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Evaluating Solutions to Marine Plastic Pollution

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Abstract: The pollution of the oceans by plastic waste is one of the major environmental problems of our time. It is estimated that there are millions of tons of polymers floating on the surface of the oceans, concentrated in several large plastic accumulations so-called plastic islands. The main consequence of marine plastic pollution is the negative impact on marine ecosystems and wildlife. The microplastics can be ingested by marine organisms and transferred through the food chain, potentially having harmful effects on human health. Humanity needs to take immediate action to reduce the high number of plastics that end up in the oceans, otherwise the harmful consequences for our oceans and for humanity will be irreversible. In view of this scenario, the present bibliometric review reflects a growing global commitment to sustainability. Major areas of research, including data-driven models for plastic waste management, technological innovations in the circular economy and the impact of microplastics on ecosystems and human health, exemplify the diverse strategies being employed to promote sustainability. Integrating advanced technologies with sustainable practices is crucial to reduce the environmental footprint of plastic waste and mitigate its adverse effects on both marine ecosystems and human health.

Keywords: plastic waste management; environmental problems; circular economy; pollution remediation technologies; microplastics; marine ecosystems

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1. Introduction

The pollution of oceans by plastic waste has rapidly become one of the most pressing global environmental challenges, with profound implications for both marine ecosystems and human health. Since the mid-20th century, the exponential increase in the production and improper disposal of synthetic plastics has led to a widespread accumulation of plastic debris in oceans worldwide [1,2]. This escalating issue poses severe threats to marine life through ingestion, entanglement and habitat disruption, and it also poses risks to human health due to the potential transfer of toxic chemicals through the food chain [3–5]. Estimates suggest that more than 5 trillion plastic pieces, collectively weighing over 250,000 tons, are currently afloat in the world's oceans, impacting marine environments from the surface to the deep sea [6].

One of the most visible consequences of this pollution is the formation of large "plastic islands" within the world's oceans, particularly within the five major subtropical gyres. The Great Pacific Garbage Patch, situated between Hawaii and California, is the most notable of these, covering an estimated area of 1.6 million square kilometers [7]. Recent studies have identified up to eight such zones of plastic accumulation, underscoring the global magnitude of this issue [8,9]. These floating debris fields range in size from large, visible pieces to microplastics, which have a significant impact on marine ecosystems [10,11]. For example, microplastics, defined as particles smaller than 5 mm, are pervasive in marine environments and can be ingested by a broad spectrum of marine organisms [12–14].

Microplastics enter the marine food chain through multiple pathways, the main ones being direct ingestion by marine organisms that mistake them for food and trophic transfer between species [15]. The bioaccumulation process begins with the ingestion of microplastics by plankton and other small organisms, which are then consumed by species at higher trophic levels [16]. As microplastics move up the food chain, biomagnification occurs, resulting in higher concentrations in top predators [17,18]. In addition, microplastics act as vectors for organic pollutants, toxins and heavy metals, which attach to their surface and are indirectly incorporated into the food web [19]. This process affects a wide range of marine organisms, from zooplankton to large predators, and can have negative impacts on the survival, feeding and reproduction of affected species [20].

The sources of oceanic plastic pollution are predominantly land-based, with certain countries contributing more significantly due to their high levels of plastic production and inadequate waste management systems [21,22]. Nations such as China, Indonesia, the Philippines, Vietnam and Thailand are among the largest contributors to marine plastic pollution [23,24]. The effectiveness of policies and waste management practices varies widely across these countries, directly influencing their contributions to the problem [25]. While some countries have enacted stringent regulations to curb plastic waste, others continue to struggle with enforcement and infrastructural challenges [26,27]. The success of policies like bans on single-use plastics and enhanced waste management practices can significantly reduce plastic pollution levels [28,29].

Globally, plastic production has surged to approximately 400 million metric tons annually, with a substantial portion being used for single-use products and packaging [30,31]. Despite increasing awareness, only about 9% of plastic waste is recycled, 12% is incinerated and a staggering 79% accumulates in landfills or the natural environment, including oceans [32,33]. This inefficiency in waste management exacerbates the problem, highlighting the urgent need for improved recycling and waste reduction strategies [34,35]. Research indicates that marine plastic debris not only contaminates surface waters but also penetrates deep-sea sediments, affecting a wide range of marine habitats [36–38].

The urgency to address ocean plastic pollution is amplified by its extensive impact on both marine ecosystems and human health. Studies have shown that microplastics are ingested by a wide variety of marine organisms, from zooplankton to large marine mammals, causing physical and chemical stress [39–42]. Microplastics have been detected in the digestive systems of over 100 marine species, impairing their ability to feed and reproduce, and in zooplankton, which are crucial to the marine food web; microplastics can reduce feeding efficiency and growth rates, potentially disrupting entire ecosystems [40]. Larger marine animals, including whales and seabirds, have also been found with significant amounts of plastic debris in their stomachs, sometimes leading to fatal outcomes [41,42].

The presence of microplastics in seafood raises serious concerns about human exposure to these contaminants and their potential health risks [43,44]. Microplastics can act as carriers for harmful pollutants, such as heavy metals and persistent organic pollutants (POPs), which can leach into the tissues of marine organisms and bioaccumulate up the food chain [43]. When humans consume seafood contaminated with microplastics, they risk ingesting these toxic substances, which have been linked to a range of health issues, including endocrine disruption, reproductive toxicity and carcinogenic effects [44]. Furthermore, plastics can serve as vectors for POPs and other hazardous chemicals, exacerbating their ecological and health impacts [45–47]. These chemicals can adhere to the surface of microplastics, leading to higher concentrations of pollutants in the marine environment and increasing exposure risks for marine life and humans alike [46].

The effects of plastic pollution are not confined to ecological impacts alone (Figure 1). The impacts of plastic pollution extend beyond environmental concerns, affecting the socio-economic stability of coastal communities, particularly those reliant on tourism and fisheries. Littered beaches can deter tourists, diminishing local economies, while declining fish populations due to plastic ingestion adversely affect fisheries [48,49]. Coastal tourism, a vital economic sector for many regions, suffers from reduced aesthetic value due to marine litter, leading to a decrease in tourist visits and associated revenues [48]. Additionally, fisheries face economic losses as fish stocks diminish due to plastic ingestion, which can cause physical harm and reduce reproductive success in marine species [49]. The costs associated with cleaning up marine litter and the loss of biodiversity further strain economic resources, as governments and local authorities must divert substantial funds from other critical areas to manage the problem [50]. Moreover, the decline in biodiversity can have long-term impacts on ecosystem services, such as carbon sequestration, which are essential for mitigating climate change [51].

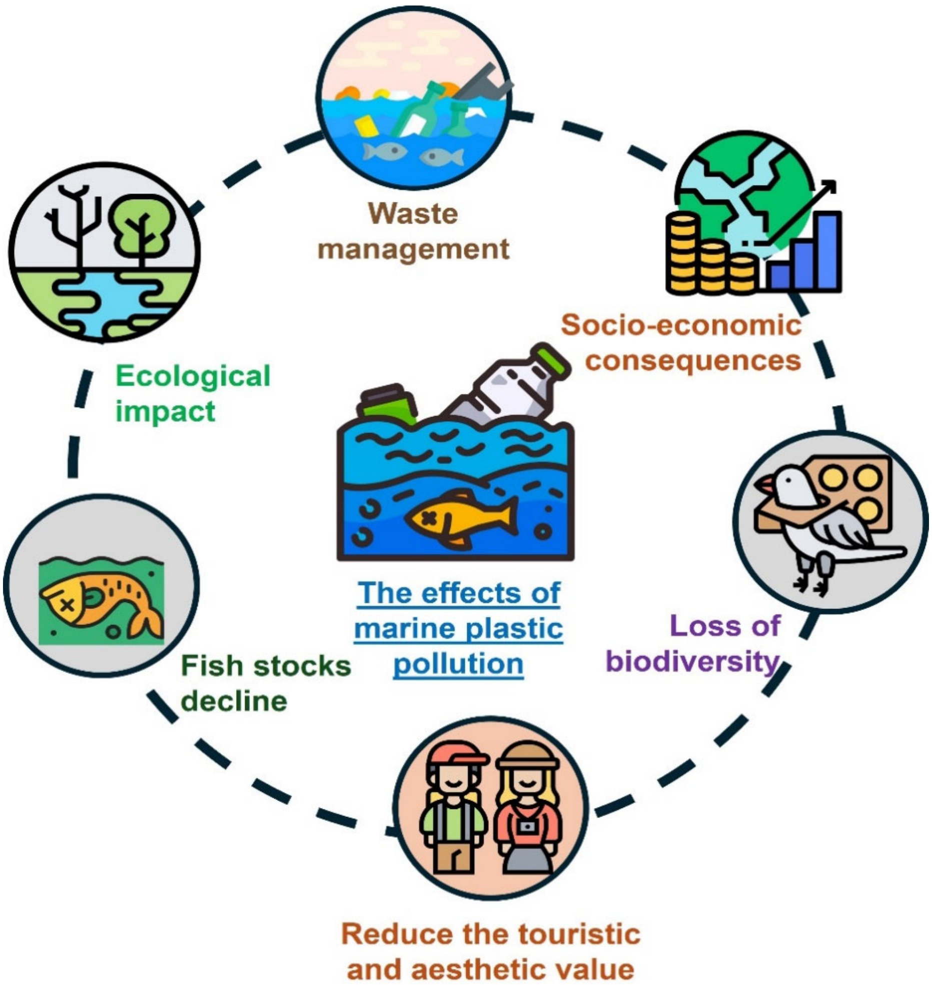


Figure 1. The effects of marine plastic pollution.

If current trends continue without effective interventions, the volume of plastic entering the oceans could triple by 2040 [52,53]. Such a scenario would exacerbate the ecological and socio-economic impacts, further affecting marine biodiversity, fisheries, tourism and human health [48,49]. Increased plastic pollution could accelerate the degradation of marine habitats, including coral reefs and mangroves, which are already threatened by climate change and other human activities [52]. Additionally, the accumulation of plastics on the food web could disrupt predator–prey relationships and alter nutrient cycles, leading to cascading effects throughout marine ecosystems [53]. The socio-economic impacts would also intensify, placing greater financial burdens on communities and governments tasked with managing the growing amounts of marine litter [54]. This paper aims to synthesize scientific publications addressing solutions to ocean plastic pollution, providing a comprehensive bibliometric review to identify current trends, gaps and emerging strategies.

Given the global scope of ocean plastic pollution, it is essential to consolidate existing research to inform policy and practice effectively. This paper provides a comprehensive bibliometric review of scientific publications proposing solutions to this pressing issue. By analyzing trends, identifying research gaps and highlighting innovative approaches, we aim to contribute to the global effort to mitigate ocean plastic pollution. This review focuses on evaluating the effectiveness of various mitigation strategies, including policy interventions, technological innovations and community-based initiatives [55–58]. Through this synthesis, we hope to provide a clearer understanding of the current state of research and to identify pathways for future investigations and policy developments [59–61].

In this study, an integrated methodology that combines bibliometric analysis with topic modeling based on machine learning techniques, specifically Latent Dirichlet Allocation (LDA) was implemented [62]. The investigation into the existing scientific literature on marine plastic pollution (MPP) aimed to address several key questions:

1. What are the primary sources of publication and significant contributors to MPP research and control technologies?
2. What scientific collaborations exist between countries in these research areas?
3. What are the primary research topics in these fields?
4. How do these research topics evolve?
5. What are the distributions of these topics across countries and scientific journals?

2. Materials and Methods

2.1. Data Collection

For the systematic collection of data, we adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [63,64]. Our dataset was exclusively sourced from the Web of Science (WoS) database, a widely recognized platform for retrieving the pertinent literature, tracking citation metrics and assessing research impact [65]. WoS encompasses a diverse range of academic disciplines, including the sciences, social sciences, arts and humanities [65,66]. Although other databases such as Scopus offer extensive coverage, we confined our study to WoS to maintain consistency and focus within our dataset.

The data search was executed on 24 June 2024, employing the following query: TS = (“marine plastic pollution” OR “plastic waste” OR “plastic debris” AND (“control technologies” OR “mitigation strategies” OR “remediation techniques”)). This query yielded a total of 8170 documents (Figure 2). During the screening process, only articles and reviews were selected (n = 7979), while books, book chapters, conference papers and other document types were excluded (n = 191). We also removed duplicate records (n = 189), resulting in 7790 documents at this stage.

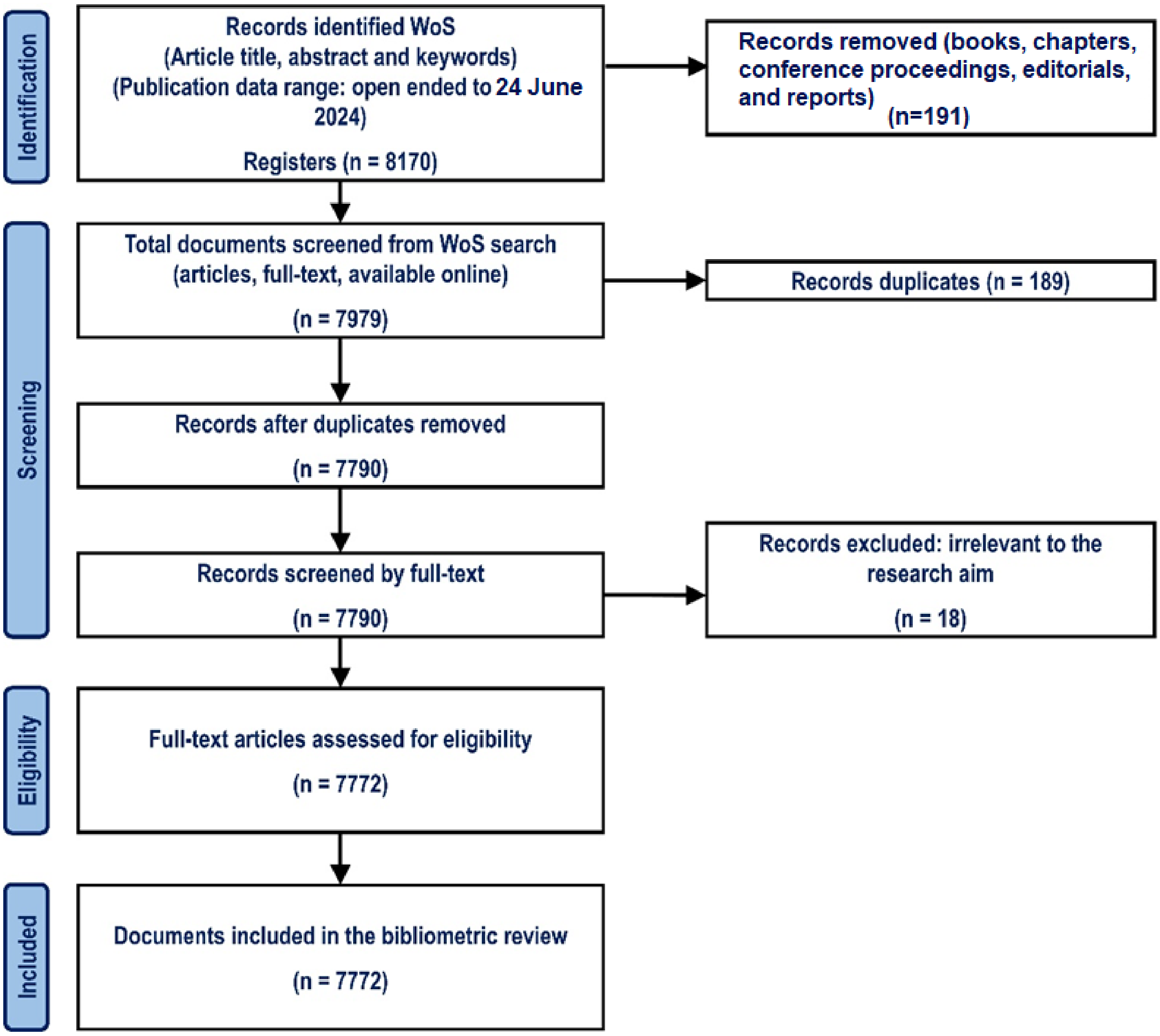


Figure 2. PRISMA protocol in the present review.

In the eligibility assessment phase, 18 documents were excluded from the analysis—10 due to the absence of abstracts and 8 because of missing affiliation information. Consequently, our final analysis focused on a refined dataset of 7772 articles.

2.2. Bibliometric Analysis

Bibliometric analysis, a quantitative technique used to evaluate and describe the academic literature, was employed to assess various research outputs by analyzing bibliographies. This method provides a structured approach to describe, evaluate and monitor the scientific literature, enabling the exploration of production patterns, trends and the impact of publications across different disciplines [67]. Bibliometric indicators are particularly valuable for examining the research literature and offer insights into various topics and disciplines by studying trends, production and the influence of publications.

In this study, we implemented a rigorous and objective bibliometric approach to address key research questions, including identifying the main sources of publication and significant contributors to marine plastic pollution (MPP) research (Q1) and examining scientific collaborations between countries in this domain (Q2). The bibliographic data collected allowed for an in-depth quantitative analysis, providing a comprehensive overview of the scientific output within the scope of our study. This analysis covered aspects such as document distribution, publication dynamics and the identification of influential contributors, including researchers, institutions, countries and publication sources, thereby offering essential insights into the landscape of MPP research.

To conduct this analysis, we utilized the bibliometrix R-Tool [67], an R package, version 4.4.2, (R-Team, 2024) designed specifically for quantitative bibliometric and scientometric research.

2.3. Latent Dirichlet Allocation

To address research questions Q3, Q4 and Q5, Latent Dirichlet Allocation (LDA)—a topic modeling approach—was employed. LDA is a Bayesian probabilistic model that assumes that documents consist of a mixture of topics, each represented by a distribution of words, allowing for the capture of the diverse topics present in scientific publications. This machine learning technique is used to automatically identify topics within a single document or a set of documents without prior labeling.

LDA is considered a mixed-membership model in statistics and extends the Probabilistic Latent Semantic Analysis [62,68]. The model assumes that documents are represented by a random combination of latent topics, each characterized by a distinct distribution of words [62]. It also assumes a fixed number of topics distributed across the entire document collection, with each document contributing to multiple topics. Each term in the document is assigned a probability of belonging to a particular topic, allowing for the inference of topic probability distribution for each document.

The objective of LDA is to infer or estimate latent variables by calculating their conditional distribution relative to the observed data. Equation (1) outlines the statistical assumptions underlying LDA's generative process:

$$p(\beta_K, \theta_D, z_D, w_D) = \prod_{k=1}^{K} p(\beta_K|\eta) \prod_{m=1}^{M} p(\theta_m|\alpha) \prod_{n=1}^{N} p(z_{m,n}|\theta_m) P(w_{m,n}|z_{m,n}, \beta_{m,k}) \tag{1}$$

where k represents the number of topics, M is the number of articles, N denotes the number of words in a document and α and η (Dirichlet hyper-parameters) define the prior distributions over θ and β, respectively. θ_m represents the topic distribution for article m, $z_{m,n}$ denotes the topic for the n-th word in the m-th article, $w_{m,n}$ is the n-th word of the m-th document and β_k represents the distribution of words for the topic k. The goal is to estimate the hidden structure with statistical inference methods based on the only observed variable—the words within the documents. The conditional probability, known as the posterior probability, is expressed by Equation (2):

$$p(\beta_K, \theta_M, z_M|w_M) = \frac{p(\beta_K, \theta_M, z_M, w_M)}{p(w_M)} \tag{2}$$

Although the exact computation of the posterior probability is complex due to the denominator term [62], statistical posterior inference methods provide an approximation. Two main inference techniques are commonly used: variational-based algorithms [68,69] and sampling-based algorithms [70], such as the Gibbs sampler [71]. Both methods offer similar levels of accuracy [72]. The topic identification process using LDA involved three main stages: (i) preprocessing, (ii) LDA model creation and (iii) topic labeling. The first two stages were carried out using LDAShiny [73], an open-source R package that offers a web-based graphical user interface. LDAShiny facilitates scientific literature reviews by applying Bayesian LDA and machine learning algorithms.

During preprocessing, bigrams (pairs of consecutive words) were used to tokenize each abstract. This process, while straightforward, involved critical steps such as converting text to lowercase, removing punctuation marks, hyphens, brackets, numbers, whitespace and other non-essential characters. Additionally, we removed "stopwords", which are common words used to construct grammatically correct sentences but add no significant meaning (e.g., articles and prepositions).

Topic models rely on the assumption that topics (latent variables) can be identified through the correlations between words and semantic topics in a collection of documents [74]. The selection of an appropriate number of topics for the analysis is critical and challenging, as it requires a balance between capturing all relevant topics in the document collection and producing understandable results. To assess the quality of the LDA model, we conducted simulations varying the number of topics (k) from 4 to 40 in incremental steps of one, using the Gibbs sampling inference algorithm with 500 iterations [75]. It was evaluated the model quality using a measure of topic coherence [76], which is a measure of a topic model from the perspective of human interpretability, to determine the quality of the LDA model. This measure is considered more appropriate than computational metrics such as perplexity [77].

Although the LDA model does not assign semantic labels to topics, algorithmic approaches have inherent limitations in comprehending the underlying meanings of human language. As a result, manual labeling is widely adopted as standard practice in topic modeling [78]. To ensure a semantically accurate interpretation, it was manually labeled the topics using two sources of information: the lists of the most frequent words (with the highest likelihood) and a sample of the titles. Then, it was summarized the three articles with the highest loadings for each topic.

The primary outputs of the LDA model include document-topic distributions and topic-word distributions. Given the large number of documents and words, it can be challenging to intuitively understand the topics or trends. Therefore, we utilized quantitative indices as proposed by [79], which aggregate document-topic and topic-word distributions at various levels to clarify the results.

The resulting measures are described as follows: the distribution of topics over time is calculated as

$$\theta_k^y = \frac{\sum_{m\epsilon y} \theta_{mk}}{n^y} \tag{3}$$

where $m\epsilon y$ represents articles published in a given year, θ_{mk} is the proportion of the k-th topic in each item and n^y the total number of articles published in that year. The distribution of topics across journals is defined as the ratio of the k-th topic in the journal j:

$$\theta_k^j = \frac{\sum_{m\epsilon j} \theta_{mk}}{n^j} \tag{4}$$

where $m\epsilon j$ represents the articles in a particular journal, θ_{mk} the proportion of the k-th topic on each item and n^j the total number of articles published in the journal j. The distribution of topics across countries is defined as the ratio of the k-th topic in country c:

$$\theta_k^c = \frac{\sum_{m\epsilon c} \theta_{mk}}{n^c} \tag{5}$$

where $m\epsilon c$ represents the articles in a particular country, θ_{mk} is the proportion of the k-th topic on each item and n^c the total number of articles published in that country.

To characterize the trends of the topics, we employed simple regression slopes, where the year served was the dependent variable and the proportion of the topics in the corresponding year was the response variable [70]. Topics identified through regression analysis as having statistically significant positive or negative trends were classified accordingly.

3. Results

The bibliometric analysis of research on marine plastic pollution control technologies, covering the period from 2003 to 2024 (Table 1), reveals a substantial increase in publications, with an annual growth rate of 23.35%. This trend underscores the growing global recognition of the urgent need to address marine plastic pollution within the framework of sustainability. The 7772 documents analyzed, published in 1500 different sources, demonstrate the wide-ranging interest in this critical environmental issue. With an average of just over three years, these documents reflect the current and influential nature of the research, as evidenced by an average of 30.33 citations per document. The depth and breadth of the research are further highlighted by the extensive reference base of 264,300 citations.

Table 1. Main information about bibliometric analysis of research on marine plastic pollution.

Description	Results
Main information about data	
Timespan	2003:2024
Sources (Journals)	1500
Documents	7772
Annual Growth Rate %	23.35
Document Average Age	3.06
Average citations per doc	30.33
References	264,300
Document contents	
Keywords Plus (ID)	9207
Author's Keywords (DE)	15,779
Authors	
Authors	26,445
Authors of single-authored docs	239
Authors collaboration	
Single-authored docs	278
Co-Authors per Doc	5.04
International co-authorships %	30.53
Document types	
Articles	6640
Reviews	1132

The research community studying marine plastic pollution is large and diverse, with 26,445 authors contributing to this body of work. Single-authored publications are rare, with only 239 authors producing 278 such documents. Instead, collaboration is a hallmark of this field, evidenced by an average of 5.04 co-authors per document and a notable 30.53% of publications involving international collaboration. This collaborative approach is essential for advancing sustainability goals, as it fosters the exchange of ideas and the development of innovative solutions to global challenges.

Figure 3 illustrates a notable trend in the evolution of research on marine plastic pollution control technologies. Since 2012, there has been a significant increase in the number of published articles, reflecting a growing interest and concern within the scientific community regarding this environmental issue. The average number of citations per year, represented by the blue line, shows fluctuations over time. Peaks are observed around the years 2015 and 2017, indicating that some articles published during those periods had a considerable impact in the field. However, starting in 2020, despite the continued increase in the volume of publications, there is a noticeable decline in the average number of citations per article. This could suggest a possible saturation in the production of studies or that more recent works have not yet had enough time to accumulate a significant number of citations.

With regard to the sources analyzed, Table 2 presents a selection of the 25 most influential journals in marine plastic pollution control technologies research, chosen from a total of 1500. These journals stand out for their relevance and contribution to the field, assessed through several key indicators: the h-index (H), total accumulated citations (TC), number of published articles (NP) and the year they began publishing on this topic (PY_start).

Table 2. Top 25 scientific journals for research on marine plastic pollution. H = h-index, TC = total citations, NP = number of publications and PY_start = year of publication start. The table is organized in descending order by NP.

Source	H	TC	NP	PY_start
Science of the Total Environment	57	13,508	265	2011
Journal of Cleaner Production	42	6123	212	2004
Waste Management	56	9974	207	2004
Sustainability	23	2076	199	2018
Polymers	25	2534	178	2014
Marine Pollution Bulletin	41	6312	162	2007
Journal of Hazardous Materials	37	4589	126	2003
Construction and Building Materials	43	5306	125	2008
Environmental Science and Pollution Research	25	2378	116	2003
Environmental Pollution	35	5090	109	2016
Resources Conservation and Recycling	43	5803	108	2006
ACS Sustainable Chemistry & Engineering	27	3454	107	2013
Chemical Engineering Journal	24	2339	97	2010
Journal of Analytical and Applied Pyrolysis	32	3451	95	2003
Fuel	26	2436	89	2003
Journal of Environmental Management	25	2268	78	2010
Materials	20	1446	78	2014
Journal of Material Cycles and Waste Management	15	819	72	2009
Journal of Environmental Chemical Engineering	18	1038	69	2017
Energies	15	642	64	2013
Chemosphere	24	2825	62	2006
Process Safety and Environmental Protection	19	1499	61	2016
Energy	22	1623	59	2011
Green Chemistry	20	2328	56	2015
Energy Conversion and Management	29	3287	55	2007

Among the most prominent journals are Science of the Total Environment and Waste Management, with h-indices of 57 and 56, respectively. These publications not only accumulate a high number of citations but also have a significant number of articles, highlighting their influence in the field of marine plastic pollution. Journal of Cleaner Production and Marine Pollution Bulletin also play a crucial role, with h-indices of 42 and 41, and a substantial number of articles published since they began addressing this topic in 2004 and 2007, respectively.

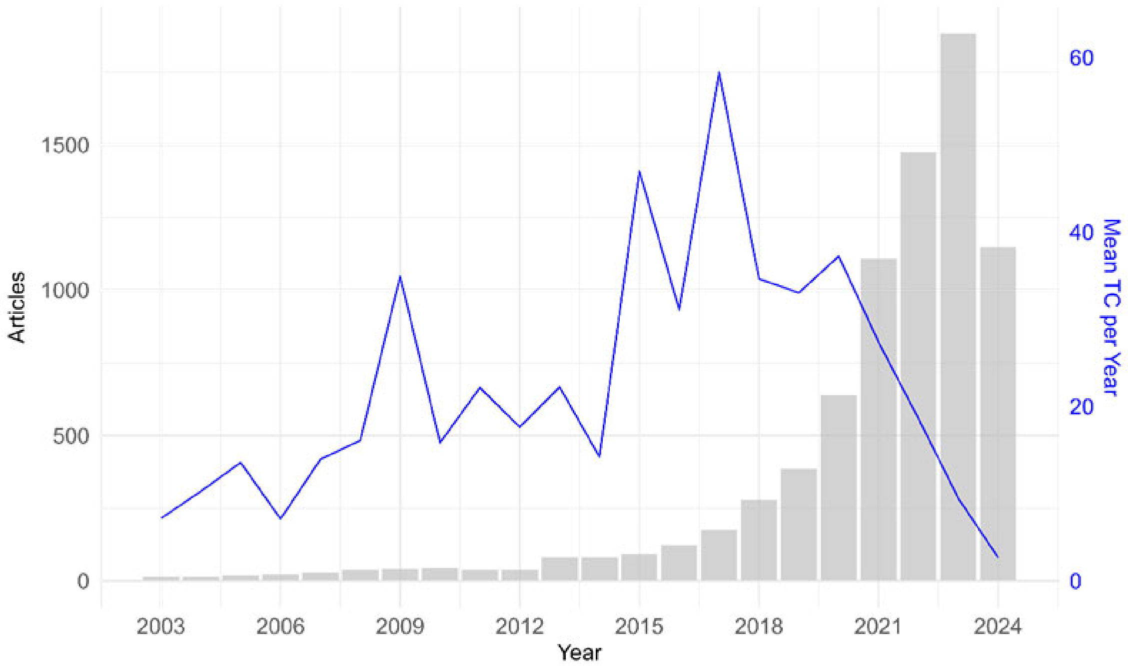


Figure 3. Annual scientific production about the collection of marine plastic pollution.

More recent journals such as Sustainability and Polymers, although with more modest h-indices and citation volumes, have shown significant growth since their more recent beginnings in 2018 and 2014. This increase reflects their growing importance in the scientific discussion on marine plastic pollution.

Figure 4 presents the geographic distribution of global scientific output from the 128 countries and regions researching marine plastic pollution control technologies, while Table 3 highlights the 20 most active countries in this field. China leads the ranking with 1108 publications and a total of 32,164 citations, establishing itself as the primary contributor to research in this area. India ranks second with 758 publications and 14,771 citations, demonstrating its growing prominence. The United States, while third in terms of the number of publications (600), stands out with the highest number of accumulated citations (35,441), underscoring the significant influence and impact of its studies.

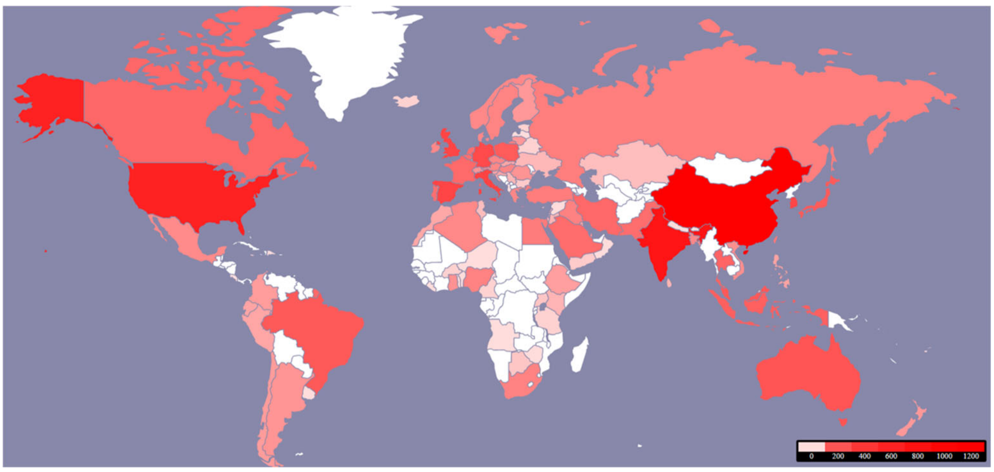


Figure 4. Distribution of geographical origins in the analysis of 7772 published articles on marine plastic pollution.

Table 3. Top 20 most prolific countries in marine plastic pollution based on 7772 articles published.

Country	NP	TC
China	1108	32,164
India	758	14,771
USA	600	35,441
United Kingdom	339	21,785
Italy	299	7353
Spain	289	8786
South Korea	278	6295
Germany	252	8506
Australia	201	5330
Malaysia	180	4691
Brazil	176	3353
Japan	169	2674
Poland	168	2599
Indonesia	150	1341
Thailand	133	1913
Canada	124	6764
Iran	122	2106
France	117	4111
Saudi Arabia	109	3322
Pakistan	106	3963

European countries such as Italy, Spain and the United Kingdom also show strong participation, with a substantial volume of publications and citations that reflect their commitment to research on marine plastic pollution. In Asia, alongside China and India, South Korea and Japan emerge as key contributors, while in the Americas, Brazil and Canada have a significant presence in scientific production on this topic.

4. Discussion

The analysis of trends in marine plastic pollution control technologies using Latent Dirichlet Allocation (LDA) has revealed a broad range of research areas, each reflecting different approaches to sustainability in this field. The results provide a comprehensive view of current trends in marine plastic pollution control research, emphasizing the importance of technological innovation and sustainability in waste management. The coherence score for all examined LDA models is displayed in Figure 5. The results indicate that the LDA model with the highest coherence score contains 25 topics (k = 25).

One of the most notable findings is the prominence of the topic on fuel production from plastic waste via pyrolysis (t_23), which highlights the importance of this technology in sustainable waste management (Table 4). The t_2, which addresses the Use of Plastic Waste in Concrete, also shows significant interest, with 542 publications. This topic explores how plastic waste can be incorporated into construction materials to enhance their properties, reflecting a growing trend in the reuse of plastics in infrastructure applications. The t_7 covers Technological Innovations in Circular Economy, focusing on the technological advancements needed to promote this approach.

This topic underscores the increasing importance of integrating technologies that not only manage plastic waste but also reintegrate it sustainably into the economy. The t_8 features Life Cycle Assessment, emerging as another crucial aspect, with studies analyzing the environmental impact of waste management technologies. This topic emphasizes the importance of evaluating the environmental benefits and challenges at each stage of material life cycles. t_15 highlights the management of Microplastics in Ecosystems and Human Health, with a particular focus on the associated risks and possible mitigation measures. This topic reflects the growing concern about the impact of these contaminants on the environment and human health.

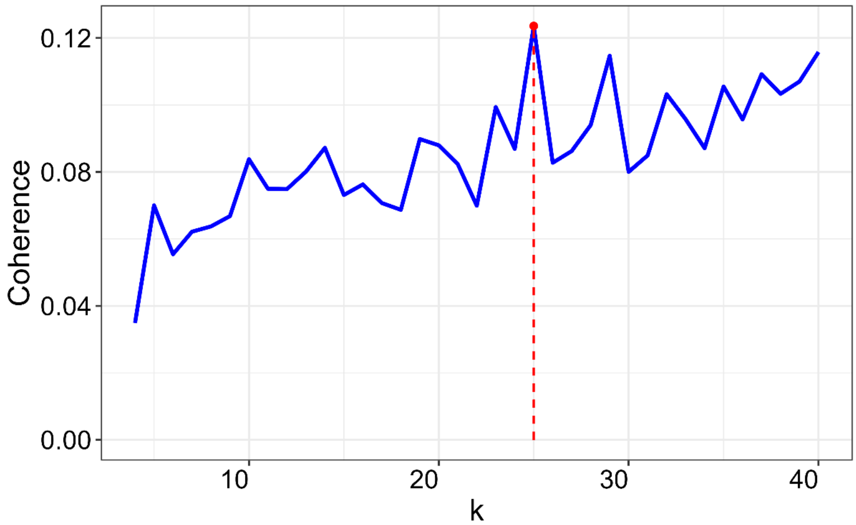


Figure 5. Coherence scores for Latent Dirichlet Allocation models with different numbers of topics (k). The red dot indicates the maximum coherence score.

Table 4. Topics identified in marine plastic pollution control technologies articles published between 2003 and 2024. (T = topic; N = Number of published documents).

T	N	Top_Terms	Label
t_1	170	carbon, activ, perform, materi, deriv, exhibit, util, wast, effici, surfac, applic, fabric, graphen, straw, structur, capac, prepar, demonstr, synthes, devic	Carbon-Based Materials from Waste
t_2	542	concret, strength, aggreg, wast, compress, replac, construct, increas, compress_strength, properti, mix, cement, fiber, sand, natur, investig, materi, decreas, flexur, test	Use of Plastic Waste in Concrete
t_3	285	model, method, base, analysi, design, propos, data, develop, optim, predict, appli, techniqu, evalu, approach, determin, methodologi, network, identifi, time, set	Data-Driven Models for Plastic Waste
t_4	398	wast, manag, gener, dispos, wast_manag, landfil, solid, solid_wast, wast_gener, increas, municip, mask, COVID, pandem, inciner, treatment, protect, msw, wast_dispos, household	Municipal Solid Waste Management
t_5	173	sampl, water, particl, microplast, size, type, concentr, surfac, detect, rang, abund, observ, averag, distribut, sediment, investig, mp, fragment, studi, presenc	Microplastic Distribution in Water Bodies
t_6	40	polyethylen, densiti, hdpe, ldpe, densiti_polyethylen, p, polypropylen, polystyren, polyethylen_hdpe, polyethylen_ldpe, type, polystyren_p, polyethylen_polypropylen, weight, polym, studi, blend, linear, mixtur, observ	Effects of Pyrolysis on Polyethylene
t_7	462	review, product, technologi, circular, economi, develop, discuss, current, challeng, base, futur, circular_economi, strategi, includ, industri, approach, provid, advanc, highlight, resourc	Technological Innovations in Circular Economy
t_8	273	impact, environment, life, assess, emiss, econom, cycl, cost, product, environment_impact, reduc, scenario, global, life_cycl, potenti, benefit, compar, reduct, analysi, consumpt	Life Cycle Assessment in Waste Management
t_9	274	polym, chemic, upcycl, depolymer, monom, function, polymer, solvent, effici, demonstr, membran, bond, chain, poli, molecular, method, structur, promis, select, report	Chemical Recycling and Polymer Upcycling

Table 4. *Cont.*

T	N	Top_Terms	Label
t_10	244	recycl, materi, wast, process, product, industri, mechan, post, manufactur, consum, recycl_wast, applic, wast_recycl, raw, post_consum, mechan_recycl, virgin, raw_materi, print, produc	Mechanical Recycling of Post-consumer Plastics
t_11	306	energi, process, biomass, gasif, product, wast, effici, fuel, ga, increas, produc, ratio, hydrogen, heat, bed, combust, convers, feedstock, content, temperature	Waste-to-Energy Conversion via Gasification
t_12	464	polici, reduc, manag, countri, consum, behavior, consumpt, implement, level, practic, factor, public, respons, environment, chang, govern, bag, social, singl, find	Consumer Behavior and Plastic Reduction Policies
t_13	98	wast, separ, recoveri, sort, rate, collect, stream, mix, recycl, process, plant, chain, close, packag, achiev, wast_stream, qualiti, improv, flow, suppli	Plastic Waste Recovery Systems
t_14	44	environment, sustain, solut, develop, wast, issu, friendli, green, effect, cost, approach, concern, util, address, eco, altern, challeng, potenti, environment_friendli, contribut	Environmental Sustainability and Eco-solutions
t_15	562	environ, microplast, pollut, mp, human, effect, organ, health, contamin, risk, potenti, ecosystem, impact, soil, exposur, aquat, environment, human_health, toxic, increas	Microplastic Impact on Ecosystems and Health
t_16	113	pvc, treatment, metal, concentr, chlorid, compound, oxid, addit, polyvinyl, organ, pc, chlorin, polyvinyl_chlorid, electron, extract, light, separ, electr, chemic, heavi	Chemical Treatment of PVC and Metal Waste
t_17	223	pet, terephthal, polyethylen, polyethylen_terephthal, bottl, terephthal_pet, spectroscopi, electron, analysi, transform, scan, ftir, infrar, character, sem, microscopi, pet_wast, fourier, ethylen, surfac	PET and Plastic Degradation Processes
t_18	167	test, perform, mixtur, modifi, asphalt, mix, addit, improv, soil, wast, increas, binder, ag, resist, bitumen, content, stabil, evalu, term, properti	Asphalt Modification with Plastic Waste
t_19	196	rate, activ, kinet, adsorpt, process, p, remov, reaction, mass, model, mol, paramet, method, investig, adsorb, interact, energi, polystyren, analysi, activ_energi	Adsorption Processes for Pollutant Removal
t_20	411	catalyst, catalyt, product, reaction, acid, yield, select, activ, convers, hydrogen, crack, format, aromat, zeolit, catalyt_pyrolysi, oxid, metal, valuabl, promot, chemic	Catalytic Processes in Waste Conversion
t_21	549	marin, pollut, ocean, sourc, debri, litter, global, river, fish, sea, region, transport, speci, marin_pollut, beach, data, major, item, coastal, estim	Marine Pollution and Oceanic Waste Transport
t_22	294	properti, composit, mechan, thermal, blend, addit, improv, fiber, increas, mechan_properti, strength, tensil, physic, polym, matrix, materi, compar, reinforc, applic, fibr	Mechanical Properties of Polymer-Reinforced Composites
t_23	727	pyrolysi, oil, degre, temperatur, product, fuel, yield, liquid, ga, time, fraction, thermal, produc, increas, rang, reactor, diesel, process, hydrocarbon, heat	Fuel Production from Plastic Waste via Pyrolysis
t_24	568	degrad, biodegrad, pla, enzym, microbi, polym, strain, acid, synthet, isol, microorgan, environ, cell, weight, potenti, bacteri, condit, dai, pha, accumul	Biodegradation of Polymers in Natural Environments
t_25	189	film, packag, food, base, water, materi, biodegrad, bio, bioplast, particl, applic, agricultur, food_packag, coat, surfac, altern, barrier, cellulos, increas, packag_materi	Biodegradable Films in Packaging and Agriculture

In the analysis of trends in marine plastic pollution control technologies, several distinct patterns were observed among the evaluated topics. Out of the 25 topics analyzed, six showed a clear upward trend in publication activity. These topics are as follows: t_12, which addresses data-driven models for plastic waste; t_14, focused on technological innovations in the circular economy; t_15, examining the impact of microplastics on ecosystems and health; t_21, related to marine pollution and oceanic waste transport; t_25, dealing with biodegradable films in packaging and agriculture; and t_7, which centers on technological innovations in the circular economy (Figure 6). The sustained increase in these topics can be attributed to growing awareness of environmental issues and the development of new technologies to address them.

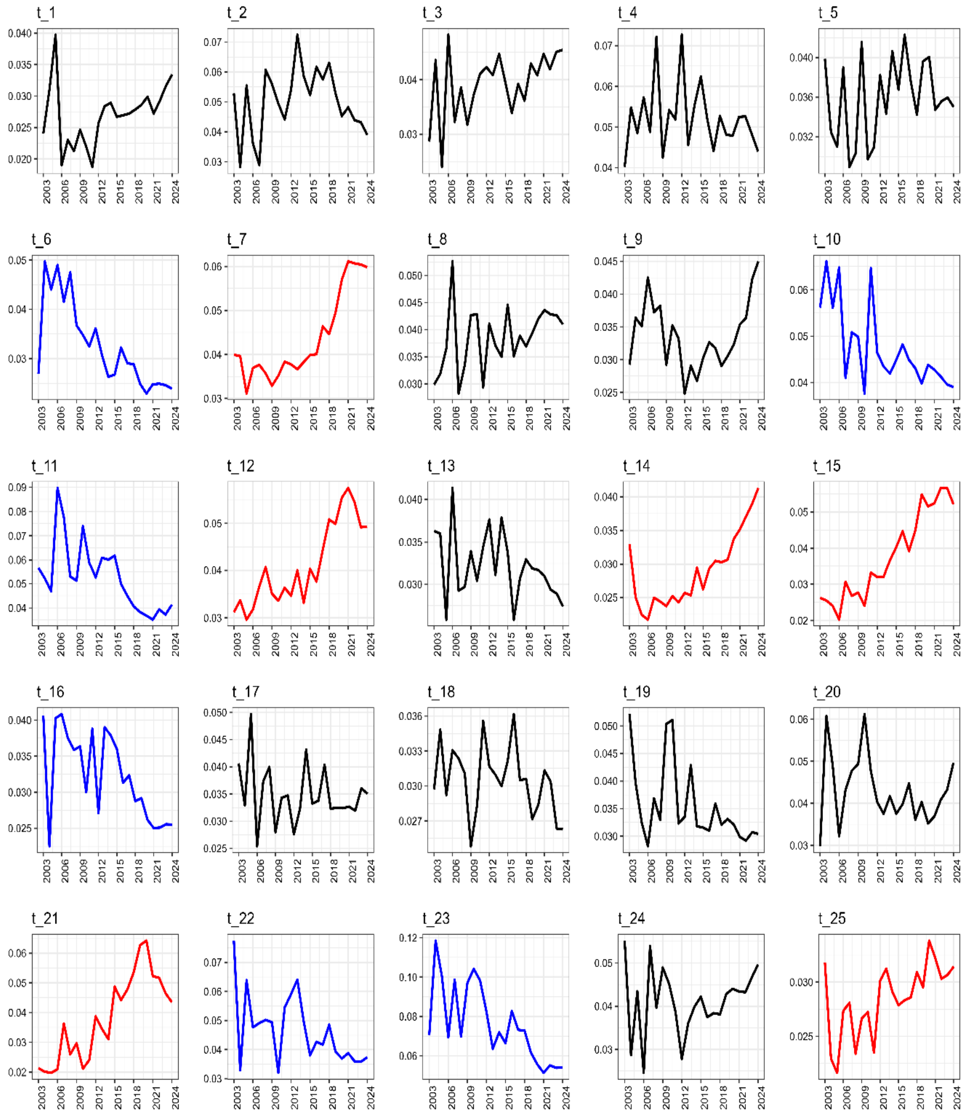
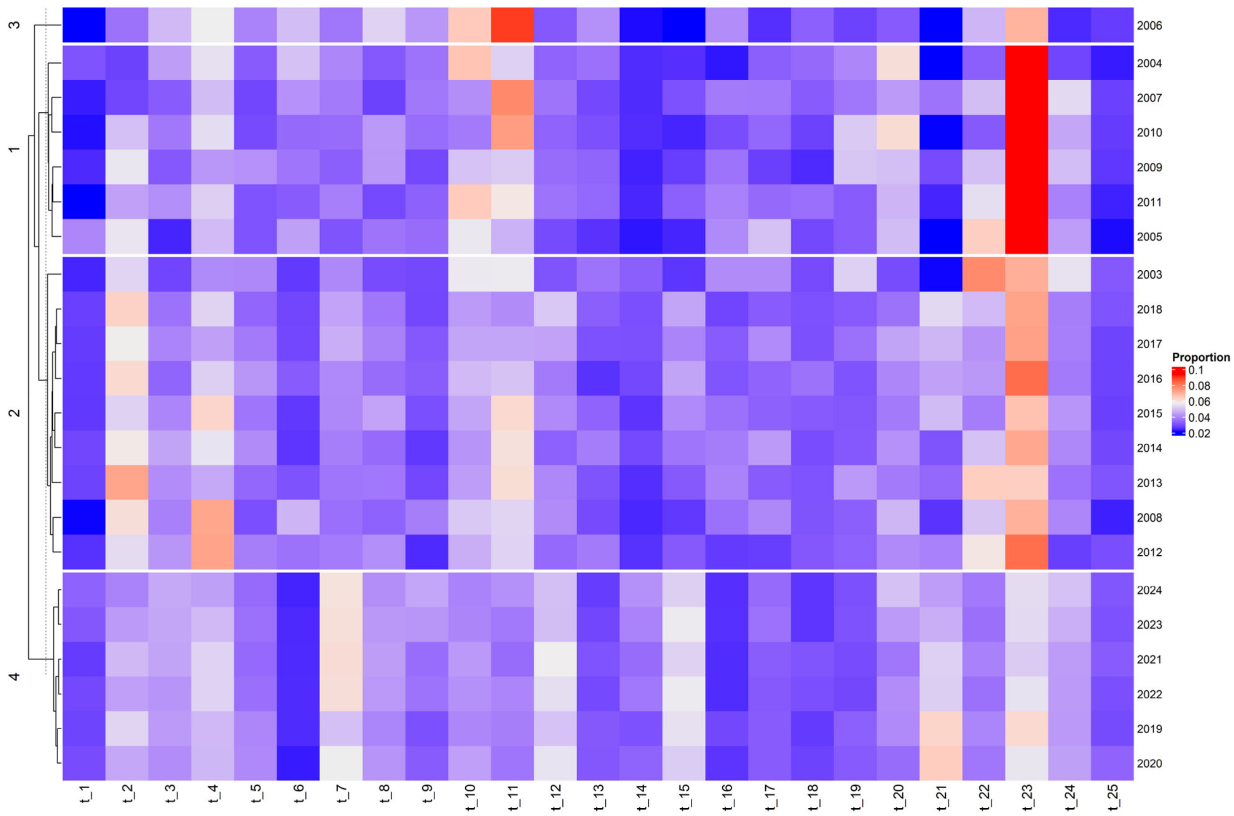


Figure 6. Trends of topics. The red line indicates topics with an increasing trend, the blue line indicates a decreasing trend and the black line represents fluctuations.

In contrast, five topics showed a downward trend in research activity. These topics are t_10, concerning the mechanical recycling of post-consumer plastics; t_11, which examines chemical treatment of PVC and metal waste; t_16, related to PET degradation and plastic degradation processes; t_19, focusing on adsorption processes for pollutant removal; and t_23, which addresses fuel production from plastic waste via pyrolysis. This decline may be due to shifts in research focus or saturation of knowledge in these areas, prompting researchers to explore new topics or innovative approaches.

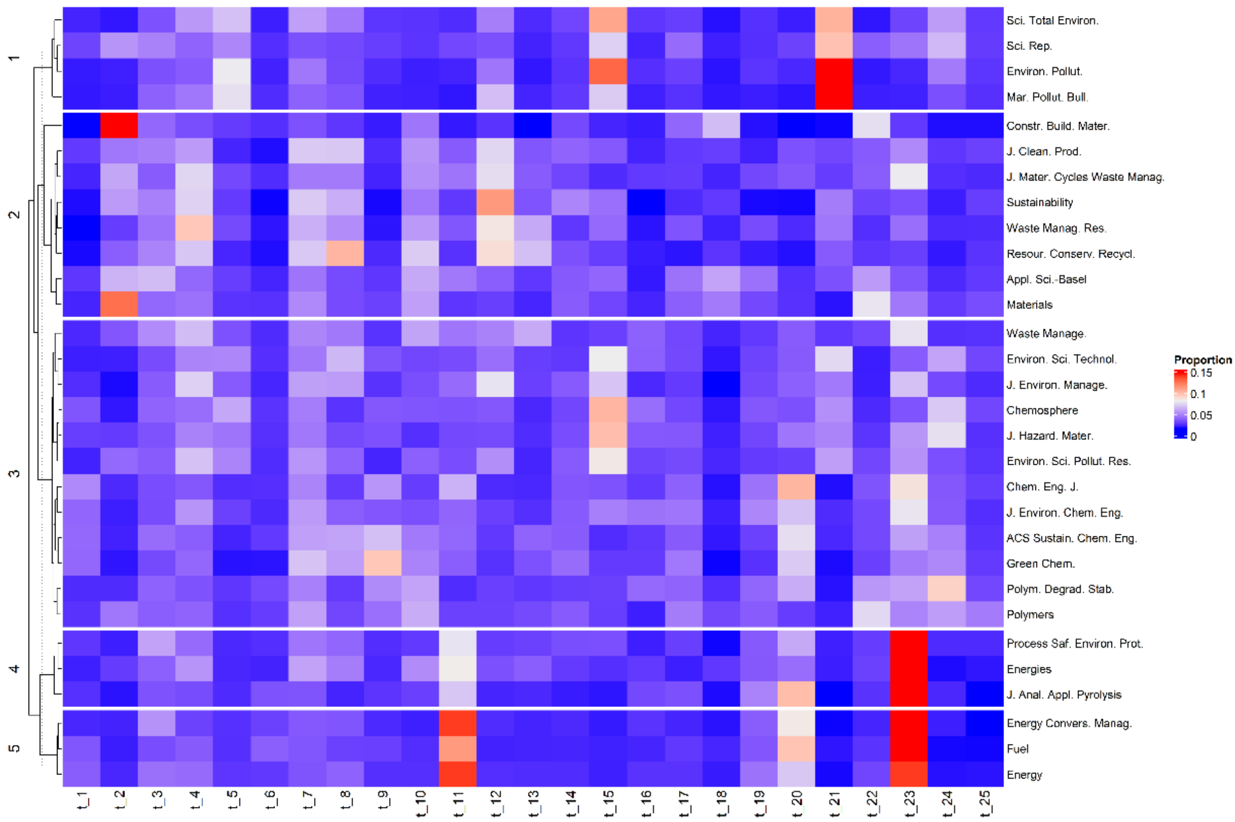
The remaining topics exhibit fluctuations in publication activity (Figure 6) without a clear trend, suggesting that interest in these areas may be influenced by specific factors such as targeted research initiatives or changes in policies, rather than consistent growth or decline.

Figure 7 presents a comprehensive analysis of thematic distribution in research on marine plastic pollution control technologies, utilizing three heatmaps that explore different dimensions: temporal, by sources (journals) and by countries. In part (a), the evolution of the 25 topics over the years is visualized. This heatmap highlights how certain themes have gained relevance during specific periods. For instance, the topic related to Fuel Production from Plastic Waste via Pyrolysis (t_23) shows a significant increase in 2016, while others, such as Biodegradation of Polymers in Natural Environments (t_24), display a more consistent presence over time. The temporal distribution reflects peaks of interest in different areas of research on marine plastic pollution control technologies, demonstrating how scientific focus has evolved over the years. Additionally, the clusters on the left side group topics that have followed similar trajectories; for example, those focused on Life Cycle Assessment (t_8) and Microplastic Impact on Ecosystems (t_15) show peaks around 2017 and 2018. In part (b), the distribution of topics in relation to sources, i.e., the journals in which these studies are published, is examined. It is observed that certain journals specialize in specific themes; for instance, the journal Fuel has a strong concentration in topics related to Pyrolysis for Waste-to-Energy Conversion (t_23), while Marine Pollution Bulletin is more focused on themes such as Microplastic Distribution in Water Bodies (t_5) and Microplastic Impact on Ecosystems and Health (t_15). The clusters on the left side organize journals according to their thematic alignment, highlighting, for example, those specialized in ecological impacts and sustainability.

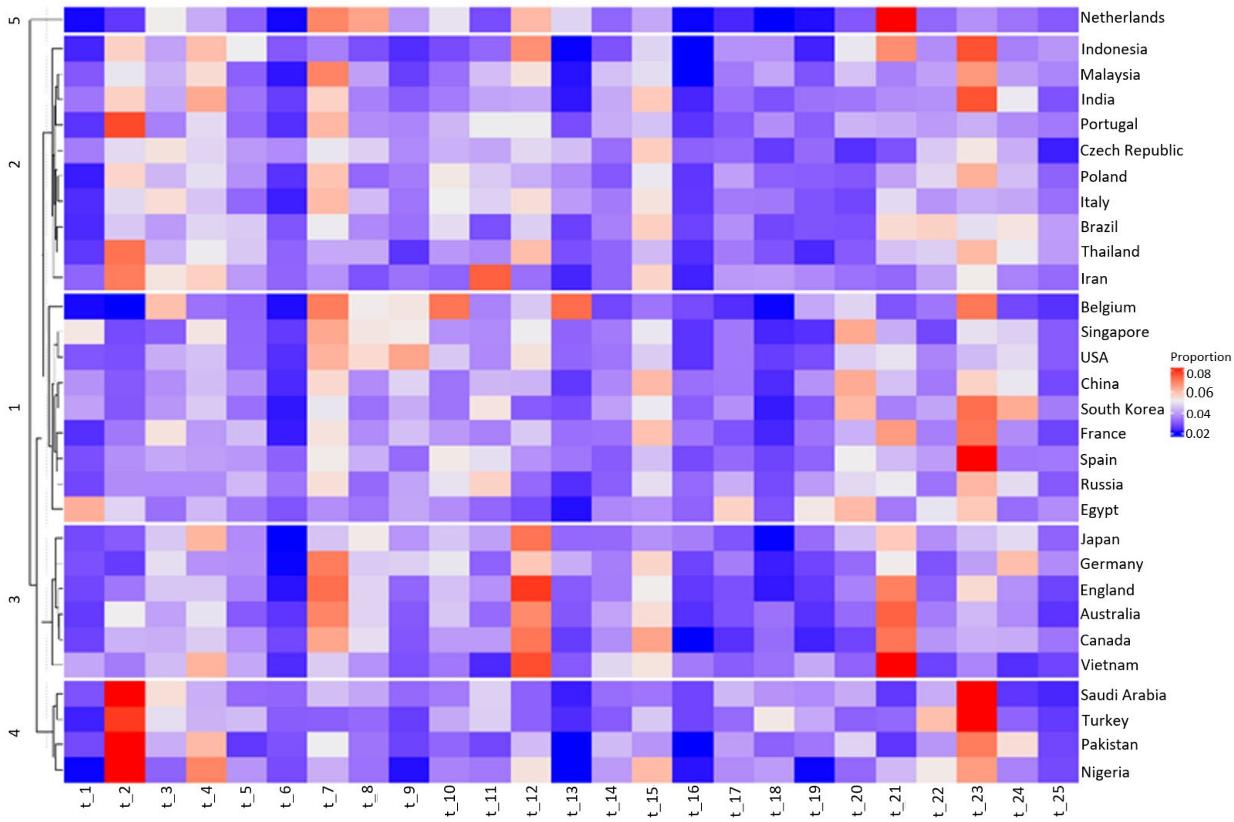


(**a**)

Figure 7. *Cont.*



(**b**)



(**c**)

Figure 7. Heatmaps of topic proportions: (**a**) Over Time (2003–2019) in Marine Plastic Pollution Control Technologies; (**b**) by Journal in Marine Plastic Pollution Control Technologies; (**c**) by Country in Marine Plastic Pollution Control Technologies.

Finally, in part (c), the distribution of topics by countries is displayed. This heatmap reveals the priority research areas in different regions of the world. China and the United States, for example, have a significant presence across a broad range of topics, with a particular focus on Pyrolysis of Plastic Waste (t_23) and Fuel Production (t_23). In contrast, countries like the United Kingdom and Germany are more concentrated on Technological Innovations in the Circular Economy (t_7) and Life Cycle Assessments in Waste Management (t_8). The clusters on the left side group countries with similar focuses, highlighting the different priorities and specializations in global research on marine plastic pollution control technologies.

The bibliometric analysis underscores the significant upward trend in research on sustainable marine plastic pollution control technologies, highlighting the global awareness and urgency to address this critical issue. The growth in topics such as data-driven models for sustainable plastic waste management, technological innovations in the circular economy and the impact of microplastics on ecosystems and health underscores the multifaceted approach researchers are taking to mitigate the environmental impacts of plastic pollution within a sustainability framework [42–44]. Data-driven models are essential for optimizing sustainable waste management strategies, while technological advancements in the circular economy emphasize waste reduction, reuse and recycling. These practices are crucial for minimizing the environmental footprint of plastic production and disposal, thereby contributing to a more sustainable future [3,7,9]. Furthermore, the pervasive presence of microplastics in marine environments and their associated risks to marine organisms and human health have been well-documented, revealing significant ingestion by various species, leading to physical and chemical stress and potential bioaccumulation of harmful pollutants. This situation underscores the need for sustainable solutions to mitigate these impacts [12,21,24].

Conversely, some research topics have seen a decline in activity, which may be attributed to a saturation of knowledge or a shift in research focus towards more pressing or emerging issues within the sustainability agenda. Mechanical recycling of post-consumer plastics, while it is a cornerstone of plastic waste management, faces challenges such as material degradation and contamination, prompting exploration of advanced or alternative methods that are more sustainable and efficient [26,29]. Similarly, the complexity and cost of chemical treatments for certain types of waste may limit their widespread adoption, suggesting the need for more sustainable and cost-effective alternatives [40,41]. The socio-economic impacts of marine plastic pollution are significant, particularly for coastal communities reliant on tourism and fisheries. Littered beaches deter tourists and reduce local revenues, while declining fish populations due to plastic ingestion impact fisheries. The economic burden extends to clean-up costs and the loss of biodiversity, with governments and local authorities diverting substantial resources to manage marine litter, thereby affecting other critical areas. These challenges highlight the importance of integrating sustainability into marine plastic pollution control measures [46,51].

Future research should prioritize the development and optimization of sustainable technologies for plastic waste management, focusing on minimizing environmental impact and maximizing the efficiency and effectiveness of these technologies. Emphasis should be placed on advancing the circular economy, which integrates the principles of sustainability into plastic production, use and disposal processes, thereby reducing the overall environmental footprint. Moreover, the exploration of innovative materials and technologies that offer biodegradable or recyclable alternatives to conventional plastics is crucial for achieving long-term sustainability in waste management.

A deeper understanding of the long-term impacts of microplastics on marine ecosystems and human health is also essential. This knowledge is vital for guiding the development of sustainable practices and interventions that protect both the environment and public health. Research should explore the pathways through which microplastics enter the food chain and the potential consequences of their accumulation in marine organisms, with the goal of mitigating these impacts through science-based, sustainable approaches.

Evaluating the effectiveness of policy interventions through a sustainability lens is crucial, as effective policy and regulatory measures are fundamental to mitigating marine plastic pollution. Countries that have implemented stringent regulations on plastic production and waste management have demonstrated lower levels of pollution, underscoring the critical role of policy in promoting sustainability [55,61]. However, enforcement and infrastructure challenges remain significant barriers in many regions, necessitating ongoing research into the development and implementation of sustainable policy frameworks. This includes examining the socio-economic factors that influence the success of these policies and identifying best practices that can be adapted for different regional contexts.

These analyses aimed to synthesize scientific publications addressing sustainable solutions to ocean plastic pollution, providing a comprehensive bibliometric analysis to identify current trends, gaps and emerging strategies. By evaluating the effectiveness of various mitigation strategies within the context of sustainability, this review seeks to inform policy development and foster international cooperation. Such efforts are essential not only for tackling the pervasive issue of ocean plastic pollution but also for contributing to the broader global sustainability agenda. Addressing the environmental and socio-economic impacts of plastic pollution through sustainable practices and policies will be critical in advancing global sustainability goals and ensuring the health of marine ecosystems and human communities alike.

5. Conclusions

The comprehensive bibliometric analysis presented in this study highlights the dynamic and evolving landscape of research in marine plastic pollution control technologies, reflecting a growing global commitment to sustainability. The significant increase in publications underscores the urgent recognition of the need to develop sustainable solutions that effectively address the multifaceted environmental challenges posed by plastic pollution. Key research areas, including data-driven models for plastic waste management, technological innovations in the circular economy and the impact of microplastics on ecosystems and human health, exemplify the diverse strategies being employed to promote sustainability. Integrating advanced technologies with sustainable practices is crucial for reducing the environmental footprint of plastic waste and mitigating its adverse effects on both marine ecosystems and human health.

Despite the progress achieved, significant challenges remain, particularly in the areas of mechanical recycling and chemical treatments, where research activity has seen a decline. This trend suggests the need for continued innovation and the exploration of alternative, sustainable methods to overcome the limitations of current technologies. The socio-economic impacts of marine plastic pollution, especially on coastal communities reliant on tourism and fisheries, further emphasize the importance of effective and sustainable waste management practices. Reducing plastic pollution not only protects marine biodiversity but also supports the long-term sustainability and resilience of these communities.

Future research must prioritize the development of new, sustainable technologies, enhance our understanding of the long-term impacts of microplastics and rigorously evaluate policy interventions from a sustainability perspective. Effective regulation and international cooperation are essential to achieving sustainability goals in reducing marine plastic pollution and mitigating its far-reaching effects. This review synthesizes current scientific knowledge, identifies emerging strategies and provides valuable insights that will inform policy development and foster global efforts towards a sustainable future. By contributing to the ongoing fight against ocean plastic pollution, this work aims to support the broader agenda of global sustainability, ensuring the protection of marine environments and the well-being of human communities worldwide.

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