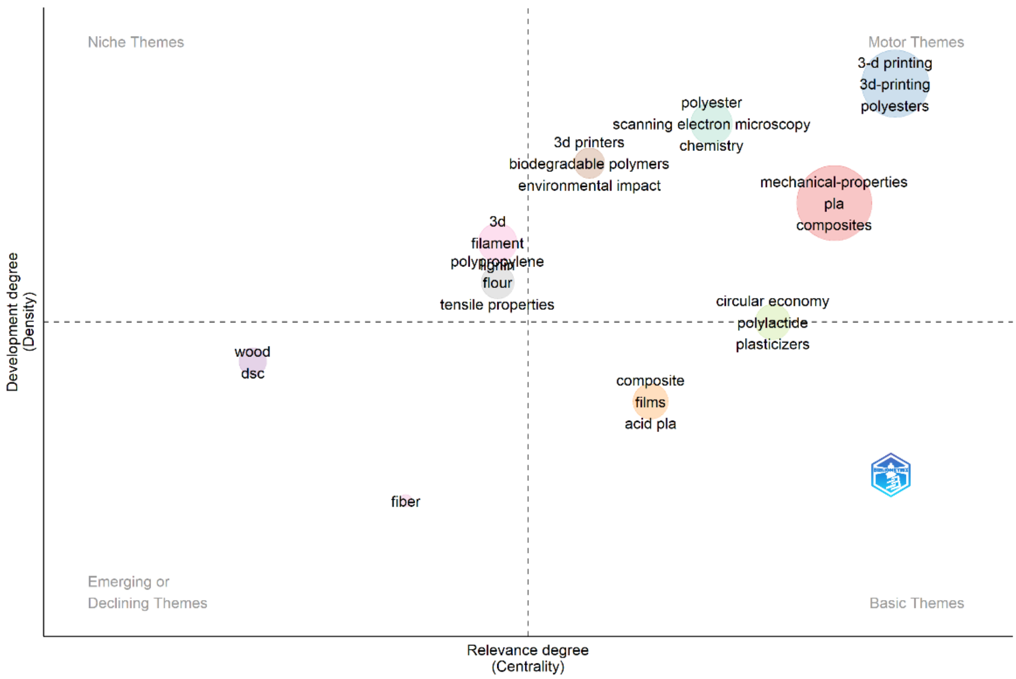

Figure 6 - Thematic map of keyword co-occurrence in research on biodegradable filaments for 3D printing.

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The word cloud, illustrated in Figure 7 and generated by the Bibliometrix R package, shows that research on biodegradable filaments for 3D printing focuses mainly on materials such as PLA and its composites, with a strong emphasis on mechanical properties and sustainability. Terms such as 3D printing, mechanical properties, composites, polylactic acid, and sustainability appear more frequently, focusing on improving material performance and reducing environmental impact. Other relevant topics include biodegradation, scanning electron microscopy, plasticizers, and the circular economy, indicating a multidisciplinary approach encompassing materials formulation and ecological assessment.

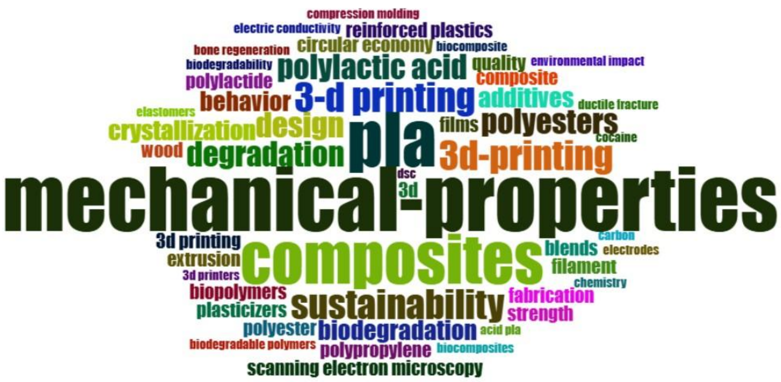

Figure 7 - Word cloud of the most frequent keywords in articles on biodegradable filaments for 3D printing.

The graph in Figure 8, presents the 20 most frequent keywords and shows that research on biodegradable filaments for 3D printing is mainly focused on terms such as “3D printing”, “additive manufacturing”, “PLA”, and “polylactic acid”, confirming the central role of these materials and technologies in the field. Other recurring topics, including “mechanical properties”, “circular economy”, “sustainability”, and “life cycle assessment”, reflect growing concerns about material performance and environmental impact. Furthermore, the presence of terms such as “fused filament fabrication (FFF)” and “fused deposition modelling (FDM)” indicates that much of the research involves extrusion-based technologies for the 3D printing of sustainable materials.

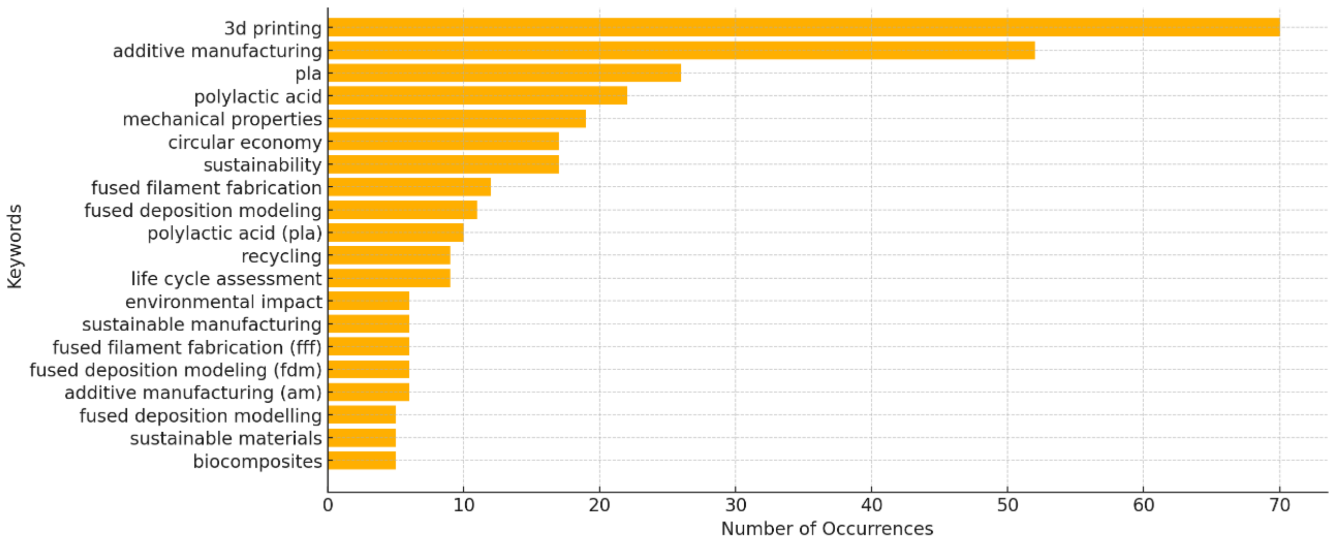

Figure 8 - Top 20 most frequent keywords in articles.

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CONCLUSION

This study highlights the growing interest and development in biodegradable filaments for 3D printing, supported by an extensive bibliometric analysis. The findings confirm that PLA, often enriched with natural fibers or biodegradable polymer blends, remains the most studied material due to its ease of processing, biocompatibility, and market availability.

The bibliometric analysis further confirms that PLA remains the most widely studied biodegradable polymer for additive manufacturing due to its good processability, commercial availability, and compatibility with FDM technologies. However, other biodegradable polymers such as PHA, PCL, PBS, and PBAT are increasingly being investigated as potential alternatives, particularly in applications requiring improved biodegradability or biocompatibility. These materials represent emerging research directions within the field of sustainable additive manufacturing. There is also a growing focus on alternative biopolymers, such as PHA, and the use of waste materials to produce more sustainable filaments, reinforcing circular economy practices.

Bibliometric analysis revealed that research in this field is driven by keywords such as 3D printing, additive manufacturing, composites, mechanical properties, and sustainability. The thematic map identified PLA composites as core and mature topics, while terms such as circular economy and plasticizers represent emerging or developing areas. Furthermore, the word cloud and co-occurrence maps emphasize the integration of environmental concerns into the materials development process, particularly through life cycle assessment (LCA) studies.

The data also shows a significant contribution from countries such as India, China, and the United States, and journals such as Polymers and Applied Chemical Engineering stand out as the main sources of publication. Highly cited articles highlight topics such as recycling, natural reinforcement, and performance optimization of biodegradable filaments.

Overall, biodegradable filaments are not only a viable alternative to conventional plastics in 3D printing but also an essential component in advancing sustainable manufacturing. The use of bio-based and recycled materials helps reduce environmental impact and opens up new possibilities for applications in biomedical, packaging, and industrial design. Future research should continue to explore new bio-sourced polymers, advanced composites, and biodegradable polymer blends, while also evaluating the role of recycled conventional polymers in hybrid or composite filaments aimed at improving sustainability.

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AUTHORS´ CONTRIBUTION

Conceptualization, A.G., S.M., T.F. and D.G.; data curation, A.G.; formal analysis, A.G., S.M., T.F. and D.G.; investigation, A.G. and S.M.; methodology, A.G., S.M., T.F. and D.G.; supervision, A.G., T.F. and D.G.; validation, A.G., T.F. and D.G.; writing – original draft, A.G. and S.M.; writing – review & editing, A.G., S.M. and T.F.

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