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THE ACADEMIC INTEREST FOR BIOPLASTICS – A BIBLIOMETRIC ANALYSIS

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ABSTRACT: Plastic materials are shaping modern society and making our lives easier. However, due to improper handling of plastic waste, plastics are no longer ubiquitous only in our homes, villages and cities but also in the natural environment. In line with the concept of bioeconomy, bioplastics are presented as a sustainable option that could help the economy overcome its dependence on fossil fuels and contribute to the reduction of overall plastic pollution. The study aims to identify the areas of academic interest in bioplastics. The study's methodological approach is based on a bibliometric (scientometric) analysis. It was found that in academia, biology, chemistry, and biotechnology are the main areas dealing with bioplastics, focusing on the whole process of product development. At the same time, there is a significant lack of research in areas such as social sciences, including economics. These findings should contribute to the global scientific discourse.

KEYWORDS: bioplastics, plastics, bioeconomy, bibliometric analysis, circular economy

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Introduction

Since the early beginnings of their production in 1869, plastics have permeated the global market due to their relative ease of processing into lightweight, cost-effective, and durable products of high quality and wide use that are omnipresent (Špajcar et al., 2012; Avio et al., 2017). Society has benefited from their versatility and manufacturability at low cost, but the environment pays the price and dependence on fossil fuels (Ashok et al., 2018). Global plastic consumption is estimated to increase from the current volume of around 350 million metric tons per year to 1 billion metric tons per year in 2050, increasing the amount of mismanaged waste entering the environment (Valderrama et al., 2019; Lebreton & Andrady, 2019). Plastics durability combined with poor waste management has led to plastics being ubiquitous and accumulating in landfills, nature and ecosystems in the form of large plastics, as well as degraded pieces such as microplastics or nano plastics (Heller et al., 2020; Shen et al., 2020). Bioplastics, some of which are biodegradable, are touted as an environmentally friendly alternative to petrochemical plastics because they are considered ecologically safe, energy-efficient, have a smaller carbon footprint, allow independence from fossil sources, and reduce biomass waste (Shamsuddin et al., 2017).

The bioeconomy, based on the substitution of fossil resources with biological resources for production, seems to be a promising economic concept to address various challenges. However, bioplastics can be seen as a possible solution and a potential threat (Jander, 2022). The bioeconomy, often presented as a concept leading to sustainable development, can also be controversial and raise doubts in some aspects. The academic debate on its sustainability is evident. Although the bioeconomy should be approached more interdisciplinary or transdisciplinary, most scientific publications focus on processing and technology, resources, environmental impacts, and social aspects. Economic issues seem to receive less attention (Pfau et al., 2014). The importance of the bioeconomy is not balanced across research disciplines. We suppose that a similar situation will occur with bioplastics. As bioeconomy and bioplastics production are relatively novel fields of research, their development in the future can be expected. With emerging topics, some problems need to be solved for the successful market launch of the products while minimising the adverse effects of the alternatives that promise to be more sustainable. We want to point out the challenges that could be labelled as problems connected with plastics and bioplastics. This paper aims to identify the areas of academic interest in bioplastics when it comes to topics researched more often and to identify the scientific fields that contribute the most to bioplastics research.

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Problems associated with plastics

Animal species often suffer from entanglement or ingestion of plastic debris, leading to gastrointestinal blockages, malnutrition or perforation, and even death. Evidence shows that 80 marine species, including megafauna species such as cetaceans, have died due to plastic ingestion, although microplastics rarely cause death. Nevertheless, high amounts of microplastic ingestions by fishes and seabirds were reported (Thiel et al., 2018; Roman et al., 2020). Moreover, microplastics adsorb toxic chemicals, transmit pathogenic microorganisms, contaminate freshwater and marine environments, enter the food chain, and accumulate at higher trophic levels (Liu et al., 2021; Boni et al., 2021; Athey et al., 2020; Mercogliano et al., 2020; Lots et al., 2017; Ivleva et al., 2016). Increasing consumption, depletion of fossil resources, and awareness of the problems associated with plastics such as lack of degradability, increasing soil and water pollution, the planned closure of landfills and pressure on waste management capacities are behind the push to develop alternative materials and to introduce biodegradable plastics (Shah et al., 2008). Given the general assumption of plastic production growth, more sustainable production and waste management methods are being considered. Improved collection, recycling and reuse of plastics when they become waste is a part of the solution.

Moreover, this requirement is in line with the philosophy of the circular economy (Rhodes, 2018). Nevertheless, recycling is not without problems due to the different properties and composition of plastics, some of which are not recyclable at all, and the composition of waste, which also includes unwanted and unidentifiable materials (Egun & Evbayiro, 2020; Roosen et al., 2020; Lahtela et al., 2019). Some non-recyclable materials can be subjected to downcycling, while others, such as films or bags, can clog recycling machines (Egun & Evbayiro, 2020; Sharuddin et al., 2017; Hou et al., 2018). Waste management problems worsened when China, which has extensive recycling infrastructure and capacity, played an important role in plastic recycling and the global circular economy, imposed an import ban on foreign waste. Since 1992, China has imported 45% of the world's plastic waste (Brooks et al., 2018). While developed countries lack recycling capacities due to their reliance on exports in the past, developing countries lack environmental regulations and proper treatment technologies. Yet, they may become new endpoints for waste from both developed and developing countries (Qu et al., 2019). After the Chinese ban, Asian countries saw a rapid increase in plastic waste imports, so many began to limit them (Liang et al., 2021). In addition, the disposal of plastics is still a challenge in many places. In India, landfilling, incineration or littering are the common methods to get rid of

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plastics (Nkwachukwu et al., 2013). In South Asian countries, burning waste in fires is still common, increasing the amount of harmful emissions that threaten human health and ecosystems (Saikawa et al., 2020). The burning of plastics releases not only CO_2 emissions but also various toxic substances into the air (Verma et al., 2016). Many countries and cities worldwide have introduced bans on single-use plastic or at least plastic bags that African countries have also adopted (Herberz et al., 2020; Turpie et al., 2019). However, the whole situation has been significantly affected by the COVID-19 pandemic, which has increased our dependence on plastics, mainly for safety and hygiene reasons. It has also exacerbated problems related to waste management and to lift bans on single-use plastics (Vanapalli et al., 2021; Prata et al., 2020).

Bioplastics as a potential solution or threat

Bioplastics are those plastics produced from renewable biological sources or are biodegradable or both (Imre & Pukánszky, 2013). Biodegradable plastics are considered the main alternatives to conventional plastics (Song et al., 2009). Switching plastic production from fossil to renewable resources is necessary to achieve the goals of the Paris Agreement (Valderrama et al., 2019). Global demand for bioplastics has increased in recent decades. Their popularity continues to grow, thanks to a fundamental shift in consumer behaviour that encourages the development of more environmentally friendly plastics and also influences the willingness to pay a higher price for them (Al-Battashi et al., 2019; Cinar et al., 2020; Jaconis et al., 2019; Klein et al., 2019). Unfortunately, bioplastics are still not competitive with conventional plastics, not only because of their higher cost but also because of their poorer mechanical properties (Jiménez-Rosado et al., 2020; Coppola et al., 2021). One way to reduce the cost is to utilise waste from agriculture, food industry, forestry and other by-products as feedstock (Saharan et al., 2012; Jõgi & Bhat, 2020). The current challenge is to develop such bioplastics that provide a sustainable and cost-effective alternative while achieving comparable mechanical properties to conventional plastics but are biodegradable and safe for the environment (Krishnamurthy & Amritkumar, 2019). However, about half of current bioplastics are not biodegradable, and waste disposal becomes increasingly problematic as production volumes increase.

Bioplastics, therefore, pose new challenges for waste management and policymakers (Rahman & Bhoi, 2021). Moreover, there is a risk of contamination of the recycling process if bioplastics are not separated from conventional plastics (Arikan & Ozsoy, 2015). Low consumer awareness of and information about bioplastics and their disposal when they become waste, including various disposal guidelines, seems to be a barrier to their adoption.

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Bioplastics are disposed of illegally by consumers and thrown into nature, buried in the ground or burned. The lack of an efficient and intuitive recycling system for bioplastics leads to consumer frustration (R×3, 2011; Selvamurugan & Sivakumar, 2019). Biodegradability should lead to a reduction in plastic waste, especially in agriculture, where this property is crucial. The decomposition of plastics releases various substances into the soil that may affect plant growth and development, such as germination, root development, expansion of above-ground parts, and increase in stress. In the case of mulch materials, it is necessary to monitor biodegradability itself and ecotoxicity, environmental safety, and effects on the soil environment (Serrano-Ruíz et al., 2018). One of the under-studied areas is the potential impact of microplastics from bioplastics, which should be prioritised to understand their decomposition, degradation, even potential toxicity and impact on organisms and whole ecosystems.

Similarly, methods of disposal and collection of bioplastics need to be identified and facilitated to ensure a proper and vital recycling process (Shruti & Kutralam-Muniasamy, 2019). To solve the problems related to bioplastics and their use, important questions must be answered. In particular, we need to focus on cost-effectiveness and competitiveness of bioplastics, non-biodegradable bioplastics, microplastics and nanoplastics, environmental safety, safe disposal of waste bioplastics, their recycling and separation from conventional plastics, and how to improve their properties. We suppose these and similar questions to be reflected by researchers, and if so, this shall be evidenced by the scientometric analysis. The issues are related to various research fields, including technology, chemistry, biology, environmental sciences, and social sciences and economics as production and prices should reflect costs and demand.

Research methods

To identify the prevailing academic concern, when it comes to most emphasised topics and scientific fields researching bioplastics, a bibliometric (scientometric) analysis was performed using VOSviewer software (version 1.6.15) and Web of Science. "Analyze results" tool. Bibliometric analysis is a pretty recent approach for research documents analysis providing an extensive review of the literature (Paltaki et al., 2021). It enables a method to identify and map the development of publications, in this case, scientific literature, based on statistical indicators regarding the outputs of scientists, and enables to map new fields of science, networks, and the development within (Konstantinis et al., 2018). VOSviewer was used for bibliometric analysis and mapping by, e.g. van Eck and Waltman (2010; 2017), Jeong and Koo (2016), Shah and Lei (2020). Within the bioeconomy, this software was used,

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for example, to define bioeconomy (Konstantinis et al., 2018), an overview of factors influencing the bioeconomy (Muizniece et al., 2019), an overview of bioeconomy and livestock production (Paltaki et al., 2021), an overview of forest bioeconomy (Biancolillo et al., 2020), or biorefineries in the context of circular bioeconomy (Ubando et al., 2020). For this paper, all records indexed in the Web of Science database related to the bioplastic topic available up to 21st January 2021 were selected. The dataset consisted of 2,257 publications, and the search for keywords in the abstract, title and keywords sections was conducted. This made a total of 8,250 keywords, of which 715 keywords are analysed as they occurred at least in five different articles. The results are displayed using network visualisation and density visualisation. Network visualisation reveals the importance of individual keywords within a given dataset by their occurrence and also linkings of the use of these keywords. At the same time, the second method visualises only the use of keywords by their density. This analysis serves to identify the topics that are most emphasised by academia regarding bioplastics. To determine the research areas dealing with bioplastics and to support our results, we used a bibliometric tool, "Analyze results", provided by the Web of Science which enabled analysing the search results. This tool was used for a bibliometric analysis by e.g. Carmona-Serrano et al. (2020), Marín-Marín et al. (2021), López-Belmonte et al. (2020). Within the bioeconomy, this tool seems to be not used often. Still, it was used, for example, to review publications on energy resources by Grubert and Zacarias (2022) or to review the utilisation of orange peel waste by Jiménez-Castro et al. (2020). This analysis was conducted on 11th March 2022. Although we used the advanced search to set a date range back up to 21st January 2021, it provided more results than the analysis made earlier up to this date, with a total of 2521 publications. It may be a result of some publications and journals indexed later. However, as for the results, we had decided to use the TOP 20 research areas and the TOP 20 Web of Science categories as we perceived a threshold laying there and kept the results well arranged. Furthermore, we examine year-wise publications distribution in the given period. The only exception is the year 2021, as we try to keep the consistency of the paper.

Results of the research

Depending on how many times each keyword appears, the most important topics in current scientific discourse in bioplastics are listed. Besides the terms bioplastic and bioplastics, the most frequently mentioned topics are polylactic acid, polyhydroxyalkanoates, mechanical properties, films, which appear in more than 200 cases. This is followed by polyhydroxybutyrate, biodegradation, degradation, biosynthesis, composites, acid starch, poly-3-

hydroxybutyrate, glycerol and blends, which occur in more than 100 cases. At least 80 studies mentioned polymers, behaviour, water, biomass, poly-beta-hydroxybutyrate, cellulose, protein, fermentation, morphology, biopolymers and plastics. *Escherichia coli* appears in 79 cases. However, other important topics include nanocomposites, *Ralstonia-eutropha*, and growth, covered in at least 60 articles. Optimisation, wheat gluten, waste, bacteria, extrusion, barrier properties, biopolymer, thermal properties, temperature, polyester, accumulation, chitosan and crystallisation are topics covered in more than 50 studies. Thermoplastic starch, sustainability, performance, *Alcaligenes-eutrophus*, metabolism, biodegradability, lignin, edible films, proteins, poly(3-hydroxybutyrate-co-3-hydroxy-valerate), expression, cross-linking, fibres, as key terms occur in at least 40 cases. Biorefineries, physical properties, recombinant *Escherichia coli*, renewable resources, life cycle assessment, food, plasticisers, extraction, fed-batch culture, functional properties, rheological properties, biodegradable plastics, nanoparticles, wastewater, conversion, kinetics, energy, culture, identification, cyanobacteria, circular economy, impact and oil occur as keywords in more than 30 scientific articles. Genes and purification appear in 29 cases, food waste, PHA production, green composites, P3HB production, polyethylene and plasticisers in 28 cases, genes in 27 cases, microalgae, soy protein, metabolic engineering, molecular-weight, poly(l-lactic acid) and chemicals in 26 cases. The density of keywords is shown in Figure 1.

Figure 1. Density of keywords

Source: author's work based on VOSviewer.

Obviously, the main academic focus is on the properties, composition, processes, synthesis and degradation of bioplastics or their types. The analysis of the literature shows that mostly chemistry, biochemistry, biology and biotechnology as scientific fields are dealing with the topic of bioplastics, while socio-economic and interdisciplinary research is missing. The economic context of the production of these plastics seems on the periphery of interest, even though it is one of the crucial tasks of their production. Nevertheless, the terms like sustainability, bioeconomy, circular economy, innovation, management appear as well. Although the terms efficiency, growth and optimization also appear in the results, it can be stated that in these are rather aspects of biotechnological processes than the economy. Using the analysis based on the minimum occurrence of the keyword in at least two articles, the economic aspects can be extended by low-cost production, efficient production, cost, purchasing, branding, consumption, waste management, industry and few keywords regarding bioplastic products, bioproducts or by-products.

The network analysis presented in Figure 2 shows that mechanical properties are related with morphology, i. e. physical, thermal, functional, barrier and rheological properties, also water vapour permeability, rheology, biodegradability, degradation, or, vice versa, to stability, and also to behaviour including crystallization behaviour.

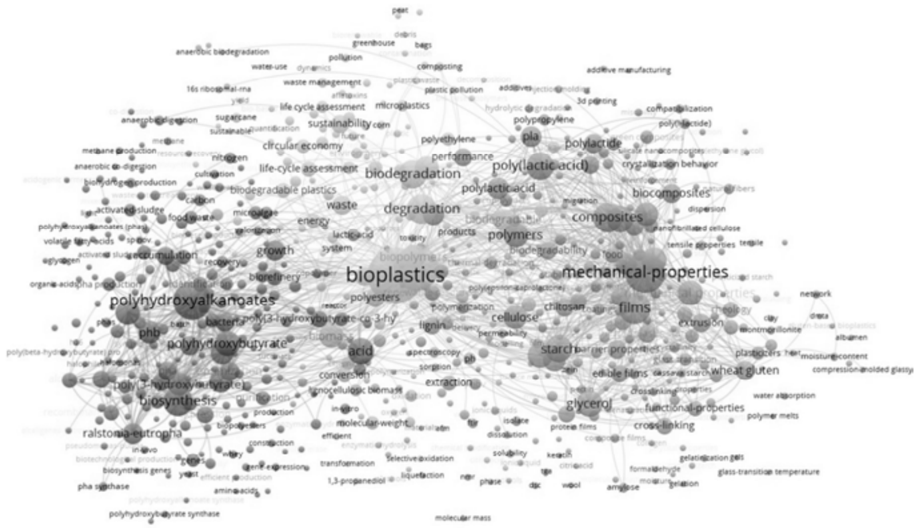

Figure 2. The network analysis

Source: author's work based on VOSviewer.

In addition to mechanical properties, the processes and processing of bioplastics are often studied, including the issues related to plasticization, plasticizers, crosslinking, extrusion, crystallization, plastic injection, polymer blends, composites, green and biocomposites, silicate nanocomposites, composite films, edible films and films in general. There are also links to individual types of various thermoplastics, bioplastics, biopolymers, biodegradable polymers, PE, PP, and feedstocks to produce bioplastics, which include proteins, thermoplastic starch, cassava starch, wheat gluten, glycerol, gelatin, lignin, cellulose, soy proteins, acids, especially polylactic acid, or fibres and natural fibres, or renewable resources in general, and waste. The issue of coatings also appears. Some of the keywords already mentioned in connection with mechanical properties also associate with polyhydroxyalkanoates. These include mainly biodegradable polymers and polymers, biodegradation, biodegradability, blends, acids, and again polylactic acid. Polyhydroxyalkanoates are also associated with copolymers, polyesters, oil and biomass. In the context of these bioplastics, the terms connected to synthetic biology and microbiology, synthetic and microbial processes, metabolic engineering or starting materials and related organisms, are used extensively. This is evident from the use of terms such as metabolism, microorganism, bacterium, bacteria, bacillus, microbial degradation, culture, growth, fermentation, purification, biorefinery, regeneration, accumulation, optimization, biosynthesis, synthase, batch, batch culture, *Escherichia coli*, and also recombinant *Escherichia coli*, then *Pseudomonas*, *Cupriavidus necator*, *Alcaligenes eutrophus*, *Ralstonia eutropha* or activated sludge and wastewater. The individual types of bioplastics and their constituents such as polyhydroxyalkanoates as well as the preparation of PHA, beta-hydroxybutyric acid, polyhydroxybutyrate, and similarly the preparation of PHB, poly-3-hydroxybutyrate, the preparation of poly-3-hydroxybutyrate, including also poly(3-hydroxybutyrate-co-3 hydroxyvalerate) are mentioned. However, terms like molecular weight, carbon, and storage also occur.

As for the research areas that deal with bioplastics, the dominance of engineering, polymer science, chemistry, biotechnology, microbiology, technology, as well as materials science is inevitable. Similarly, environmental sciences, biochemistry, microbiology, agriculture play a crucial role. However, the results differ depending on the measure, as indicated by Figure 3, which shows research areas, and Figure 4, which presents Web of Science categories. What is also clearly visible from both figures is the lack of social sciences addressing bioplastics; the only exception is education and educational research. There are just a few publications from fields like business economics, social sciences, anthropology, urban studies, and surprisingly even art.

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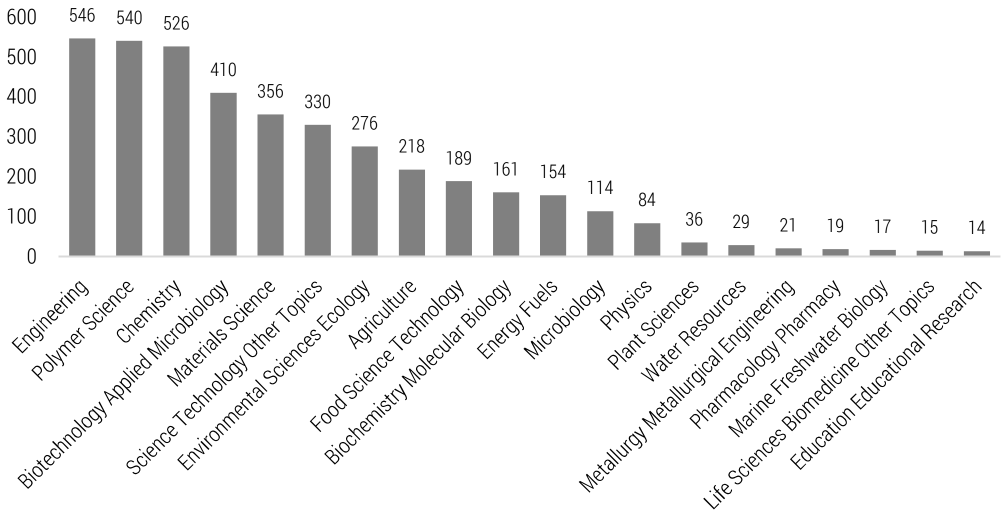

Figure 3. Research areas

Source: author's work based on Web of Science.

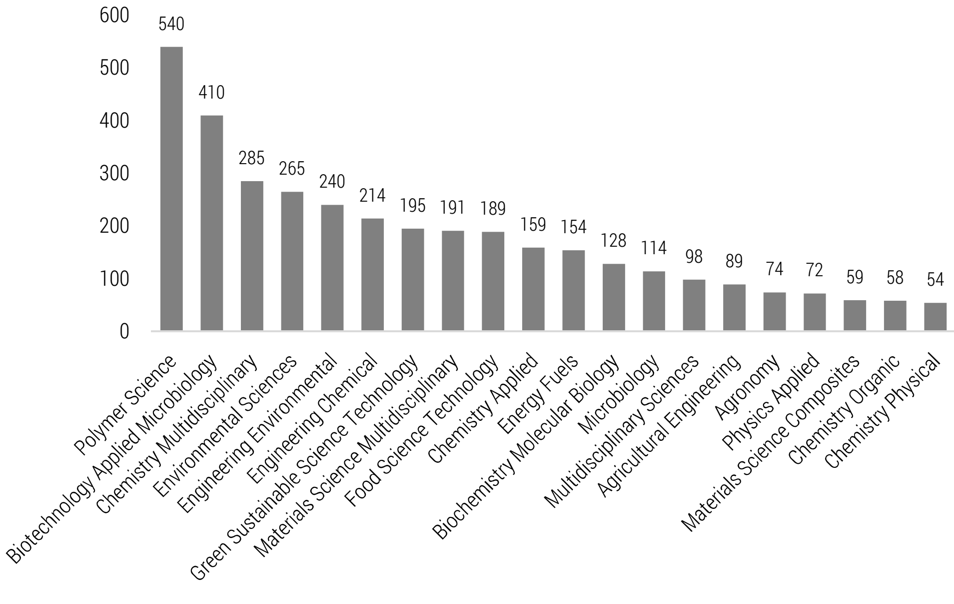

Figure 4. Web of Science categories

Source: author's work based on Web of Science.

The year-wise distribution of publications in the given period is shown in Figure 5. Some years are missing as there were no records of publication activity in Web of Science. Although the data for the year 2021 present just

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the first 21 days of the first month, the amount of the publications reach nearly the same level as the year-wise publications for the year 2011. This reflects the growing popularity and interest in bioplastics in the scientific community. The increasing publication activity is permanently evident since the year 2005. In 2020, the number of publications was more than 22 times higher than in 2005.

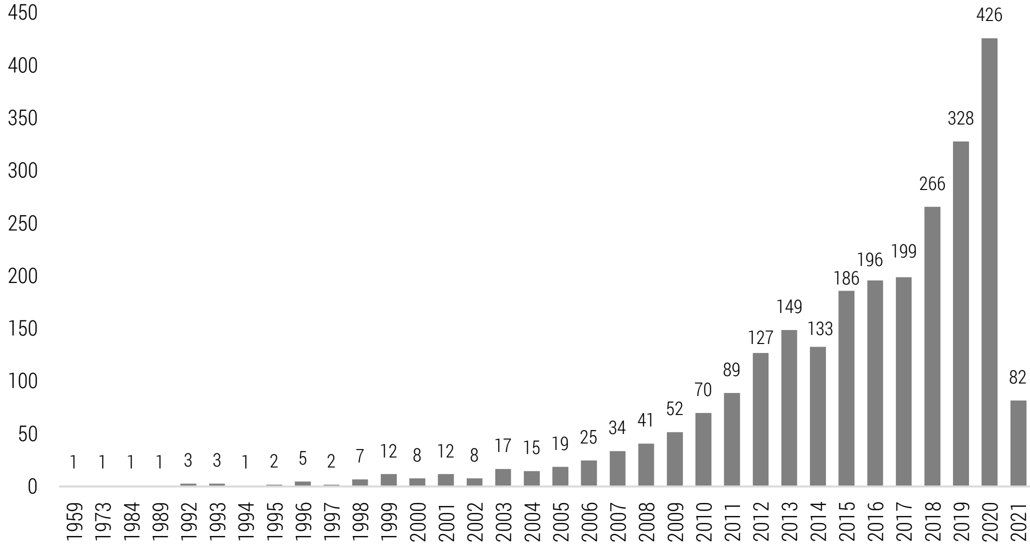

Figure 5. Annual publication

Source: author's work based on Web of Science.

Discussion

The methods employed in this paper can be conducted relatively quickly and may provide results that could not be attained manually. The topics related to bioplastics are gaining more attention and are increasingly more addressed by scientists. The recent science also increasingly reflects the bioeconomy and circular economy (Paltaki et al., 2021). However, most scientific publications in bioplastics focus on polymers processing, technology, resources, and other following issues, with a lack of attention on treating economic issues of the production similarly as in the case of the bioeconomy pointed out by Pfau et al. (2014). The current research reflects some problems that need to be addressed, mainly the materials and their properties, waste utilisation, biodegradability, and degradability of bioplastics. There are also publications targeting life-cycle-assessment, sustainability, bioeconomy, and circular economy.

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Nevertheless, the issues of the economy of production, cost optimisation, or some broader aspects related to the society and economy, which both shall treat the materials when they become waste, seem to be understudied, similarly like the issue of microplastics and nanoplastics, possible ecotoxicity and the impact on the organisms that degrade these materials. These findings are in line with the results of Serrano-Ruíz et al. (2018), who focused on the decomposition of plastics, especially in the case of mulch plastics degrading in soil or Shruti and Kutralam-Muniasamy (2019), who concerned about the possible impact on organisms and ecosystems. The growing interest in waste biomass utilisation that could help the environment and the cost of bioenergy and chemicals production was pointed out by Usmani et al. (2021). Similarly, a business plan covering the use of organic municipal solid waste was thought out by Moscato et al. (2020), who also expect an increase in bioplastics use and, therefore, waste in Italy and some other countries. We perceive waste utilisation as a good and sustainable resource for the bioeconomy in general. Paltaki et al. (2021) emphasise waste management, manure, biorefineries, fermentation, and circular economy as the future directions for sustainable growth and bioeconomy.

Conclusions

The number of studies dealing with bioplastics has increased significantly in recent years, and this trend will continue as bioeconomy strategies are launched worldwide. Bioplastics are frequently mentioned in these strategies. Currently, mainly biologists, technologists, and chemists are researching bioplastics. Scientists' main issues relate to primary resources, production processes, biotechnologies, end products, and their properties, including degradation and biodegradation. Thus, mainly technical, technological, biotechnological, chemical, biochemical, microbiological and other biological issues are under consideration and receive great attraction by academia. But the market introduction of these materials, which has already taken place, means contact and interaction with society and its construct – the economy, so the lack of interest of the social sciences, particularly economics, and the related issues are shocking, to say the least. The absence of economic topics and aspects, such as the standard topics like cost-benefit analysis of production processes, financial instruments to support this production (subsidies, tax relief...) and topics with a broader overlap with the circular economy, the bioeconomy, reflects a certain lack of interest among experts, but probably also in society and politics. As we supposed, academia mainly reflects processing technology and resources as in the case of bioeconomy, while the social and economic issues tend to receive low attention. We also expected more articles considering and assessing the sustainability of bioplastics as

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such or their recycling as important issues that scientists would reflect. Nevertheless, circular economy, which should consider recycling and closing the loops, partly occurs as a topic of interest related to sustainable development.

The contribution of the authors

Nikola Sagapova: conception – 90 %, literature review – 90 %, acquisition of data – 100 %, data analysis and interpretation – 90 %, manuscript – 90 %.

Eva Cudlínová: conception – 10 %, literature review – 10 %, data analysis and interpretation – 10 %, manuscript – 10 %.

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