

Sustainable Innovation: the role of biochar in microplastic remediation – a bibliometric view

Inovação Sustentável: o papel do biocarvão na remediação de microplástico – uma visão bibliométrica

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Abstract

Microplastics pose a risk to the ecosystem due to their ability to bioaccumulate and adsorb toxic compounds. Biochar has emerged as an alternative for removal due to its high porosity. This study presents a bibliometric analysis, using Proknow-C to select articles from the Web of Science, with VOSviewer and Orbit for patents. The most common areas of research and technology are Environmental Technology, Chemical Engineering, Chemistry, and Biotechnology. Biochars are prepared from lignocellulosic biomass from wood and agricultural waste to remove mainly polystyrene and polyethylene with micrometric diameters. The articles are connected to the Sustainable Development Goals, the most common of which are: Clean Water and Sanitation, Life Below Water, Sustainable Cities and Communities, and Sustainable Consumption and Production. China has the most influential institutions, while Brazil is still very incipient, with room for research development and creation of public policies.

Keywords: Microplastic; Emerging Pollutant; Adsorption.

Resumo

Os microplásticos são um risco ao ecossistema devido à sua capacidade de bioacumulação e de adsorção de compostos tóxicos. O biocarvão surge como alternativa para remoção por causa da alta porosidade. Este estudo apresenta uma análise bibliométrica, utilizando ProKnow-C para seleção de artigos na Web of Science, com o VOSviewer e o Orbit para patentes. As áreas mais recorrentes de pesquisa e tecnologia são Tecnologia Ambiental, Engenharia Química, Química e Biotecnologia. Os biocarvões são preparados a partir de biomassas lignocelulósicas de resíduos de madeira e da agropecuária para remoção, principalmente, de poliestireno e polietileno com diâmetros micrométricos. Há conexão dos artigos com os Objetivos de Desenvolvimento Sustentável, sendo os mais recorrentes: Água Potável e Saneamento, Vida na Água, Cidades e Comunidades Sustentáveis e Consumo e Produção Sustentável. A China apresenta as instituições mais influentes, enquanto o Brasil ainda é muito incipiente, existindo espaço para o desenvolvimento de pesquisas e a criação de políticas públicas.

Palavras-chave: Microplástico; Poluente Emergente; Adsorção.

Technological Areas: Bibliometric Foresight, Technological Applications, and Sustainable Development Goals.



1 Introduction

Plastic, developed in the twentieth century from petroleum, became widely recognized for its versatility and durability. However, its slow degradation rate has led to its accumulation in the environment, particularly in aquatic ecosystems and soils (Thompson *et al.*, 2009), raising concerns regarding its impacts on both human and environmental health (Sajid *et al.*, 2023). The COVID-19 pandemic further exacerbated this issue by increasing the consumption of disposable plastic products, including Personal Protective Equipment (PPE) and delivery packaging materials (Silva *et al.*, 2021).

As a result of anthropogenic and natural processes, including ultraviolet and thermal radiation as well as biological degradation, plastic debris is fragmented into microscopic plastic particles known as microplastics (Sajid *et al.*, 2023). These particles are smaller than 5 mm and can be classified as primary microplastics, which are intentionally manufactured at microscopic sizes, such as fibers, pellets, and microbeads used by industries including the cosmetics and textile sectors, or secondary microplastics, which originate from the fragmentation of larger plastic materials due to physical, chemical, or biological factors, including UV radiation, heat, humidity, oxygen exposure, and the activity of microorganisms or chemical agents (Thompson *et al.*, 2009; Ritchie, Samborska, & Roser, 2018; Al-Thawadi, 2020).

Microplastics belong to the class of Emerging Pollutants, compounds characterized by high stability and resistance to degradation, which allows them to persist in the environment and pose a significant threat to ecosystem sustainability (Montagner, Vidal, & Acayaba, 2017). Furthermore, plastics exhibit the capacity for bioaccumulation and can adsorb toxic substances such as pesticides, metals, and pharmaceuticals due to their large specific surface area. Consequently, there is an urgent need to develop strategies aimed at reducing their impacts, capturing and removing these pollutants from the environment, and preventing further harm to human and environmental health. A bibliometric analysis of filtration technologies for microplastic removal in freshwater environments has recently been conducted (Garfansa *et al.*, 2024).

One promising alternative is the use of biochar, an adsorbent material derived from renewable biomass that has attracted increasing attention as an effective solution for pollutant removal. Plant residue based adsorbents offer several advantages, including their organic nature, renewability, abundance, selectivity, and ease of regeneration (Sahay *et al.*, 2023).

Biochar stands out because of its porous structure, the presence of tunable active sites, and the simplicity of its

production process. In addition, it exhibits high flexibility, functionalization potential, and structural robustness, characteristics that support its application across a wide range of environmental contexts and treatment processes (Wang *et al.*, 2021; Abuwatfa *et al.*, 2021). Its abundance and high porosity make it particularly versatile for the removal of various contaminants, including microplastics.

Biochar possesses a variety of surface functional groups that may contribute to the adsorption of microplastics. Recent studies have primarily focused on electrostatic interactions as the main adsorption mechanism. However, several experimental observations also suggest that complexation phenomena play a role in the removal process (Singh *et al.*, 2021). Given the complexity of the interactions involved, further research is needed to address multiple aspects of this technology, ranging from biochar production and characterization to adsorption studies involving different types of microplastics, as well as the recovery and reuse of spent biochar. Bibliometric studies have investigated the application of biochar in agriculture, as an energy source (Wu *et al.*, 2024), and as a green remediation technology (Ngaba *et al.*, 2025) for wastewater treatment (Wang *et al.*, 2024; Li *et al.*, 2023). Additional bibliometric analyses have focused on the remediation of antibiotics (Liu *et al.*, 2024) and toxic metals (Liu *et al.*, 2023).

Given the increasing prevalence of emerging pollutants such as microplastics, expanding research efforts aimed at environmental remediation is essential. Equally important is the investigation of the patent landscape, as it reflects global technological and economic developments in this field. Furthermore, international action plans designed to promote sustainable development play a critical role in guiding scientific and technological advances. The use of biochar for microplastic remediation represents an emerging area of research that aligns closely with the objectives of the 2030 Agenda (United Nations Brazil, 2025), a global action plan established by the United Nations (UN) that encompasses 17 Sustainable Development Goals (SDGs) and 169 associated targets. The Agenda has been endorsed by all 193 UN Member States, including Brazil, with the commitment to achieve these goals by 2030 (Figure 1).

The Sustainable Development Goals (SDGs) aim to eradicate poverty, protect the environment, address climate change, and promote peace and prosperity for all people, everywhere. To achieve these objectives, they are founded on the balance among the economic, social, and environmental dimensions of sustainable development (United Nations Brazil, 2025). In this context, scientific research is expected to align with at least one SDG, thereby contributing to sustainable development and supporting the achievement of the targets established by the 2030 Agenda.

To define a research objective appropriately, it is essential for researchers to understand the current state of

Figure 1 – Sustainable Development Goals (SDGs)

Source: United Nations Brazil (2025)

knowledge within their scientific field of interest. In this regard, conducting a literature review and a prospective study becomes fundamental for identifying trends, research gaps, and opportunities for future investigation.

Accordingly, this article aims to present a process for selecting bibliographic references on the topic of microplastic remediation using biochar, as well as to perform bibliometric analyses of scientific publications and compare them with patent documents.

To this end, several aspects were investigated, including the organizations involved, references cited, citation counts, keywords, geographical origin of the studies, year of publication, technological applications, types of biochar and microplastics employed, and the Sustainable Development Goals (SDGs) most prominently associated with this research field.

2 Methodology

The methodology adopted in this study followed a qualitative and quantitative approach (Bogdan & Biklen, 1994; Gatti, 2004), characterized by a bibliometric review and scientific mapping of the theme *Biochar Utilization for Microplastic Remediation*. Data were collected between April and May 2025 using the keywords “biochar\$” and “microplastic\$”, combined with the Boolean operator AND. Scientific publications were retrieved from the Web of Science (WoS) database using the document type filters “article” and “review article”, while patent documents were investigated using the Orbit platform developed by Questel.

Bibliometric analysis is a technique within information science that applies quantitative and statistical methods to examine the production, dissemination, and use of knowledge recorded in academic documents, such as scientific articles, patents, theses, dissertations, and books.

This approach enables the identification of publication patterns, research trends, and the development of scientific fields, providing valuable insights into scientific production (Costa *et al.*, 2012). Based on a portfolio of selected articles, parameters such as references, authors, organizations, citation counts, and relevant journals were analyzed. Furthermore, bibliometric studies complement literature reviews by offering a more objective and visual understanding of a scientific field through statistical analyses and data visualization techniques.

This study adopted the ProKnow-C (Knowledge Development Process – Constructivist) methodology (Lacerda, Ensslin, & Ensslin, 2012), supported by Microsoft Excel software (version 2503). This methodology comprises a series of stages for article selection aimed at identifying the state of the art of a given research topic. Bibliographic data were exported as metadata files and processed using VOSviewer software (version 1.6.20) to perform co-authorship, co-occurrence, and co-citation analyses through graph-based representations of correlation networks. Additionally, a complementary investigation was conducted to identify the principal biomass feedstocks used in biochar production, as well as the main types and sizes of microplastics adsorbed by biochar.

3 Results and Discussion

This section presents the results of the bibliometric review and scientific mapping of the research topic. The section is divided into four parts. First, the ProKnow-C process is applied to select the articles. Second, the selected publications are analyzed using VOSviewer software to identify correlations among organizations, keywords, countries, and co-citations, and these findings are compared with patent data obtained from the Orbit platform. Third,

the biomass feedstocks used for biochar production and the types and sizes of microplastics investigated in the studies are identified. Fourth, the articles are analyzed according to their relationship with the Sustainable Development Goals (SDGs).

Initially, an investigation was conducted on the individual keywords that compose the research topic over the past 25 years. Between 2000 and 2024, a total of 42,192 publications containing the keyword “biochar\$” were identified, of which 1,259 included Brazilian authors. For the keyword “microplastic\$”, 23,916 publications were found, including 684 authored by Brazilian researchers. As shown in Figure 2, research on biochar remained relatively limited until 2009. From the following year onward, publication output increased exponentially, reaching 7,742 articles in 2024. Research on microplastics exhibited a similar growth pattern, although with a later onset beginning around 2014, culminating in 6,023 publications in 2024.

3.1 ProKnow-C Process

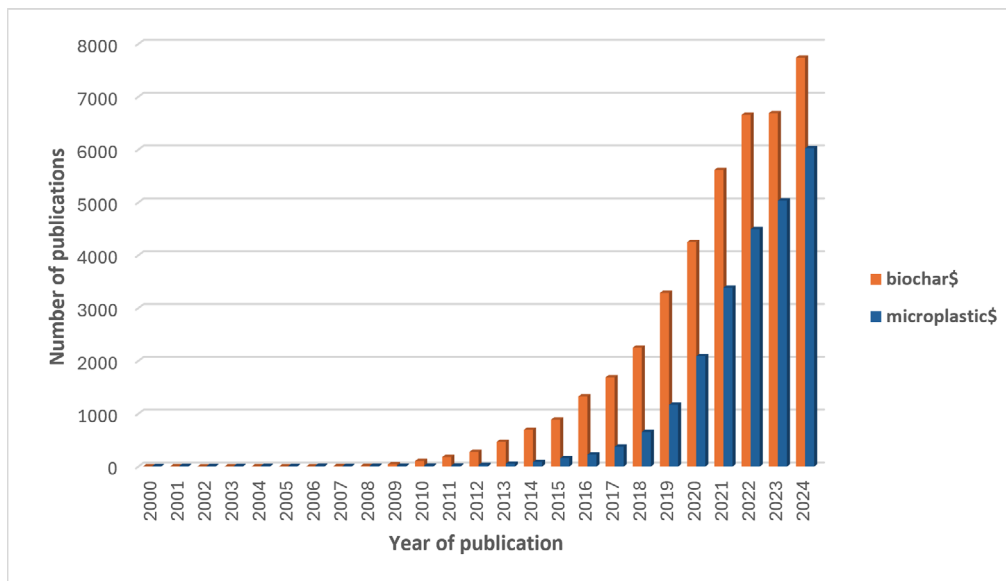
The number of articles and the continuous growth in publications on these two topics demonstrate a strong interest within the scientific community. However, when the terms “biochar\$” and “microplastic\$” were combined, only 315 scientific articles and 178 patent documents were identified. The earliest publication dates were 2017 for scientific articles and 2015 for patents. These two research fields began to converge only after each had already undergone substantial individual development, as illustrated in Figure 2.

It is necessary to investigate and select the studies that effectively employ biochar for microplastic remediation, since these two terms may be associated in different contexts. Therefore, the ProKnow-C process, illustrated in Figure 3, was applied to select the articles composing the research portfolio in order to identify the state of the art of the theme “Biochar Utilization for Microplastic Remediation”.

The titles of all 315 retrieved articles were examined, and only 87 were considered title-aligned with the research topic. The main reasons for excluding a large proportion of the studies included: the article’s primary focus not being biochar or microplastics, with only a brief mention of these terms; the use of plastic as a feedstock for biochar production rather than for microplastic removal; and situations in which microplastics were present in the biochar application environment, but the study focused on the removal of another pollutant or on evaluating plant or microorganism growth parameters.

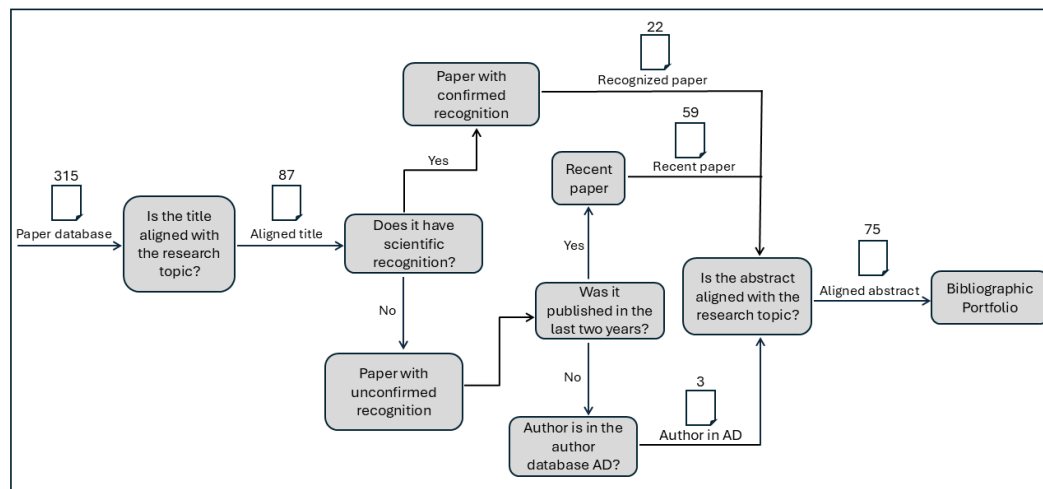
The next stage was based on the Pareto principle, which assumes that 80% of outcomes are generated by 20% of the causes. Accordingly, a citation threshold was established by selecting the most highly cited articles until the cumulative percentage of citations exceeded 80% of all citations received by the 87 title-aligned articles. This threshold was set at 32 citations, since the 22 articles with 32 or more citations accounted for 81.05% of the total citations. The less-cited articles then underwent an additional screening process based on publication year, prioritizing the most recent studies. Articles published between 2023 and 2025 were considered, given that less than one-third of 2025

Figure 2 – Evolution of Publications on Biochar and Microplastics



Source: Prepared by the authors (2025)

Figure 3 – ProKnow-C Process for article selection



Source: Prepared by the authors (2025)

had elapsed at the time of data collection. A total of 59 articles were published during this period. An additional reassessment was conducted using the Author Database (AD), composed of the authors of the 22 articles with the highest scientific recognition. Among the remaining five articles, three included at least one author from the AD. The final stage consisted of reading the abstracts and selecting only those aligned with the research topic. As a result, 75 articles presented aligned abstracts and constituted the final research portfolio to be analyzed using VOSviewer software.

For the patent analysis, all titles and, when necessary, the abstracts were examined to verify their alignment with the topic of interest, resulting in a final portfolio of 40 patents. The reasons for patent exclusion were the same as those applied to the scientific articles, in addition to cases where insufficient information prevented a clear understanding of the patent’s intended function. Both the selected articles and patents were published within the last eight years, and an exponential increase in the number of publications can be observed over time, as shown in Figure 4.

In 2022 and 2023, the number of articles and patents, respectively, doubled. This increase may be associated with the substantial rise in the production and consumption of Personal Protective Equipment (PPE) and disposable packaging during the COVID-19 pandemic, which intensified microplastic contamination and its associated impacts. Consequently, greater efforts in research, technological development, and innovation became necessary in this field. Academic research appears to be more advanced than technological development, indicating that significant opportunities remain for further investigation in both domains. Furthermore, the establishment of the 17 Sustainable Development Goals

(SDGs) by the United Nations in 2015 has contributed to the advancement of research and technologies aimed at environmental protection and restoration, including those related to the present area of study.

3.2 Analysis Using VOSviewer Software and the Orbit Platform

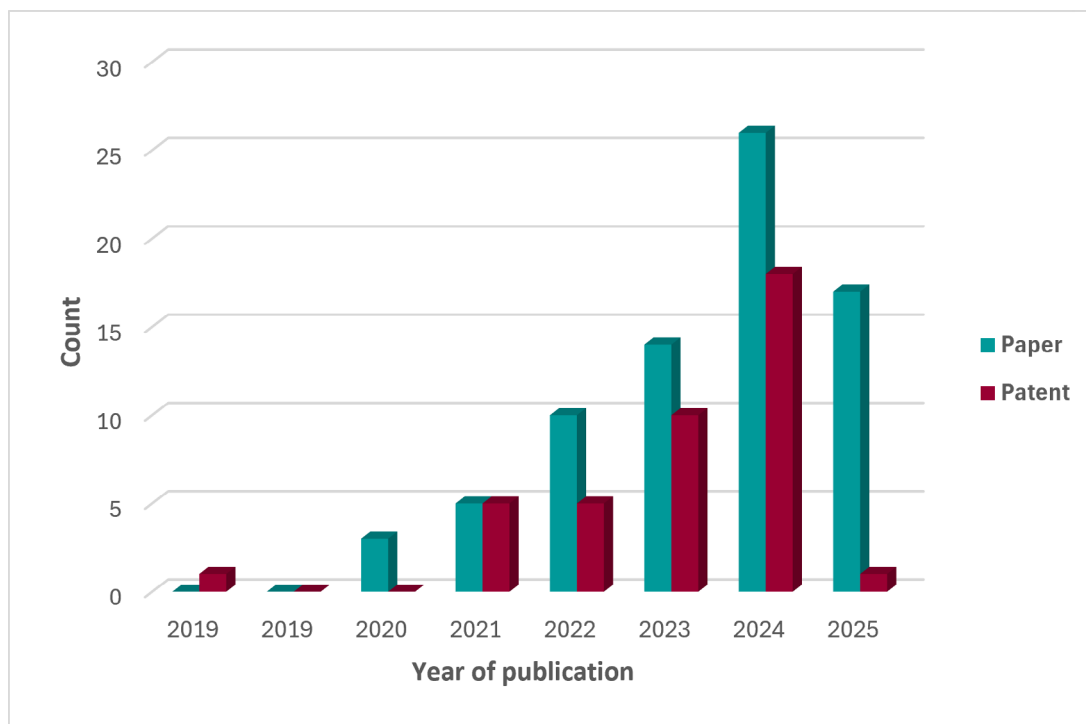
By analyzing the data from the 75 articles selected through the ProKnow-C process using VOSviewer software, a broad range of information was extracted regarding the most influential authors in the field, the most frequently occurring keywords, the countries with the highest scientific output, and Brazil’s position within this research area. VOSviewer serves as a quantitative and analytical tool for scientific literature, enabling the construction and visualization of maps based on bibliometric networks, as well as tables containing quantitative indicators.

The analysis revealed the existence of several research groups working on this topic. Among the authors with the highest number of publications within the selected portfolio, Li, Chen, Ganie, and Darbha stand out, each having authored four published articles. The first two researchers are affiliated with the School of Environmental Science and Engineering at Yangzhou University in China, while the latter two are associated with Indian Institute of Science Education and Research Kolkata in India.

Regarding scientific impact, Wang, Lea-Langton, and Sedighi exhibited the highest citation counts, with a total of 254 citations. All three researchers are affiliated with The University of Manchester in England.

Since the connection between biochar and microplastics has emerged only within the last six years,

Figure 4 – Evolution of publications in the bibliographic portfolio



Source: Prepared by the authors (2025)

no single researcher has yet achieved a substantially greater prominence than others in the field. This observation suggests considerable opportunities for future scientific exploration and development. Figure 5 presents the most influential organizations in this area, considering both scientific articles, represented in blue, and patents, represented in orange, among the 75 selected articles and the 40 patents analyzed.

Among the 40 patents aligned with the research topic, only three have been revoked, potentially due to reasons such as lack of novelty, insufficient inventive step, or failure to exploit the patented technology. Fourteen patents have already been granted, ensuring exclusive rights to their inventors or assignees. The remaining 23 patents are still pending, which can be attributed both to the lengthy period required between patent filing and grant and to the relatively recent filing dates of many applications.

Although the authorship analysis does not reveal the existence of researchers who overwhelmingly dominate this field, a different pattern emerges when research output is examined at the country level. In this context, China stands out remarkably in comparison with other nations in terms of both scientific production and technological development. Among the 15 most influential institutions identified, 13 are located in China, with the only exceptions being Al-Azhar University in Egypt and Indian Institute of Science Education and Research Kolkata in India.

Furthermore, 45 articles were found to include at least one author affiliated with a Chinese institution, highlighting the country’s strong presence and leadership in this research domain. These findings demonstrate China’s prominent role in the studied field, significantly surpassing the participation of other countries in both scientific and technological contributions (Figure 6).

China’s dominance in both research and patenting activities related to the use of biochar for microplastic adsorption stems from long-standing national science and technology policies focused on areas such as environmental remediation, waste management, and green technologies. This leadership has also been strengthened by governmental incentives for patent filing, including academic reward policies. Such efforts are driven by the need to address severe plastic and microplastic pollution affecting the country’s aquatic ecosystems, as well as by the vast availability of agricultural residues, including rice straw, sugarcane bagasse, and peanut shells, which serve as essential feedstocks for biochar production (Fürst & Feng, 2022).

Following China, India ranks second with 11 articles, while Canada occupies third place with seven publications. Brazil contributed two articles, one authored by researchers from the Fluminense Federal University and another involving a researcher from the Federal University of Mato Grosso. These findings indicate substantial opportunities for further research in this field within Brazil. Currently,

no specific public policies addressing microplastic remediation or biochar production have been implemented in the country. However, Bill No. 260/2024 proposes the establishment of specific guidelines and the implementation of treatment systems aimed at removing microplastics, persistent organic pollutants, endocrine disruptors, and other contaminants from wastewater and drinking water sources (Agência Senado, 2024).

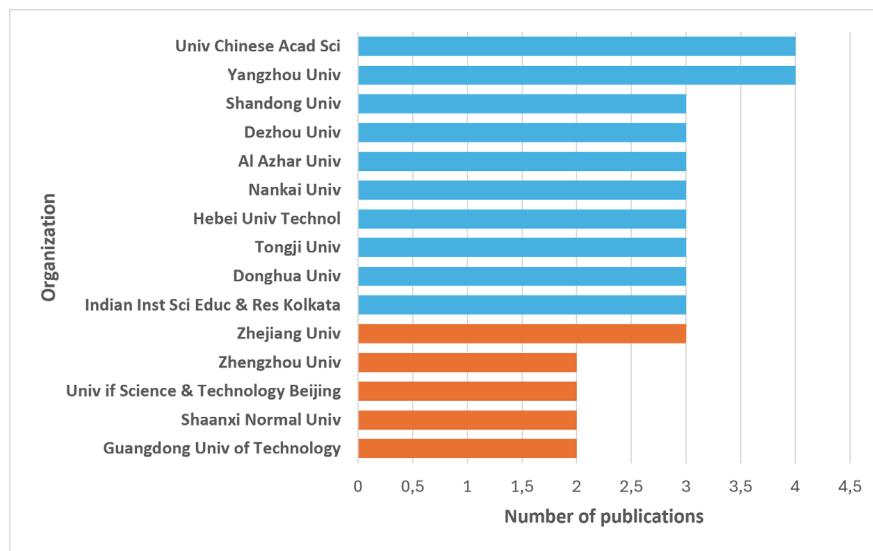
It is important to note that the use of biochar is associated with broader environmental and bioeconomy policies that encourage the sustainable use of resources and the development of technologies designed to improve environmental quality and remediate environmental damage. Examples include the National Solid Waste

Policy (PNRS), which seeks to reduce waste generation and promote reuse, recycling, and proper waste treatment, and the National Environmental Policy (PNMA), which establishes the principles and objectives of environmental management in Brazil, including the protection of water resources and soils (Tera Ambiental, 2025; Vertown, 2025).

Despite China’s overwhelming leadership, the present study included articles originating from 31 different countries, representing all five continents: Asia, Africa, the Americas, Europe, and Oceania (Box 1).

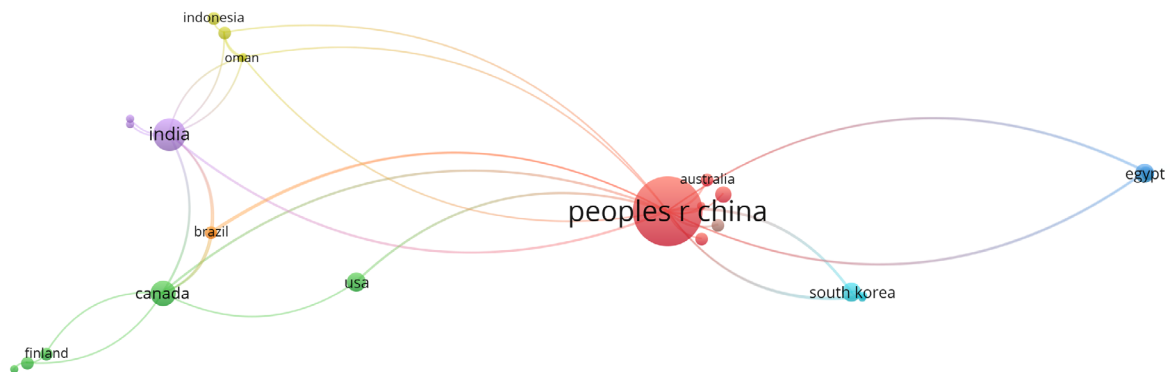
To identify the correlations among the keywords used in the selected articles, Figure 7 presents the 24 most frequently occurring keywords, each appearing at least five times within the research portfolio.

Figure 5 – Most influential institutions in the field



Source: Prepared by the authors (2025)

Figure 6 – Graph of the Countries with the Highest Number of Publication



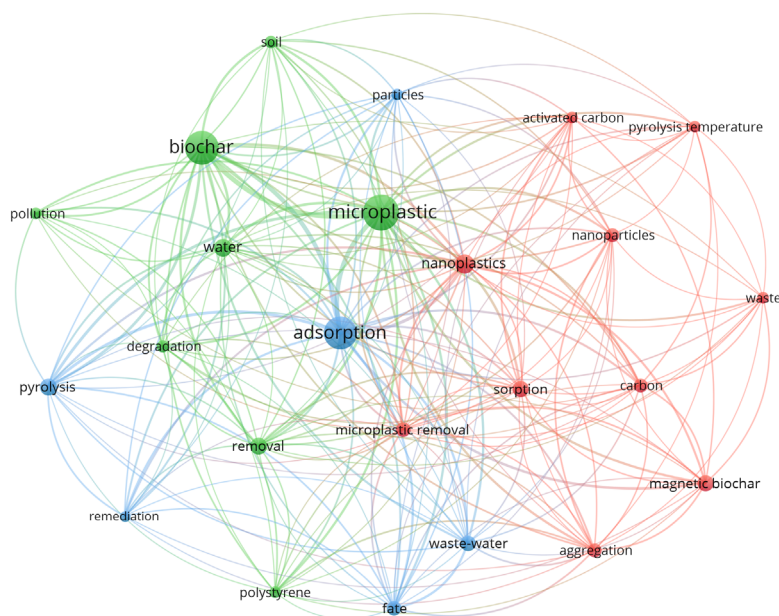
Source: Prepared by the authors using VOSviewer (2025)

Box 1 – Representation of the continents

CONTINENT	COUNTRY
Asia	China; India; South Korea; Indonesia; Malaysia; Saudi Arabia; Bangladesh; Lebanon; Oman; Singapore; Sri Lanka; Taiwan; Thailand; United Arab Emirates
Africa	Egypt; Algeria; Nigeria
Americas	Canada; United States; Brazil
Europe	England; Finland; Germany; Italy; Netherlands; Denmark; Poland; Scotland; Sweden; Wales
Oceania	Australia

Source: Prepared by the authors (2025)

Figure 7 – Graph of keyword relationships identified in the selected studies



Source: Prepared by the authors using VOSviewer (2025)

Among the most recurrent terms, the keyword “microplastics” stood out with 48 occurrences, followed by “biochar” with 42 occurrences and “adsorption” with 41 occurrences. These findings highlight the adsorptive properties of biochar and its potential interaction with this emerging pollutant. The keywords “water,” “wastewater,” and “soil” were also prominent, appearing 13, 10, and 7 times, respectively. This indicates the environmental compartments most frequently investigated and considered most relevant for microplastic remediation using biochar.

In addition, the terms “pyrolysis” and “pyrolysis temperature” appeared 12 and 6 times, respectively. Pyrolysis, a thermochemical process involving the decomposition of organic materials under oxygen-limited

conditions, is one of the most widely employed techniques for biochar production. Beyond these terms, the keywords “removal,” “degradation,” and “remediation” occurred 12, 7, and 5 times, respectively, directly reflecting the strategies developed to address the microplastic pollution problem.

Figure 8 presents the technological applications and innovations identified in the patent documents, making it possible to correlate these developments with the most frequently occurring keywords observed in the scientific literature.

The terms “water bodies,” “wastewater,” “soil,” and “sewage” are particularly prominent, demonstrating, as observed in the scientific articles, the principal environments in which biochar is applied. Several

The most recurrent research areas associated with this topic include Ecology and Environmental Sciences, Engineering, Water Resources, Chemistry, Science and Technology, Agriculture, Applied Microbiology and Biotechnology, and Materials Science. Engineering stands out because of its direct connection to the development of applied research focused on the production and utilization of biochar. Such studies frequently require the use of large-scale and sophisticated equipment, including tubular furnaces and milling systems, which are essential for the production, characterization, and application of biochar. The findings also reveal a strong interconnection among chemistry, engineering, and environmental sciences. Scientific and technological expertise in these disciplines is fundamental for environmental restoration and the mitigation of environmental damage. These efforts are closely aligned with the Sustainable Development Goals (SDGs), which provide a framework for promoting sustainable solutions to contemporary environmental challenges.

3.3 Biochar and Microplastics

In addition to investigating the main applications and research areas associated with the selected studies, it is important to identify the biomass feedstocks used for biochar production, as well as the types and sizes of microplastics adsorbed. This approach enables the identification of underexplored or unexplored opportunities that may serve as promising directions for future research. Therefore, through a detailed examination of the abstracts and, when necessary, the Materials and Methods sections of the selected articles, Box 2 was compiled to present all biomass feedstocks employed in the studies.

A large number of studies employ biomass derived from wood, rice, corn, sugarcane, and nuts. These feedstocks are closely associated with forestry activities and agricultural production, which are linked to major food, biofuel, and paper industries. Most of these biomasses are lignocellulosic in nature, as they are primarily composed of lignin, cellulose, and hemicellulose (Syguła, Ciolkosz, & Białowiec, 2024). Consequently, there is a noticeable lack of research exploring protein-based biomasses, such as insects, as well as biomasses derived from plant species native to specific regions. In the case of Northern and Northeastern Brazil, examples include açai, cocoa, and cupuaçu. These underexplored feedstocks may represent promising opportunities for future research on biochar production and microplastic remediation. In addition, Figure 10 presents the chemical structures of the main types of microplastics removed through biochar-based adsorption processes.

It can be observed that all plastics are polymers; however, they exhibit markedly different chemical structures, such as polyamide (PA) and polyethylene terephthalate (PET), or relatively similar structures, as in the

case of polypropylene (PP), polyethylene (PE), polyvinyl chloride (PVC), and polystyrene (PS). These structural differences influence both the mechanisms and the strength of the interactions between biochar and the adsorbate (microplastic), making further investigation necessary through characterization analyses and the application of theoretical and experimental models.

Among the microplastics evaluated, polystyrene (PS) was the most frequently studied, appearing in 33 studies. Polyethylene (PE) ranked second, being employed in 13 studies. Both materials are among the most abundant plastic types found in the environment, which justifies the recurring interest in their investigation (Alimi et al., 2018). In most studies, no distinction was made between high-density polyethylene (HDPE) and low-density polyethylene (LDPE). In addition to the six plastics presented in Figure 10, other studies investigated polymethyl methacrylate (PMMA), polyurethane (PU), polyarylamide (PARA), and acrylonitrile butadiene styrene (ABS). These findings indicate that substantial opportunities remain for future investigations involving a wider variety of plastic types.

Regarding microplastic size, most studies focused on particles within the micrometer range, from 1 to 500 μm . Several articles investigated the adsorption of particles ranging from 30 to 800 nm, whereas relatively few studies employed microplastics with sizes between 1 and 5 mm. The development of biochars capable of efficiently removing microplastics with diameters of only a few nanometers remains a significant challenge. Understanding the types of biomass feedstocks and microplastics involved in these studies contributes to a better comprehension of their relationship with the Sustainable Development Goals (SDGs).

3.4 Sustainable Development Goals (SDGs)

One of the analytical features provided by the Web of Science platform is the correlation of publications with the Sustainable Development Goals (SDGs). In this context, Figure 11 presents the nine SDGs identified among the analyzed publications. Each bar represents the number of articles associated with the respective goal, with the values obtained by reading the x-axis of the graph.

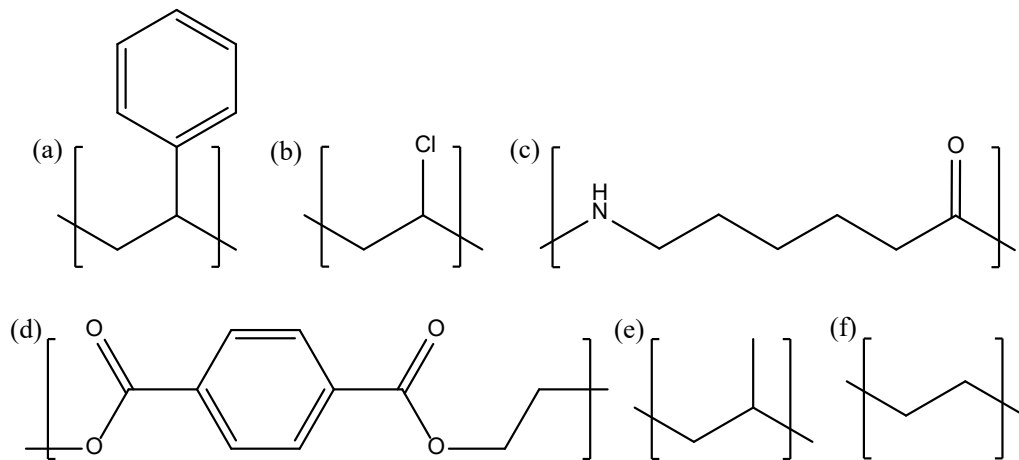
The SDGs most frequently represented in the analyzed publications were SDG 6 (Clean Water and Sanitation), SDG 14 (Life Below Water), SDG 11 (Sustainable Cities and Communities), and SDG 12 (Responsible Consumption and Production), appearing in 71, 68, 67, and 67 articles, respectively. These studies are primarily associated with the development of improvements in Water Treatment Plants (WTPs) and the remediation of microplastics in aquatic environments and soils, aiming to promote more sustainable environmental management practices.

Box 2 – Biochar feedstocks and modifications

TYPE	BIOMASS
Husk	Rice, Coconut, Walnut, Peanut, Macadamia, Palm Kernel
Straw	Rice, Wheat, Rapeseed
Bagasse	Sugarcane
Corn Cob	Corn
Spent Coffee Grounds	Coffee
Wood	Bark, Sawdust
Sludge	Sewage
Manure	Cattle, Poultry, Swine

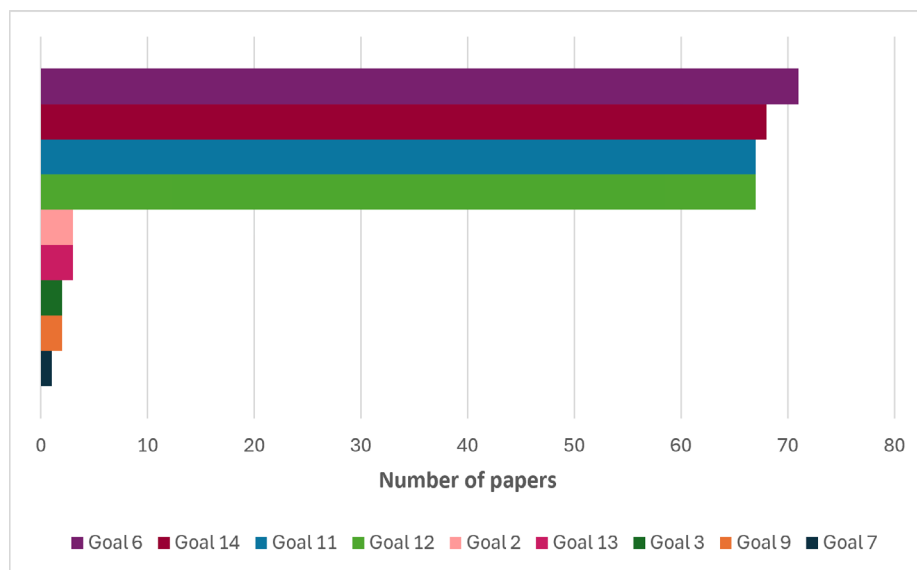
Source: Prepared by the authors (2025)

Figure 10 – Main types of microplastics :(a) PS; (b) PVC; (c) PA; (d) PET; (e) PP; (f) PE



Source: Prepared by the authors using ChemDraw (2025)

Figure 11 – Tree Map of the Sustainable Development Goals



Source: Prepared by the authors (2025)

According to the United Nations, SDG 6 seeks to ensure the availability and sustainable management of water and sanitation for all. SDG 11 aims to make cities and human settlements inclusive, safe, resilient, and sustainable. SDG 12 promotes sustainable consumption and production patterns. SDG 14 focuses on the conservation and sustainable use of oceans, seas, and marine resources for sustainable development (United Nations Brazil, 2025).

In addition to these four prominent goals, the topic is also connected to five other SDGs: SDG 2 (Zero Hunger), SDG 13 (Climate Action), SDG 3 (Good Health and Well-Being), SDG 9 (Industry, Innovation and Infrastructure), and SDG 7 (Affordable and Clean Energy), which were associated with three, three, two, two, and one article, respectively.

The strong alignment between this research field and the Sustainable Development Goals reinforces the need for further studies aimed at developing effective strategies for microplastic remediation and advancing sustainable development worldwide.

4 Final Considerations

The application of the ProKnow-C process enabled the selection of 75 articles for the construction of the research portfolio, along with 40 aligned patent documents. The results reveal significant growth in both scientific and technological production over the last eight years, highlighted by the doubling of article and patent publications in 2022 and 2023, respectively. This trend may be associated with increased environmental contamination by microplastics resulting from the rise in the production and consumption of plastic-based materials during the COVID-19 pandemic.

Chinese institutions have emerged as global leaders in this research field when compared with the rest of the world. This leadership is driven by policies that encourage patent filing by universities, as well as by the implementation of strategies focused on green technologies, environmental remediation, and waste management. Such efforts have been motivated by the widespread occurrence of microplastic pollution in aquatic environments and by the country's extensive availability of agricultural residues suitable for biochar production.

Brazil remains at a relatively early stage in the field of microplastic remediation using biochar, despite producing a considerable number of studies on both microplastics and biochar individually. Consequently, substantial opportunities exist for future research in this area, including the adaptation of already established Brazilian biochar technologies for microplastic remediation applications, in alignment with the National Solid Waste Policy (PNRS) and

the National Environmental Policy (PNMA). Furthermore, the implementation of specific initiatives, such as Bill No. 260/2024, may contribute to fostering research and positioning the country as a global reference in this branch of sustainable development.

The most recurrent keywords emphasize both the biochar production process and its interaction with microplastics through adsorption mechanisms, aiming to address the environmental challenges associated with these pollutants. The findings also highlight the most studied and relevant environments for biochar application in microplastic removal, including aquatic systems, wastewater, and soils. The principal research and technological areas associated with this topic are Environmental Technology, Chemical Engineering, Chemistry, and Biotechnology, reflecting the importance of applied research, advanced scientific knowledge, and the use of sophisticated analytical and processing equipment.

Most of the analyzed studies employ biomass feedstocks derived from agricultural and forestry sectors for biochar production, with a primary focus on the removal of polystyrene (PS) and polyethylene (PE) microplastics at micrometer-scale sizes. The establishment of the Sustainable Development Goals (SDGs) in 2015 has contributed significantly to the advancement of research and technologies aimed at removing pollutants from the environment. Accordingly, a direct relationship was identified between the analyzed studies and the SDGs, particularly SDG 6 (Clean Water and Sanitation), SDG 14 (Life Below Water), SDG 11 (Sustainable Cities and Communities), and SDG 12 (Responsible Consumption and Production), all of which are closely linked to the protection and sustainable management of aquatic and terrestrial environments.

5 Future Perspectives

This study highlights the need for and importance of increased investments and public policies aimed at implementing biochar-based technologies for microplastic removal, particularly in Brazil. Such initiatives are essential to promote both scientific and technological advancement in this field while supporting broader sustainable development goals.

In this context, it is expected that the findings of the present work will encourage future studies focused on scientific and patent landscape analyses. Furthermore, based on the bibliographic portfolio established in this research, a comprehensive review article is envisaged through an in-depth examination of the selected publications. This review may explore topics such as environmental application settings, biochar types, biochar adsorption efficiency, pyrolysis parameters, microplastic types, and other relevant factors. Such an approach would facilitate the identification of the most suitable compositions and

operational parameters for optimizing the preparation and characterization of biochars with high microplastic adsorption capacity.

Subsequently, different biochars could be produced and applied to various types of microplastics, followed by a comprehensive life cycle assessment covering all stages of material production and application. This assessment would enable the identification of the principal environmental impacts associated with the process and support the proposal of improvements aimed at reducing these impacts while enhancing the overall efficiency and sustainability of biochar-based microplastic remediation technologies.

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