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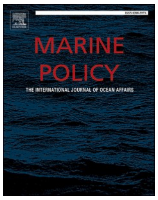

Impact of the COVID-19 pandemic on research on marine plastic pollution – A bibliometric-based assessment

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ABSTRACT

Fighting the COVID-19 pandemic has led to a dramatic increase in plastic waste, which has had a huge impact on the environment, including the marine environment. This work aims to evaluate the pattern of national research cooperation, research hotspots, and research evolution before and during the epidemic by systematically reviewing the publications on marine plastic pollution during 2015–2019 (before the pandemic) 2020–2022 (during the pandemic) using the systematic literature review and latent semantic analysis. The results show (i) Compared to pre-pandemic, publications on marine pollution during the COVID-19 pandemic declined briefly and then increased sharply. (ii) Compared with before the pandemic, the national cooperation model has changed during the pandemic, and four major research centers have been formed: Central European countries centered on Italy; Nordic countries centered on United Kingdom; South Korea, India and other developing countries in Asia and Africa and a Pacific Rim country centered on United States and China. (iii) The knowledge map of keyword clustering does not change significantly before and during the COVID-19: ecosystem, spatial distribution, environmental governance and biodegradation. However, there are differences in the sub-category research of the four types of keywords. (iv) The impact of marine plastic on organisms and the governance of marine plastic pollution have become a branch of knowledge that have evolved rapidly during the pandemic. The governance of marine plastic pollution and microplastics are expected to become an important research direction.

1. Introduction

Since the WHO declared COVID-19 a public health emergency of international concern in 2020, the disease has rapidly spread globally. As of June 2022, there have been more than 500 million confirmed cases and more than 6 million deaths [1]. In this health crisis, protecting lives and livelihoods become a priority for government decision-making and action. The WHO and governments announce guidelines to reduce the spread and health risks of COVID-19 [2], and with that comes a massive increase in plastic waste. To prevent human-to-human transmission and safeguard the most vulnerable and dangerous individual, the general public must wear personal protective equipment, such as surgical and medical masks, non-medical masks, and facial coverings. Health professionals are required to wear gloves and goggles. To limit the community spread of COVID-19, most of the single-use PPE used by healthcare professionals and the general public is thrown away every day. During the COVID-19 pandemic, the world consumes 129 billion masks and 65 billion gloves every month [3]. In addition to the health concerns of increasing plastic pollution, takeout packaging from restaurants lead to increased consumer demand for single-use products and safe materials. In April 2020, the average daily plastic waste in Bangkok, Thailand reached 3432 tons, up from 2115 tons in 2019. Energy demand decrease, global oil prices plummet, and the production cost of plastics as a by-product of petroleum greatly reduce [4]. Global plastic companies such as Ineos Styrolution in Germany and Trinseo in the United States achieve significant sales growth during the epidemic. From the perspective of economic benefits, the reduction of production costs, enterprises reduce the reproduction of plastics and choose to produce new plastic products [5]. Vigilance over the COVID-19 contagion brings global plastic recycling programs to a standstill. In the US and Europe, the plastics industry is taking advantage of pandemic fears to resist "plastic restrictions," according to Zero Waste Europe. More than half of

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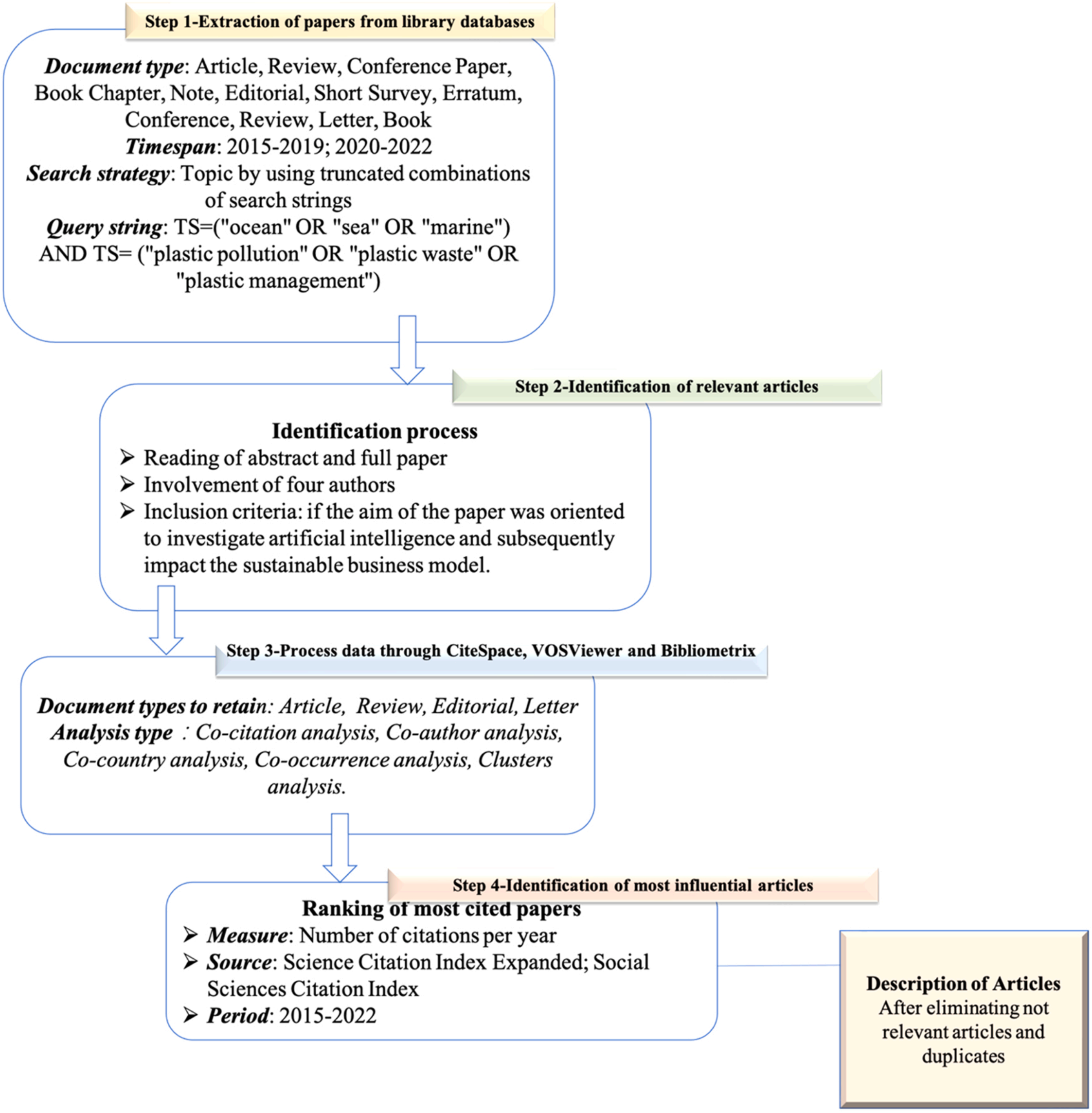

Fig. 1. The overall process of literature analysis.

U.S. states have suspended the recycling of plastic containers, and at least 50 curbside recycling programs across the country have been cut or suspended.

Plastic pollution is present at all locations in the ocean from shallow shore areas to the deepest regions sampled [6]. Because plastics are highly resistant to decomposition, they may persist in the environment for centuries, making them a hot topic of global governance [7]. Research shows that ocean plastic pollution kills 100,000 marine mammals and turtles, more than a million seabirds, and even more fish, invertebrates and other marine life each year [8]. Plastic pollution also has profound impacts on coastal communities, fisheries and economies. Conservative estimates suggest this could cost the global economy $13 billion a year and lead to a 1–5 % decline in ecosystem services, worth between $50 and $2.5 trillion. While PPE can provide important virus protection, improper handling of PPE has led to a surge in plastic pollution, especially in the ocean. In Africa, the rainy season runs from May to October each year, and the outbreak has caused a build-up of microplastics in freshwater and marine environment [9]. Governments around the world have taken different policy initiatives to reduce marine plastic pollution. West Africa is a leader in curbing marine plastic pollution, with legislative bans and taxes to reduce plastic consumption [10]. China has implemented policies of effectively banning the import of various solid wastes such as "personal/household waste plastics" and "unsorted waste paper". The United States has proposed several federal legislation to facilitate and strengthen recycling programs.

The plastic pollution caused by the epidemic has attracted widespread attention from scholars. In terms of plastic waste production, Abu-Qdais et al. designed a statistical model and found that there are 95 COVID-19 patients at King Abdullah University Hospital in Jordan, generating nearly 650 kg of medical waste every day [11]. Aragaw et al. argued that due to solid waste management practices and lack of infrastructure around the world, PPE is present in street, coastal and terrestrial environments in multiple countries [12]. In terms of the impact of plastic pollution, Ma et al. assessed the impact of masks on microbial communities in marine environments [13]. Kühn et al. believed that plastics were decomposed into nanoparticles due to physical or chemical or biological action into the environment, causing adverse effects on the human body through the food chain [14]. In terms of plastic waste management, Klemes et al. found that because the waste treatment system was designed for the volume of waste generated during normal operation, the waste generated during the epidemic far exceeded the normal treatment level [15]. Bing Li conducted a comprehensive review of the environmental risks of masks from a life cycle perspective. Igalavithana et al. proposed charcoal recovery from

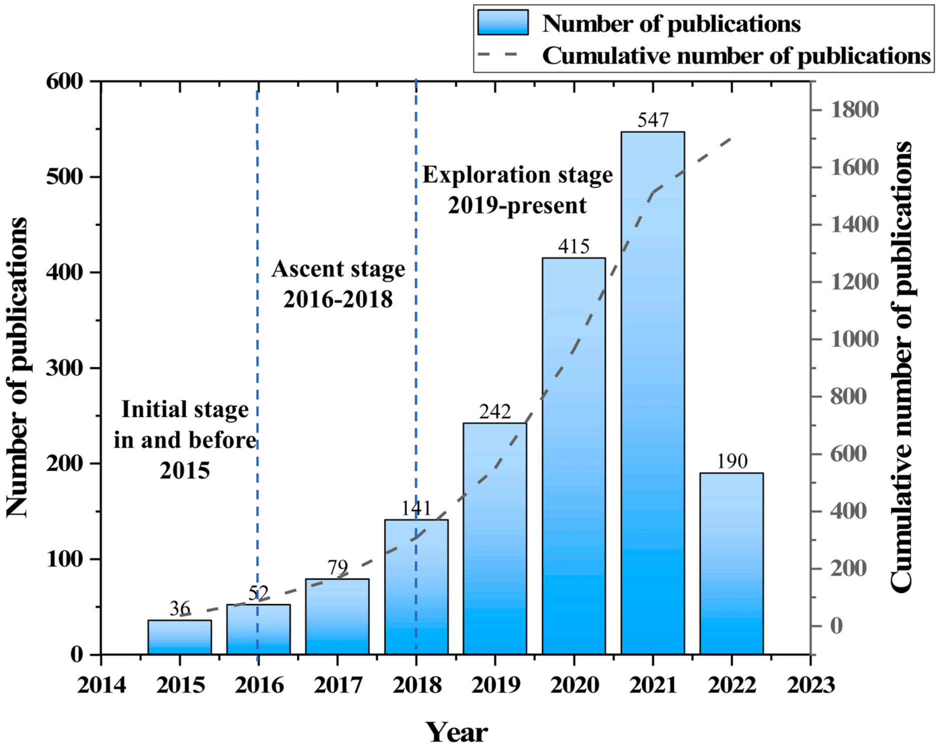

Fig. 2. Annual trends of publications (2015–2022).

plastic waste to remediate polluted environments [16].

The outbreak of COVID-19 has affected the research progress on marine plastic pollution. The first is that although there are survey reports from different countries [6,17,18], on the whole most studies are theoretical and lack empirical data. Second, in terms of geospatial selection, the field survey does not include all the breadth areas affected by the COVID-19 outbreak. Under strict government lockdowns in some countries, municipalities and NGOs have canceled annual collective clean-ups as a long-term monitoring program, and the inability to collect fragmented data has affected our ability to identify the source of the leak [19]. Bibliometric research is playing an increasingly important role in the response to public health emergencies international concern (PHEIC), helping to inform policy recommendations in response to crises. Although this approach is critical, bibliometric analysis of the impact of COVID-19 on marine plastic pollution is still lacking.

The purpose of this paper is to systematize the scientific knowledge of scholars about plastic marine pollution before and after the pandemic. Specifically, we use the methods of systematic literature review and latent semantic analysis to review systematic literature, and conduct visual analysis through CiteSpace and VOSViewer. This paper aims to solve the following three problems:

(1) Has the regional cooperation model of the study countries changed before and after the outbreak?

(2)Reveal the knowledge structure basis and key textual information of marine plastic pollution.

(3) Sort out the evolutionary context and provide suggestions for sorting out plastic pollution in the post-epidemic period.

2. Method and data

In this paper, we mainly use systematic literature review (SLR), latent semantic analysis and bibliometrics for literature analysis. The specific process is shown in Fig. 1. Systematic literature review (SLR) provides a framework for integrating existing knowledge through a reproducible, scientific and transparent process.

Compared with traditional narrative reviews, SLR can achieve a higher quality review process and results, reduce and minimize bias and errors, provide literature mapping and data collection for specific research areas, due to the reproducibility of steps in the review process, so more scientific and effective. When we use SLR, the first step is identification. The identification process is in June 2022, which defines the research question and research goal. Five bibliographic databases are considered for this review: Google Scholar, ScienceDirect, Scopus, Web of Science, and SpringerLink. Google Scholar's preprint service has exploded in volume during the COVID-19 outbreak, which is critical for understanding and predicting epidemiological dynamics, implementing containment strategies, and effective diagnosis and treatment. But it also increases the risk of disclosing false information, as they are released without any independent quality control. Web of Science supports over 95 % of the world's top research institutions, multiple governments and national research agencies. Research has shown that Web of Science is widely used when discussing scholarly publications. So the Web of Science database is selected.

In Web of Science, we choose Science Citation Index Expanded (SCI-Expanded) and Social Sciences Citation Index (SSCI), which ensures the quality of the articles reviewed in this article [20]. Finally we use "TS= ("ocean" OR "sea" OR "marine") AND TS= ("plastic pollution" OR "plastic waste" OR "plastic management")" to search in the Web of Science database. In the Web of Science database, "TS" means topic, including title, abstract, author keywords, keywords plus [21]. As of June 2022, a total of 1702 articles are obtained. The second step is screening, in which we determine eligibility, inclusion and exclusion criteria based on established criteria, and find suitable articles for inclusion in the systematic review process. During the screening phase, we choose articles published between January 2015 and 2022, including systematic reviews or review papers, conference papers, conference proceedings, book chapters, book series, and book journals. The third step is the eligibility process, in which articles are manually screened according to established criteria to remove duplicates or articles with low significance. The final step is data abstraction and analysis. Selected articles are evaluated, reviewed and analyzed through CiteSpace and VOS-Viewer, by reading titles, abstracts and full text. LSA is then used in the

Table 1
Calculation of author productivity of data mining.

Publications (x)	Authors (y)	Publication count (xy)	Accumulated publication	Accumulated publication	Accumulated Author	Accumulated Author %
1	5515	5515	5515	61.28 %	5515	82.58 %
2	728	1456	6971	77.46 %	6243	93.49 %
3	225	675	7646	84.96 %	6468	96.86 %
4	78	312	7958	88.42 %	6546	98.02 %
5	45	225	8183	90.92 %	6591	98.70 %
6	26	156	8339	92.66 %	6617	99.09 %
7	19	133	8472	94.13 %	6636	99.37 %
8	13	104	8576	95.29 %	6649	99.57 %
9	3	27	8603	95.59 %	6652	99.61 %
10	9	90	8693	96.59 %	6661	99.75 %
11	3	33	8726	96.96 %	6664	99.79 %
12	2	24	8750	97.22 %	6666	99.82 %
13	2	26	8776	97.51 %	6668	99.85 %
14	1	14	8790	97.67 %	6669	99.87 %
16	2	32	8822	98.02 %	6671	99.90 %
20	1	20	8842	98.24 %	6672	99.91 %
23	1	23	8865	98.50 %	6673	99.93 %
24	1	24	8889	98.77 %	6674	99.94 %
25	1	25	8914	99.04 %	6675	99.96 %
27	1	27	8941	99.34 %	6676	99.97 %
28	1	28	8969	99.66 %	6677	99.99 %
31	1	31	9000	100.00 %	6678	100.00 %

Table 2
Calculation of the exponent n for data mining.

Publications (x)	Authors (y)	X = log (x)	Y = log (y)	XY	XX
1	5515	0.0000	8.6152	0.0000	0.0000
2	728	0.6931	6.5903	4.5680	0.4805
3	225	1.0986	5.4161	5.9502	1.2069
4	78	1.3863	4.3567	6.0397	1.9218
5	45	1.6094	3.8067	6.1266	2.5903
6	26	1.7918	3.2581	5.8377	3.2104
7	19	1.9459	2.9444	5.7296	3.7866
8	13	2.0794	2.5649	5.3337	4.3241
9	3	2.1972	1.0986	2.4139	4.8278
10	9	2.3026	2.1972	5.0593	5.3019
11	3	2.3979	1.0986	2.6344	5.7499
12	2	2.4849	0.6931	1.7224	6.1748
13	2	2.5649	0.6931	1.7779	6.5790
14	1	2.6391	0.0000	0.0000	6.9646
16	2	2.7726	0.6931	1.9218	7.6872
20	1	2.9957	0.0000	0.0000	8.9744
23	1	3.1355	0.0000	0.0000	9.8313
24	1	3.1781	0.0000	0.0000	10.1000
25	1	3.2189	0.0000	0.0000	10.3612
27	1	3.2958	0.0000	0.0000	10.8625
28	1	3.3322	0.0000	0.0000	11.1036
31	1	3.4340	0.0000	0.0000	11.7923

next phase for topic analysis, bibliometrics for performance indicator analysis.

Bibliometrics can create useful lines of information by analyzing scientific activity and building future research. These lines of information can aid in the discovery, organization, and examination of information within a particular topic or field [22].

In our analysis, we primarily use bibliometric performance indicators and scientific mapping. Bibliometric performance indicators can illustrate the performance of authors, journals, institutions and countries, i.e. number of articles, citations, average citations per article, h-index, etc.

Scientific mapping allows visual analysis to detect research topics and emerging research trends. Three visualization softwares, CiteSpace, VOSViewer and Bibliometrix, are mainly used in this paper. CiteSpace is an information visualization software developed by Dr. Chen in the Java language. It can present the structure, law and distribution of scientific knowledge in a visual way, so as to obtain the map of scientific knowledge. Bibliometrix is an open source tool for comprehensive scientific mapping analysis of scientific literature. It is programmed in R to be flexible and easy to integrate with other statistical and graphics packages, which is an open source environment and ecosystem, and the bibliometrix workflow mainly consists of three steps of data acquisition, data analysis and data visualization. VOSViewer is a software for building visual knowledge graphs that build collaborative networks based on citations, bibliographic coupling, co-citation or co-authorship relationships. VOSViewer also provides text mining capabilities that can be used to build and visualize keyword co-occurrence networks extracted from large amounts of scientific literature.

LSA is a method that can abstract meaningful topic structures based on contextual similarity [23], it can acquire knowledge of similarity, and extract the pattern of term occurrence in a corpus to form an abstract and dense latent semantic dimension matrix [24]. LSA is a singular value decomposition (SVD) based algorithm applied to the document-by-document matrix of a corpus, reducing its dimensionality. LSA gains the ability to abstract semantics and uses this dimensionality reduction to extract knowledge from text corpora. Compared with traditional content analysis methods, the main benefit of this method is that it can reduce the subjectivity of researchers through mathematical algorithms and improve the efficiency of analysis through computational power [25].

3. Results

3.1. Overall characteristic analysis

In Fig. 2 we show the annual trend of publications related to plastic marine pollution. Since 2022 is incomplete, it is not analytically meaningful. We find a steady upward trend in the number of publications in this field during the 5 years before the COVID-19 outbreak, 2015–2019. An interesting phenomenon is found in Fig. 2, the number of publications decreased slightly in the period 2019–2020 during the time after the onset of COVID-19, and the number of publications increase rapidly after 2020. We speculate that in the short time after the COVID-19 outbreak, many research programs are disrupted due to travel bans and lockdown measures, and research projects aim at measuring plastic pollution were halted. With the normalized management of the epidemic, more scholars have paid attention to the management of marine plastic pollution in the post-epidemic period.

Table 3
The K-S test for data mining.

Publications (x)	Authors (y)	Observation by author	Cumulative values of	Expected value by author	Cumulative values	Differences of each pair of
1	5515	0.8258	0.8258	0.7682	0.7682	0.0576
2	728	0.1090	0.9349	0.1261	0.8943	0.0406
3	225	0.0337	0.9686	0.0438	0.9381	0.0305
4	78	0.0117	0.9802	0.0207	0.9588	0.0215
5	45	0.0067	0.9870	0.0116	0.9703	0.0166
6	26	0.0039	0.9909	0.0072	0.9775	0.0134
7	19	0.0028	0.9937	0.0048	0.9823	0.0114
8	13	0.0019	0.9957	0.0034	0.9857	0.0099
9	3	0.0004	0.9961	0.0025	0.9882	0.0079
10	9	0.0013	0.9975	0.0019	0.9901	0.0073
11	3	0.0004	0.9979	0.0015	0.9916	0.0063
12	2	0.0003	0.9982	0.0012	0.9928	0.0054
13	2	0.0003	0.9985	0.0010	0.9937	0.0048
14	1	0.0001	0.9987	0.0008	0.9945	0.0041
16	2	0.0003	0.9990	0.0006	0.9951	0.0039
20	1	0.0001	0.9991	0.0003	0.9954	0.0037
23	1	0.0001	0.9993	0.0002	0.9956	0.0036
24	1	0.0001	0.9994	0.0002	0.9958	0.0036
25	1	0.0001	0.9996	0.0002	0.9960	0.0036
27	1	0.0001	0.9997	0.0001	0.9961	0.0036
28	1	0.0001	0.9999	0.0001	0.9962	0.0036
31	1	0.0001	1.0000	0.0001	0.9963	0.0037

3.2. *Author productivity analysis*

To explore the author productivity of all articles, we use Lotka's Law for analysis and perform K-S test to verify the reliability of Lotka's Law. Research by Lotka's Law shows that 60 % of authors publish only one article in a given period. As the number of articles increases, the number of authors decreases. According to Lotka's Law, the number of articles x and the number of authors y can be expressed as Formula 1:

$$x^n y = C \tag{1}$$

In the analysis, the data obtained in Web of Science are followed by the steps in the paper "LOTKA'S LAW: A TESTING PROCEDURE". Here, the role of co-authors are considered. Second, the data in Table 1 and Table 2 is organized. Use Formula 2 to find the exponent $n = -2.6074$ of Lotka's Law, and the absolute value is between 1.2 and 3.8, so it satisfies Lotka's Law. We calculate $c = 0.7682$ by Formula 3, and the critical value is 0.2457, So Formula 4 and Formula 5 are obtained. Then we test it and finally get $D_{max} = 0.0576 < 0.7682$. Since the value of D_{max} in Table 3 is less than the critical value, the result matched the generalized Lotka's law, that is, the author productivity distribution data is consistent with plastic pollution studies.

$$\mathrm{n} = \frac{\mathrm{N}\sum XY - \sum X \sum Y}{N\sum X^2 - \left(\sum X\right)^2} \tag{2}$$

$$\mathrm{c} = \frac{1}{\sum_1^{p-1}\frac{1}{x^n} + \frac{1}{(n-1)p^{n-1}} + \frac{1}{2p^n} + \frac{n}{24(p-1)^{n+1}}} \tag{3}$$

$$\text{critical value} = \frac{1.63}{\sqrt{\sum Y}} \tag{4}$$

$$\mathrm{f(x)} = \frac{0.7682}{x^{2.6074}} \tag{5}$$

3.3. *Core journals analysis*

Bradford's Law is evidence of the regularity of the distribution of scientific journals. According to Bradford's law, The degree of closeness between the professional disciplines is not the same, so the number of different scientific and technological documents in the related journals is unevenly distributed. Journals can be divided into three groups according to the number of articles, and the ratio of the number of journals in each group is $1{:}a{:}a^2$. That is, a large number of professional papers are first concentrated in a few core journals, and some papers appear in other journals related to the profession [26]. Bradford's Law has been widely used to study different topic trends and author productivity [27].

To better display the information of core journals, Table 4 supplement the information of the top 20 journals. During the statistical process, the monthly journals of the same journal are combined, such as Environmental Pollution and Environmental and Pollution Barking Essex 1987.The results obtained are shown in the following Table 4:

According to the data in the Table 5 and Table 6, the journals are divided into 3 areas with roughly the same number of articles, that is, there are 3 journals with more than 100 articles, they are MARINE POLLUTION BULLETIN, SCIENCE OF THE TOTAL ENVIRONMENT, ENVIRONMENTAL POLLUTION, they publish 628 papers, which is the core area. There are 28 journals with more than 8 articles and 440 papers, which is the relevant area; there are 330 journals with 1–7 articles and 634 papers. It can be seen from the Table 6 that the core area journals account for 0.83 % of the total number of journals, and the published papers account for 36.90 % of the total number of papers; the related area journals account for 7.76 % of the total number of journals, and the published papers account for 29.46 % of the total number of papers; discrete area Journals accounted for 91.41 % of the total number of journals, and published papers accounted for 33.61 % of the total number of papers. The ratio of the number of journals in the 3 regions is 3:28:330, but it does not completely constitute a proportional sequence, so we proceed with the calculation to obtain the Bradford coefficient.

The data in Table 5 above is plotted in a coordinate system, the abscissa is the logarithm of the cumulative number of journals, and the ordinate is the cumulative number of journals*documents, and the resulting distribution curve is shown below. It can be seen from Fig. A1 that The curve in the figure can be divided into two sections: the curve AB and the straight line BC. The turning point of the two lines is point B, and the abscissa of point B is 12.

To further confirm the Bradford dispersion coefficient, the Bradford dispersion coefficient calculation method proposed are used by Egger, and its formula is:

$$m = \left(e^E * \mathrm{Y}\right)^{\frac{1}{R}} \tag{6}$$

Combine the calculation method of the number of core areas proposed by Egger, and its formula is:

$$\mathrm{P} = 2\ln\left(e^E * \mathrm{Y}\right) \tag{7}$$

In Formula 6 and Formula 7: m is the Bradford coefficient; R is the

Table 4
Information on core journals of marine plastic pollution publications.

Publication name	Country / Region	Category	Journal Citation Indicator (JCI)2021
Marine Pollution Bulletin	England	Marine & Freshwater Biology; Environmental Sciences	1.57
Science Of The Total Environment	Netherlands	Environmental Sciences	1.78
Environmental Pollution	England	Environmental Sciences	1.62
Frontiers In Marine Science	Switzerland	Marine & Freshwater Biology	1.05
Environmental Science Technology	United States	Environmental Sciences; Engineering, Environmental	1.46
Journal Of Hazardous Materials	Netherlands	Engineering, Environmental; Environmental Sciences	1.95
Environmental Science And Pollution Research	Germany	Environmental Sciences	0.81
Chemosphere	England	Environmental Sciences	1.49
Sustainability	Switzerland	Green & Sustainable Science & Technology; Environmental Sciences	0.64
Marine Policy	England	International Relations; Environmental Studies	1.62
Scientific Reports	England	Multidisciplinary Sciences	1.05
Frontiers In Environmental Science	Switzerland	Environmental Sciences	0.72
Plos One	United States	Multidisciplinary Sciences	0.88
Environmental Research	United States	Environmental Sciences; Public, Environmental & Occupational Health	1.68
Waste Management	United States	Environmental Sciences; Engineering, Environmental	1.18
Journal Of Marine Science And Engineering	Switzerland	Oceanography; Engineering, Ocean; Engineering, Marine	0.91
Environment International	United States	Environmental Sciences	1.93
Environmental Research Letters	England	Environmental Sciences; Meteorology & Atmospheric Sciences	1.25
Iop Conference Series Earth And Environmental Science	Scotland	Paleontology; Geosciences, Multidisciplinary	0.78
Journal Of Cleaner Production	United States	Engineering, Environmental; Environmental Sciences; Green & Sustainable Science & Technology	1.51

number of partitions; Y is the number of articles in the journal with the largest article load; P is the number of core areas; E is the Euler coefficient, $E = 0.5772$.

Substitute the relevant data into Formula 6 and Formula 7, and the calculation results are as follows:

$m=8\cdot 3$; $P=13$

Therefore, in the research on marine plastic pollution, the overall distribution law is "centralized-scattered".

3.4. *Geographical area analysis*

Table 5
Statistics of journal literature in the field of plastic pollution.

Number of journals	Number of documents	Cumulative number of journals	The number of journals * the cumulative number of documents	Journal cumulative logarithmic value
1	321	1	321	0.00
1	179	2	500	0.69
1	128	3	628	1.10
1	63	4	691	1.39
1	42	5	733	1.61
1	34	6	767	1.79
2	32	8	831	2.08
1	30	9	861	2.20
1	27	10	888	2.30
1	22	11	910	2.40
1	16	12	926	2.48
2	15	14	956	2.64
1	14	15	970	2.71
3	13	18	1009	2.89
2	12	20	1033	3.00
3	10	23	1063	3.14
3	9	26	1090	3.26
5	8	31	1130	3.43
4	7	35	1158	3.56
6	6	41	1194	3.71
12	5	53	1254	3.97
9	4	62	1290	4.13
27	3	89	1371	4.49
59	2	148	1489	5.00
213	1	361	1702	5.89

Table 6
Discrete status table of journal literature in the field of plastic pollution.

Category	Number of journals	Journal ratio	Loading volume	Paper ratio	Average loading density
Core area	3	0.83 %	628	36.90 %	209.33
Relevant area	28	7.76 %	502	29.49 %	17.93
Discrete area	330	91.41 %	572	33.61 %	1.73

First of all, in Fig. 3 that during 2015–2022, China, the United States, the United Kingdom, Australia, Panama, and Myanmar are the countries that have carried out more research on plastic pollution in the ocean. There is close cooperation between these countries and with other countries.. Second, compare the changes in the scientific research output of the main publishing countries before and after the epidemic.

It can be found that countries such as China, the United Kingdom, the United States, and India, which were relatively mature in conducting plastic marine pollution research before the epidemic, do not change their leadership positions significantly after the epidemic. Taking China, India, the United States, Brazil, Indonesia and other countries as examples, the production of plastic waste such as masks is positively correlated with the amount of marine plastic pollution. Indonesia, India, and the United States are the top three countries in marine plastic pollution, and they also rank among the top in the world in terms of publication volume in this field.

From Fig. 4, although developing countries have low capacity to treat medical waste and domestic waste, the outbreak of the epidemic did not have a significant negative impact on research in developing countries. Developing countries represented by China and Brazil still had high knowledge output during the epidemic. However, after the outbreak, different countries have different research interests in different types of plastic pollution. China, the United States, and India are more interested in the research of microplastics. For example, Shen and Du mainly study the harm caused by microplastics released from

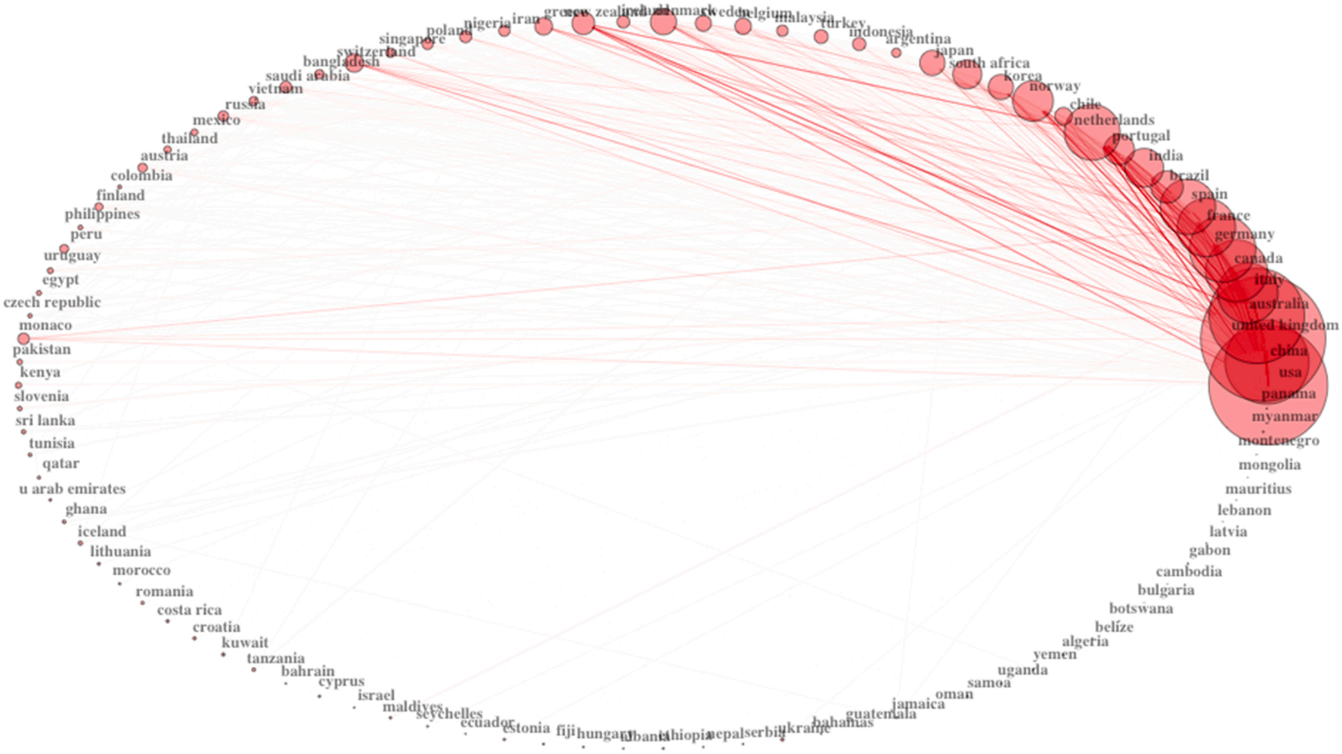

Fig. 3. Country cooperation map in 2015–2022.

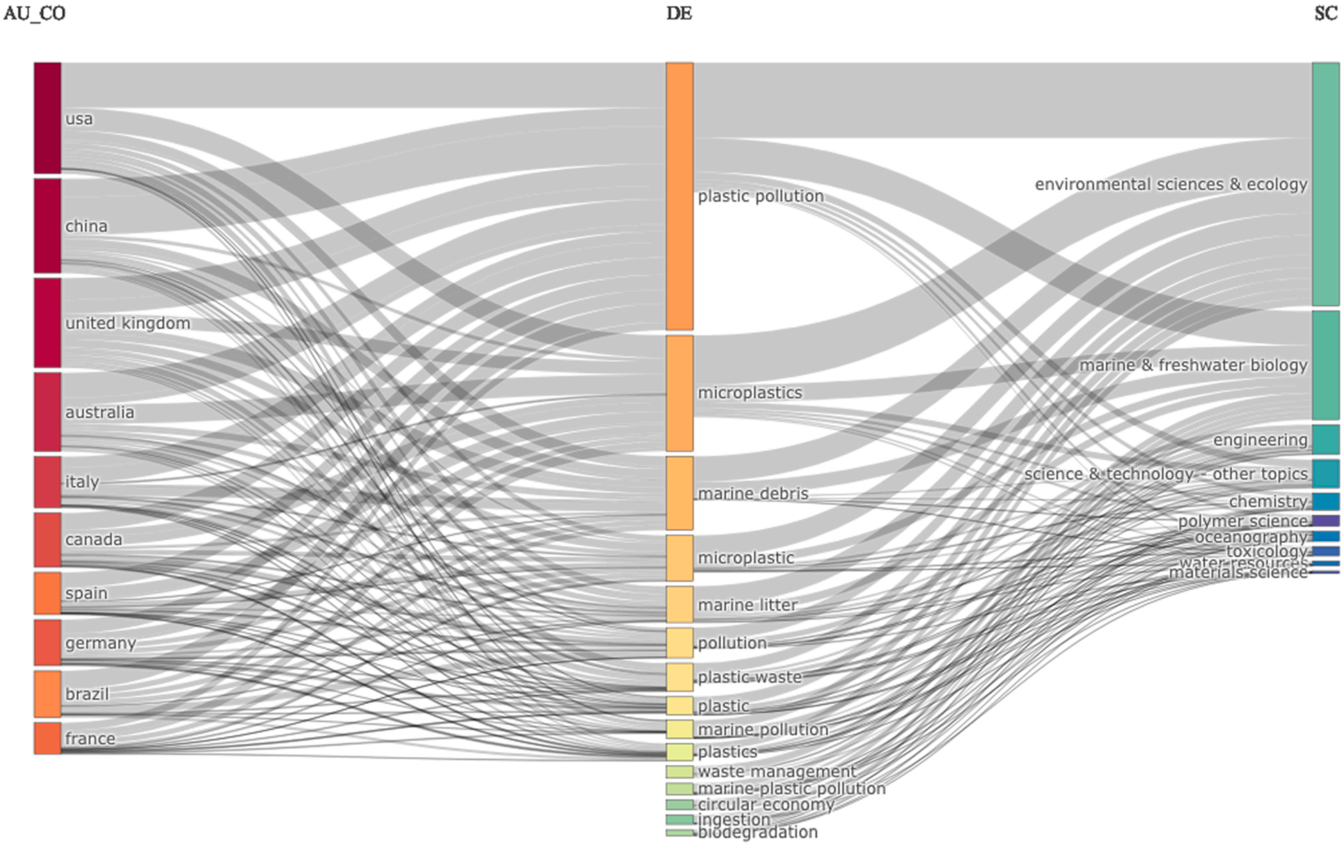

Fig. 4. Country research hotspot sankey diagram.

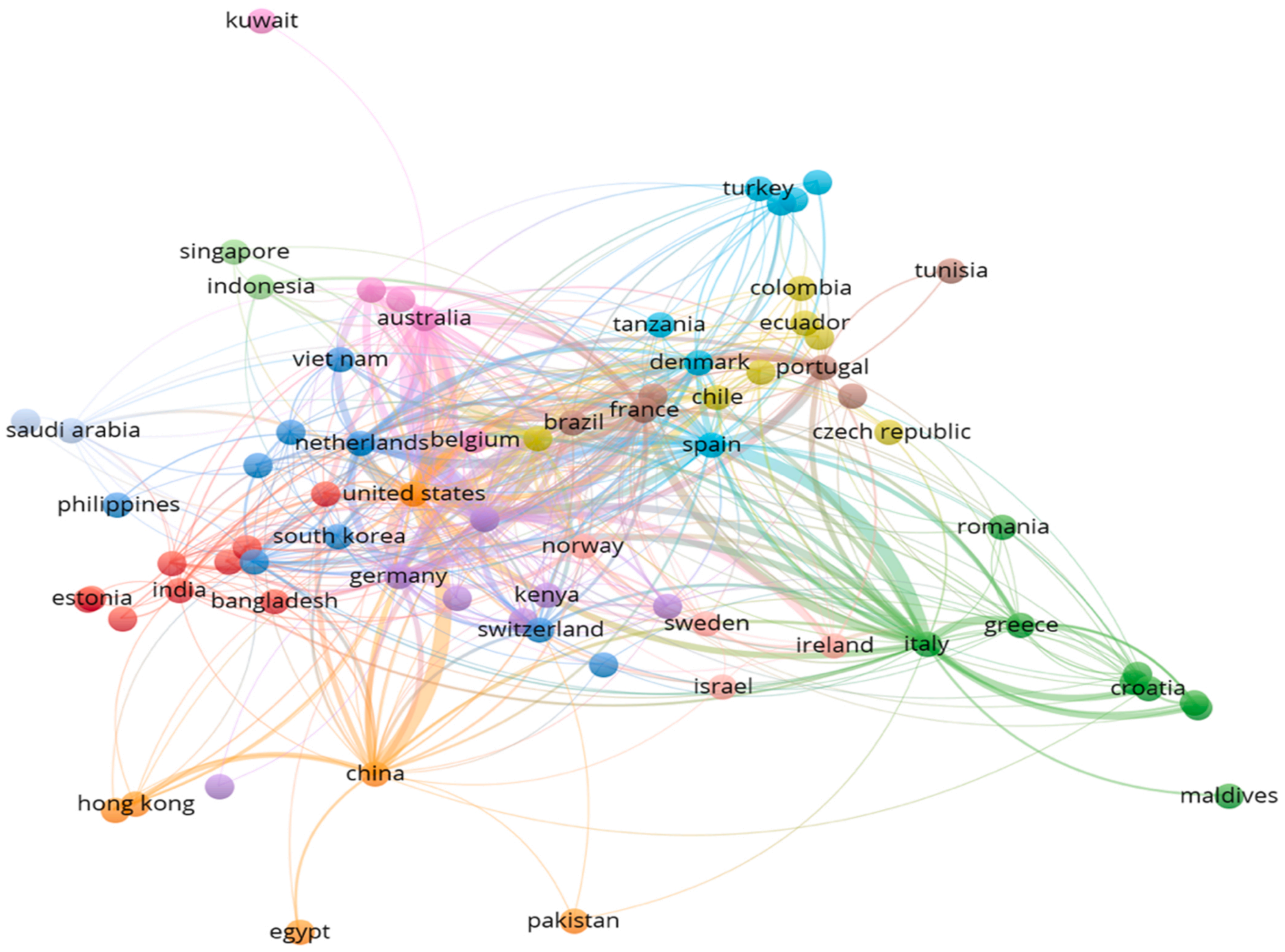

Fig. 5. Country cooperation network map before COVID-19 (2015–2019).

plastic waste into the environment [28,29]. Bansal and Silva put forward a microplastic governance plan. Scholars from the United States and the United Kingdom have paid more attention to marine pollution [30,31].

Fig. 5 is the co-authorship network of countries in the research field obtained by VOSViewer based on the co-occurrence matrix. In this view, the more important country in the study, the larger its label and circle. Colors represent clusters assigned to countries by VOSViewer's clustering technology. It can be seen that there is a strong agreement between the structure of the map and the clusters obtained by the clustering technique [32]. The connection between different countries is close and intertwined, and does not form an independent and fragmented research group. Countries in different regions and at different levels of development have carried out close cooperation. For example, the United States, the Netherlands, France, and China, all have connections with different countries. In the fringe part of the cooperation network, there are countries such as Kuwait, Tunisia, Egypt, Maldives, etc. Unlike other countries' cooperation models, these countries usually establish cooperation with a single country. For example, Kuwait and Australia, Tunisia and Portugal, Egypt and China, Maldives and Italy. This link is more vulnerable to the instability of the epidemic.

Fig. 6 shows the map of cooperation between countries after the outbreak. Compared with before the outbreak, the cooperation between countries is still relatively close. But the difference is that the figure can be distinguished more clearly by the color of the research groups in which one country is in the lead. For example, the green node represents a research group centered on Italy, including Germany, Portugal, Poland, Ireland, Greece, Lithuania and other countries. This research group is mainly composed of countries such as Europe and is geographically densely distributed. The yellow nodes represent research groups centered on the United Kingdom, including Sweden and Norway, which are mostly composed of developed countries in northern Europe. the blue nodes include research groups from South Korea, South Africa, India, Bangladesh, Kenya and other countries. These countries are from Asia and Africa and are geographically dispersed, but most are developing countries. The research group represented by the red node takes the three countries of United States, Australia and China as the central countries, including Japan, Malaysia, Singapore, Taiwan, Indonesia, Sri lanka and other countries, most of which are distributed in the Pacific Rim. Countries in this part produce more plastic waste during the epidemic, and have the highest number of publications on marine plastic pollution in the world. As a whole, they belong to a relatively influential research group.

3.5. *Comparison of research hotspots*

In this section, LSA are used to analyze the co-occurrence analysis of the keywords provided by the authors in the dataset. The same color in Fig. 7 represent similar keyword clusters. There are few keywords in the orange cluster and purple cluster, mainly focusing on marine pollution and biodegradation. Green clusters mainly study pollution control issues. The keywords in the blue cluster involve more fields, such as microplastics and resin particles representing plastic components and types; fresh water, seabirds, and fish representing ecosystems. The red

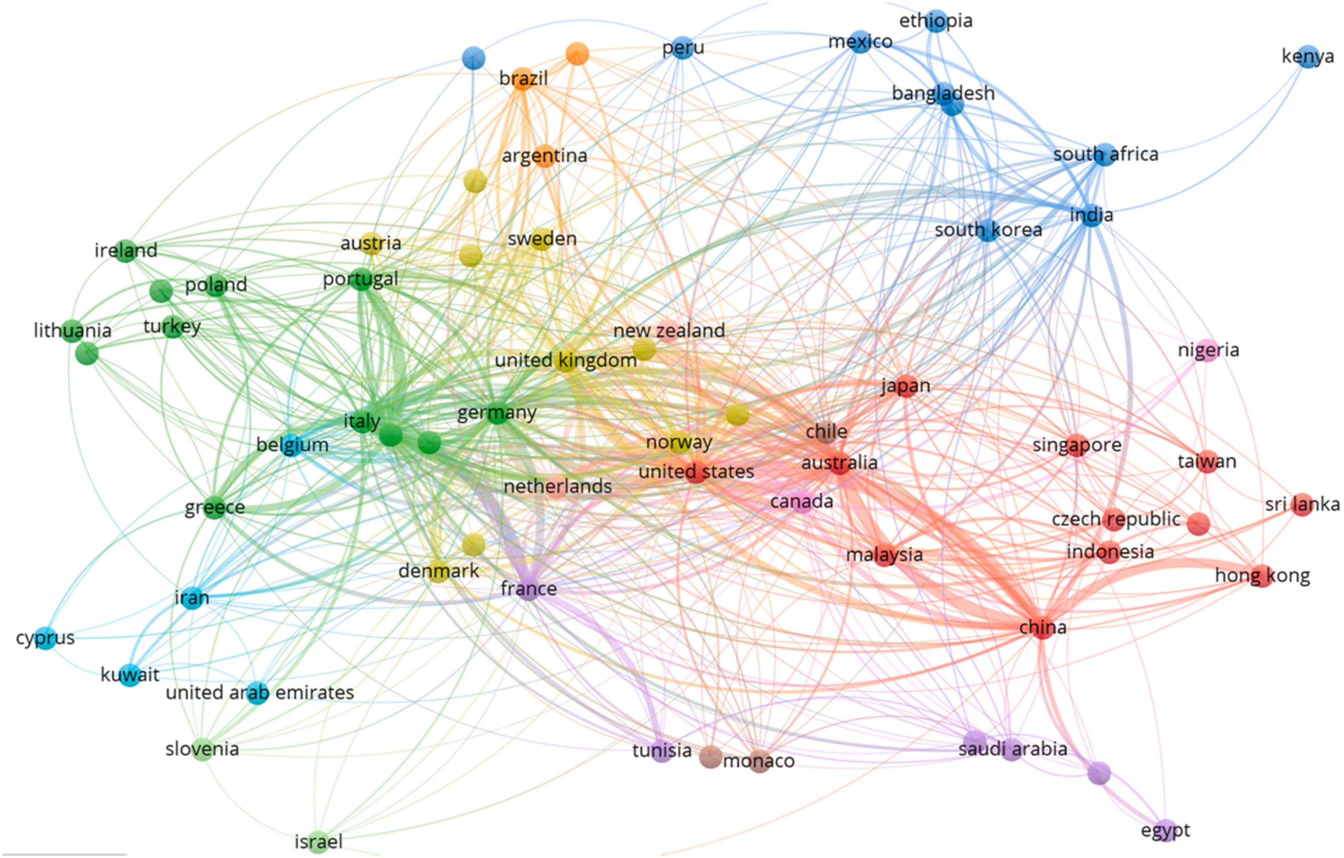

Fig. 6. Country cooperation network map after COVID-19 (2020–2022).

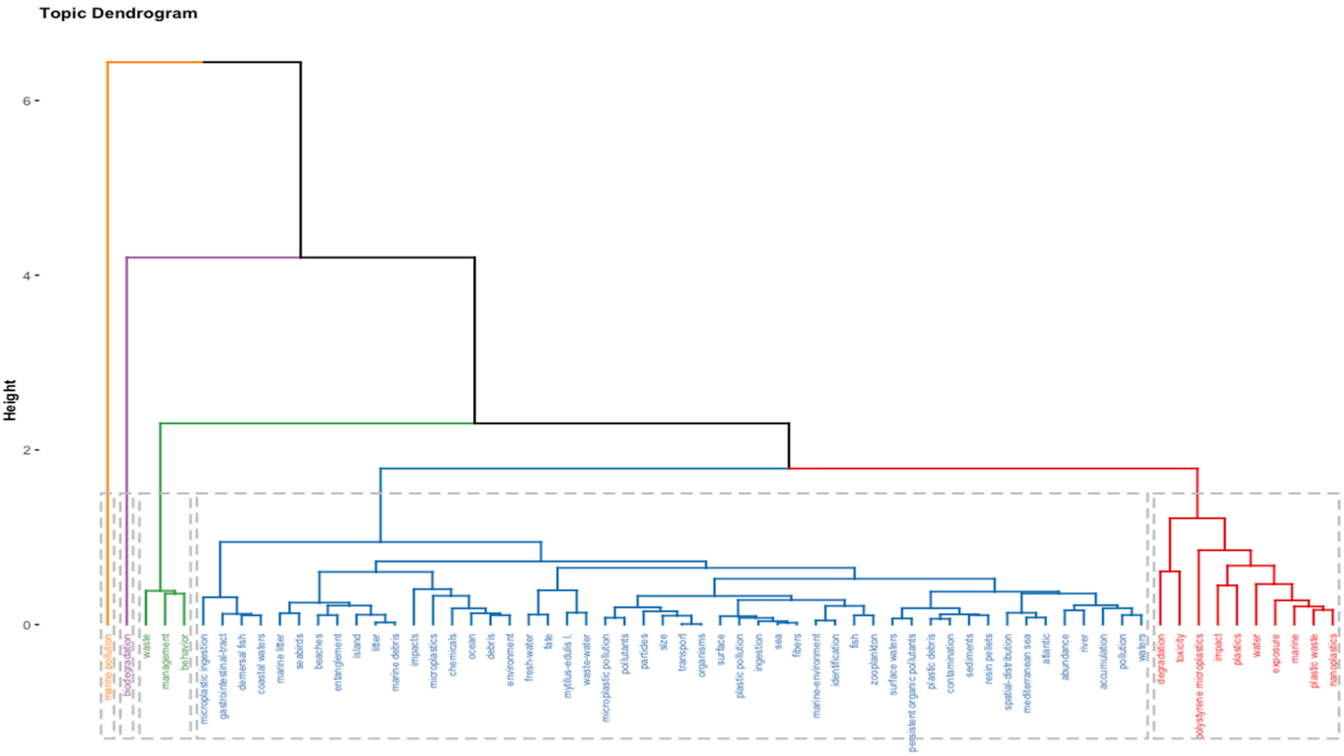

Fig. 7. Keyword co-occurrence map about ocean plastic.

clusters are still dominated by plastic as relevant keywords, such as nanoplastics, polystyrene microplastic. By clustering and merging similar keywords in different colors, four categories are got finally: ecosystem, spatial distribution, environmental governance and biodegradation. Although the main keyword clusters have not changed significantly, the research hotspots in some clusters have changed. Therefore, the four keyword clusters in detail are analysed below.

3.5.1. i Ecosystem

3.5.1.1. Vertebrates. Marine ecosystems are highly vulnerable to pollution by human activities. Scholars have detected synthetic polymers such as nylon, polyvinyl chloride, and polystyrene from marine mammals such as dolphins and whales [33]. These plastics may lead to changes in mammalian swimming behavior, altered immune responses, reduced growth rates, and reduced ability to avoid prey. The reduction in human activity following the outbreak has led to a brief recovery of marine ecosystems, but the demand and consumption of single-use plastic products experience unprecedented growth. Macro, meso and microplastics become potential carriers of pathogens. Plastic seriously injures and kills sea turtles, whales and other marine mammals [34]. In the case of sea turtles, larger marine plastic waste threatens sea turtles through direct ingestion, can cause weakness and death through internal injury and intestinal blockage, and can affect the survival of hatchlings [35].

3.5.1.2. Fish. The existence of plastic has potentially toxic effects on different fish in the ocean. At this stage, most scholars analyze the impact of plastic in the ocean on the growth of fish through field sampling and investigation methods. Studies by scholars such as Luís show that the accumulation of plastics in gills, guts and liver can lead to various toxic effects and changes in metabolic pathways [36]. Otto et al. show that acetylcholinesterase (AchE) activity is reduced in the presence of plastics and heavy metals [37]. Studies by Gola et al. show that the presence of other additives such as dyes, heavy metals, compounds, etc. make plastics more toxic to organisms [38]. Compared to non-urbanized areas, urbanized areas, especially areas with intensive human activity, show higher plastic levels in fish samples, which become more evident in the wake of the COVID-19 outbreak.

3.5.1.3. Plants. The presence of plastic in aquatic organisms can also affect algae populations. Such as Chlorella, Scenedesmus, and Dunaliella salina, which are the energy source for many other aquatic organisms that feed on these algae. Once these plastics enter the food chain they can cause serious harm [39]. The presence of plastics may reduce photosynthetic activity and produce oxidative stress. The negative charge on the algae and the positive charge on the plastic prompt the algae to take up and accumulate more plastic, reducing the overall food supply for other marine organisms that depend on the algae. On the other hand, seaweed is used as a source for the production of bioplastics due to its high biomass and ability to grow in a wide range of environments, which offers new ideas for sustainable plastic production and waste management [40,41].

3.5.1.4. Birds. Data on physical and chemical pollutants in seabirds can serve as indicators of environmental health in marine habitats [42]. Debris intake and entanglement rates for seabirds reflect the amount or distribution of plastic pollution in the marine environment [14]. Researchers use data on meat-footed gulls, northern gulls, penguins and other birds to show rapidly increasing plastic waste in the ocean have diverse and increasingly serious consequences for marine wildlife [43]. Due to the biological nature of birds, seabird colonies act as receivers of plastic debris, allowing the transfer of marine derived plastics between land and sea [44].

3.5.1.5. Invertebrates. Invertebrates are common benthic species that inhabit sediments and intertidal zones. As filter feeders, bivalve mollusks can directly absorb microplastics from the surrounding environment, resulting in microplastic residues in gills and soft tissues [45]. Marine plastic pollution can facilitate the transoceanic travel of invasive species, especially invertebrates, as trash items are often inhabited by diverse crusting biotas such as coralline algae, barnacles, and bivalve mollusks [46]. Coral reefs provide ideal habitats for a variety of marine life, and the continued accumulation of plastic affects the healthy polyp-algae symbiosis, that is the cornerstone of biologically rich coral reef ecosystems [47]. But overall, invertebrates are still relatively understudied compared to fish and mammals.

3.5.2. Spatial distribution

Plastics are now circulating globally like the biogeochemical cycle, for example, microplastics can be transported from rivers to the ocean and then back to land through the ocean [48,49], suggesting that plastic pollution creates a link between the freshwater, terrestrial and marine domains [50]. Because this link is rarely influenced by human pressure, vulnerable and remote areas are inevitably affected by ocean plastic pollution [51]. Take the polar regions as an example, which are relatively pristine environments with highly sensitive ecosystems, but the survey find a large amount of microplastics accumulated in sea ice and sediments in polar regions, which are consumed by seabird populations [52].

During 2015–2019, "Canada", "Brazil", "Spain" and other keywords appeared. The research of Canadian scholars is not limited to the coast of North America, but involves the study of the global ocean including East Asia [53], Africa [54] and the Arctic. Spain was listed as the most polluted country in Europe by the European Environment Agency (EEA) in 2015. The Canary and Balearic Islands, the Ebro delta, the Mar Menor and the Alboran coasts partly reflect the Mediterranean plastic problem [55–57]. Brazil represents the concern of scholars about plastic pollution in the South Atlantic. During 2020–2022, the keyword "China" appears. China is the country with the largest plastic production in the world. After the epidemic, China, as a country most affected by the epidemic, soar from 45 tons to 247 tons of medical waste during the outbreak, including food and lunch boxes used by patients, a medical staff of PPE etc. Chinese scholars carry out more extensive research on marine plastic pollution in different regions, including coastal Qingdao [58], freshwater Poyang Lake, and the East China Sea [59].

3.5.3. Environmental governance

The current situation requires cooperative action by individuals, national and international authorities to protect the oceans from plastic pollution, as summarized below:

3.5.3.1. Individual. Widespread awareness campaigns and volunteering are key to reducing plastic pollution before the pandemic. The difficulty of estimating the amount of personal protection products due to the outbreak has made it difficult to combat marine plastic pollution. The estimation of the quantity of plastic products such as masks has become a research hotspot. Many scholars have established models to evaluate the public's use of single-use plastics in different regions and their reliance on protective equipment such as masks and gloves [60]. The use of protective products and epidemic prevention and control have become the focus of citizens' attention.

3.5.3.2. Government. Fig. A2 mainly shows the policies of various countries on plastic waste management before the outbreak. Before the COVID-19 outbreak, countries' plastic waste management policies focused primarily on reducing the production and use of plastics, without taking into account the plastic products that have been converted into waste and entered the environment. Governments mainly used measures such as bans, restrictions and taxes to reduce the

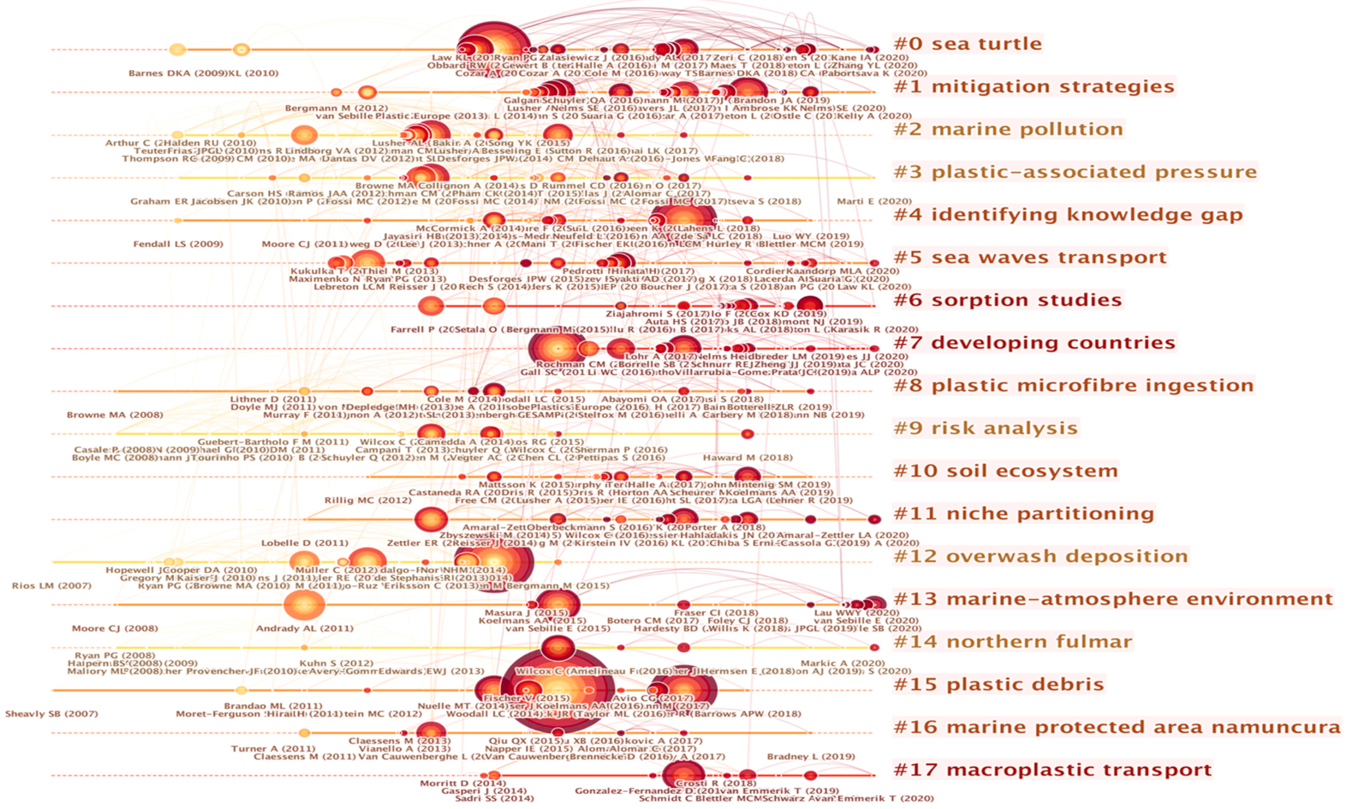

Fig. 8. Document co-citation timeline graph.

production and consumption of plastics. For example, the Malaysian government has established institutional governance structures at the national level, such as the National Environmental Quality Council, the National Solid Waste Management Department and the Solid Waste and Public Cleansing Management Corporation [61]. Turkey has imposed a ban on the import of plastic waste from developed countries [62]. But these policies often have little effect because of information asymmetries between plastic producers, waste generators, waste collectors and recyclers and governments.

The occurrence of the COVID-19 epidemic changes people's production and lifestyle, and the massive increase in plastic waste makes government authorities rethink the solutions to marine plastic pollution. Research on plastic pollution should not stop at policy measures, but should put more effort into plastic waste prevention and reduction, recycling more plastic waste back into the system to reduce the negative impact on the environment and consumption of natural resources dealing with marine plastic pollution. On the other hand, complementary government incentives are also necessary. The emergence of self-cleaning masks and water-soluble masks has eased the pressure on disposable masks, and the government funding to encourage technological innovation can reduce the pressure to manage these large numbers of discarded masks [63].

3.5.3.3. International authorities. Marine plastic governance needs to deal with marine sources, land sources, and chemical controls separately. No binding regulations have been introduced at this stage to address this issue [64]. The UN Environment Assembly in 2017 described the current framework for tackling marine plastic litter and microplastics as "fragmented and disjointed". Low-income countries have higher rates of poor waste management than upper-middle and high-income countries, suggesting that at the international level, countries at different levels of development differ in their ability to deal with marine plastic pollution [65]. International organizations should work with governments, non-governmental organizations, environmental organizations, academia and the public to reassess existing marine plastic pollution to ensure sustainable plastic waste management models [66]. The outbreak of the epidemic has increased the cost of reversing the negative externalities of marine debris, and the design of a global plastic governance treaty become more urgent. International actors should adopt effective monitoring, reporting and review procedures, adapted to the local environment, enforced by incentivizing compliance and discouraging non-compliance.

3.5.4. *Biodegradation*

Plastic is a long-lived pollutant that is highly resistant to environmental degradation. Therefore, biodegradation by chemical analysis is an important research direction for the management of marine plastic pollution [67]. Fragmentation, assimilation and mineralization are the three basic steps of plastic biodegradation. Compared with the expensive cost of physical and chemical degradation, biodegradation has more obvious time and price advantages. Soleimani isolate and identify 17 actinomycetes belonging to three genera that can efficiently biodegrade polyethylene-based plastics [68]. Mealworms, the greater wax moth, can degrade plastic polymers by using plastic as a carbon source [69]. Enterobacteriaceae and sphingobacteriaceae isolated from terrestrial snails can also degrade PS through oxidative pathways and depolymerization [70].

The keyword "bacteria" appears, suggesting the role that bacterial microbes play in plastic degradation. A large number of microbial species, including bacteria and fungi, have biodegradation potential. However, there are still some technical difficulties in biodegradation. First, bacteria-mediated degradation is a relatively long process, which usually takes several months [71]. Second, due to the interaction between different microbial types and the participation of countless enzymes, the impact of bacterial consortia on plastic degradation is difficult to accurately control. A range of environmental conditions must

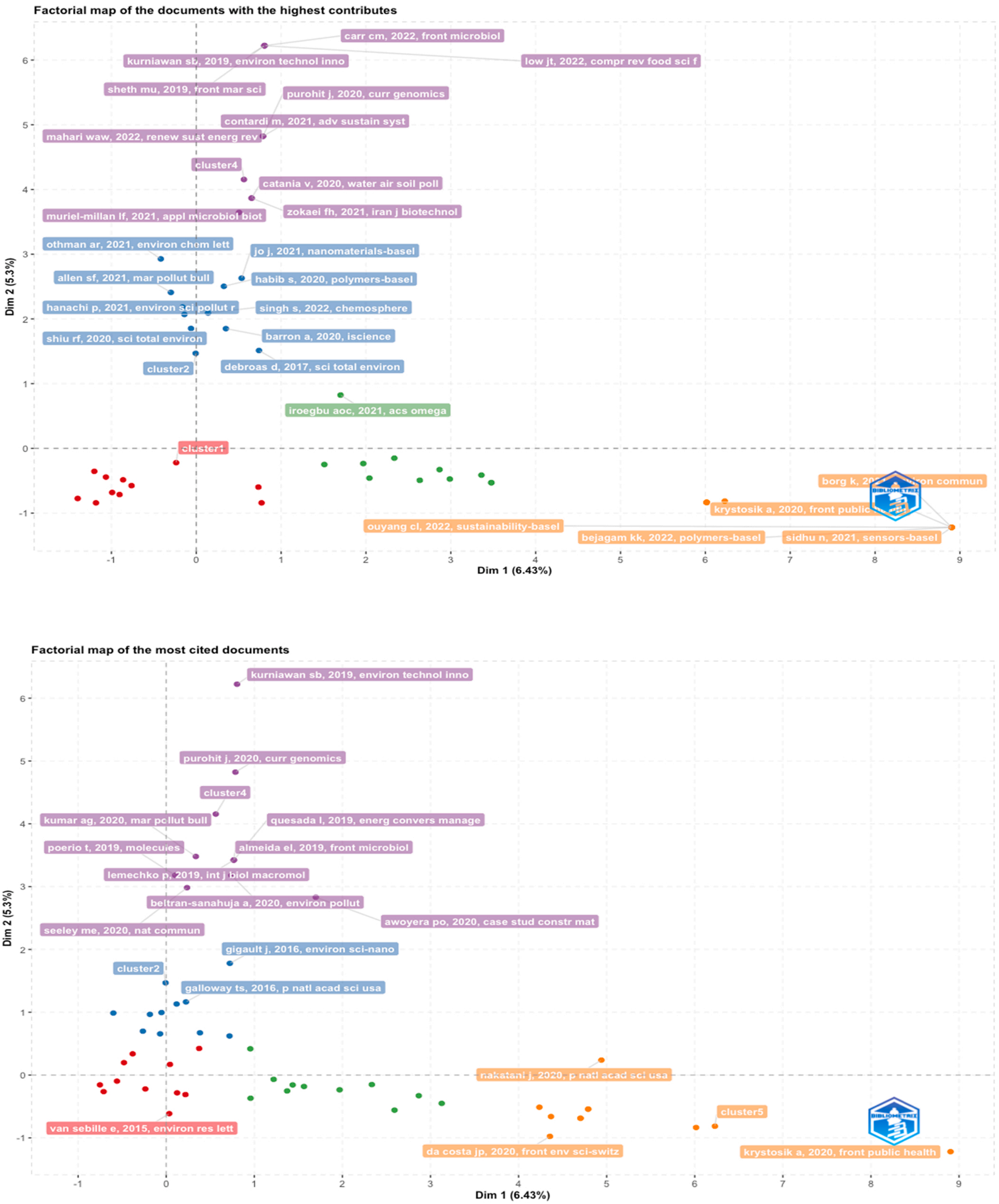

Fig. 9. Factorial map of the documents and authors with high contribute.

be assessed between individual species and microbial communities to identify limiting steps and ultimately optimize microbial activity [72].

4. Discussion

To explore changes in marine plastic pollution research focus over time, co-citation and keyword evolution analysis are conducted in this section. Co-Citation analysis means that two documents appear together

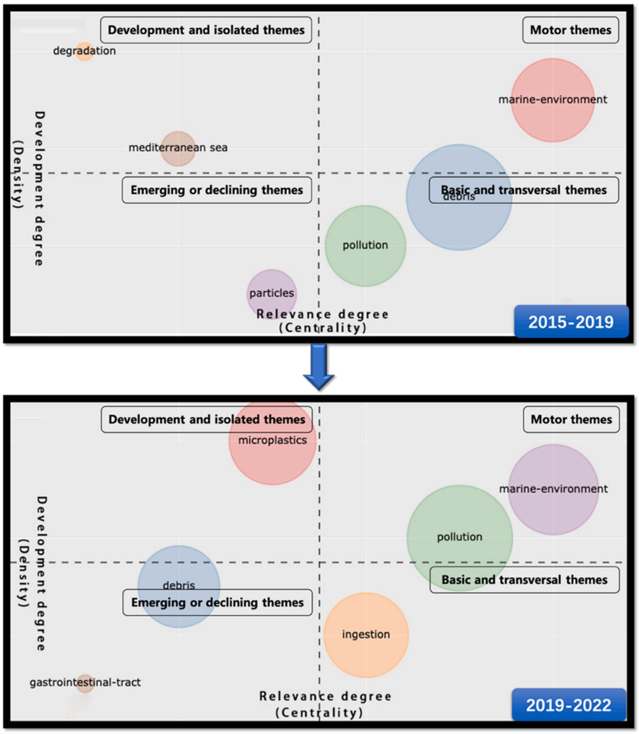

Fig. 10. Evolution of in keywords marine plastic pollution research.

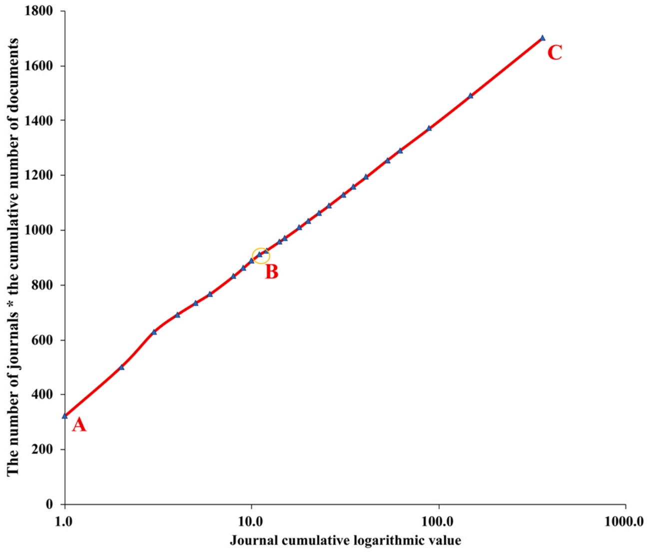

Fig. A1. The distribution curve of journal articles in the field.

in the bibliography of the third citing document and documents form a co-citation relationship. Through the process of mining the co-citation relationship of a document space data set, it can be regarded as the co-citation analysis of documents [73]. First of all, in the co-citation analysis, we use the co-citation timeline view and highly cited scholars and papers of the documents during 2015–2022. In Fig. 8, documents in the same cluster are placed on the same horizontal line. The time of the document is placed at the top of the view, and the time to the right is closer. The number of documents in each cluster can be clearly seen in the timeline view. The more documents in the cluster, the more important the resulting cluster field is. In the figure, the time span of documents in each category and the rise, prosperity and decline process of a particular clustering study can be obtained. For example, in a certain period of time, there are fewer concentric circles on the horizontal line, indicating that there are The results of influence are less, on the contrary, if the literature in a time zone is more aggregated, it indicates that a large number of influential results have been accumulated in that time zone. The Timeline view can further explore the temporal characteristics of the research areas reflected by the clusters. It is worth noting that the time when the node first appeared is not the time when the document was published, but the time when the document was first cited in the co-citation network. In Fig. 8, we obtained 17 co-citation clusters: sea turtle, mitigation strategies marine pollution plastic-associated pressure, identifying knowledge gap, sea waves transport, sorption studies, developing countries, plastic microfibre ingestion, risk analysis, soil ecosystem, niche partitioning, overwash deposition, marine-atmosphere environment, northern fulmar, plastic debris, marine protected area namuncura, microplastic transport. First of all, the cluster categories can be mainly divided into three categories. The first category is about ecological environment, such as sea turtle representing animals, soil ecosystem. The second category is the formation of plastic pollution, such as plastic microfibre ingestion, microplastic transport. The third category is the governance of plastic pollution, such as mitigation strategies marine pollution plastic-associated pressure, developing countries. When the field of recognition emerged, we mainly focused on when denser concentric circles appeared. As can be seen from the figure, during 2015–2017, prominent nodes appeared on the timeline of several keywords: 0 sea turtle, 7 developing countries, 12 overwash deposition, 15plastic debris. This means that during this period, basic research on microplastics and biology has received extensive attention from the academic community.

Since the outbreak of COVID-19, although the time is short, articles with high contributions still appear in Fig. 9. Fig. 9 is a multiple correspondence analysis performed with bibliometrix, in which text keywords are plotted on a 2D map. The more similar the words are in distribution, the closer they are represented in the map. The results can thus be interpreted in terms of the relative positions of the points and their distribution along the dimension. Jyotika Purohit conducts genomic studies of organisms used for microbial degradation of plastics [74]. The study by Wan Adibah Wan Mahari shows that microwave co-pyrolysis (MCP) was used to simultaneously convert medical plastic waste (MPW) and waste frying oil (WFO) into liquid oil products, which has the potential for sustainable production of renewable resources in the future [75]. We explore the evolution law of research hotspots at different development stages through the literature from 2015 to 2022. Three main evolutionary contexts are sorted out.

4.1. *Origin and distribution of plastic pollution in the ocean*

Plastic pollution often occurs in coastal waters and beaches, and the origin and distribution of plastic pollution have always been an important issue for scholars. This part of plastic debris mainly comes from littering at sea and direct discharge from marine industries such as fishing, aquaculture and offshore oil drilling [76]. Although the direct discharge of marine plastic pollution has attracted the attention of scholars in an earlier period, most of the research on direct discharge has remained on the collection and analysis of theoretical data. There are three main reasons. First, due to the diversity of plastic pollution sources, it is difficult to effectively predict the amount of plastic input into the ocean [77]. Second, sampling from the ocean is also difficult due to its vast size and the small size of most plastic debris [78]. Third, the complex climatic conditions and geographical features of the marine environment may increase the difficulty of measuring marine plastic pollution [79]. With the development of research, keywords such as "surface water" and "river pollution" appear, reflecting the connection between the terrestrial system and the marine system became the focus of attention. In 2017, scholars such as Laurent found that 1.15–2.41 million tons of plastic waste enter the ocean from rivers every year. The measurement of plastic pollution in surface water became the

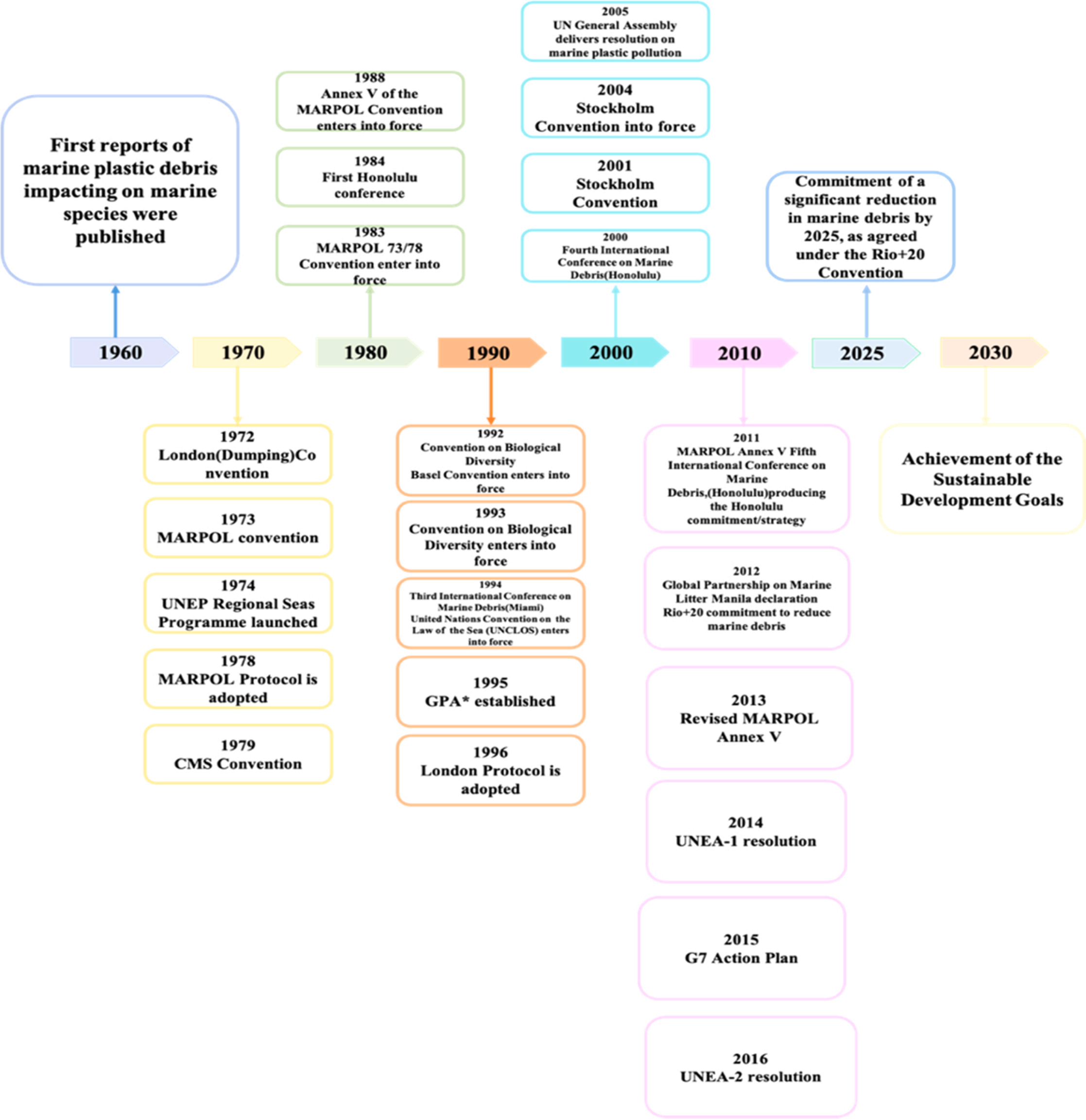

Fig. A2. Marine plastics global policy timeline [85].

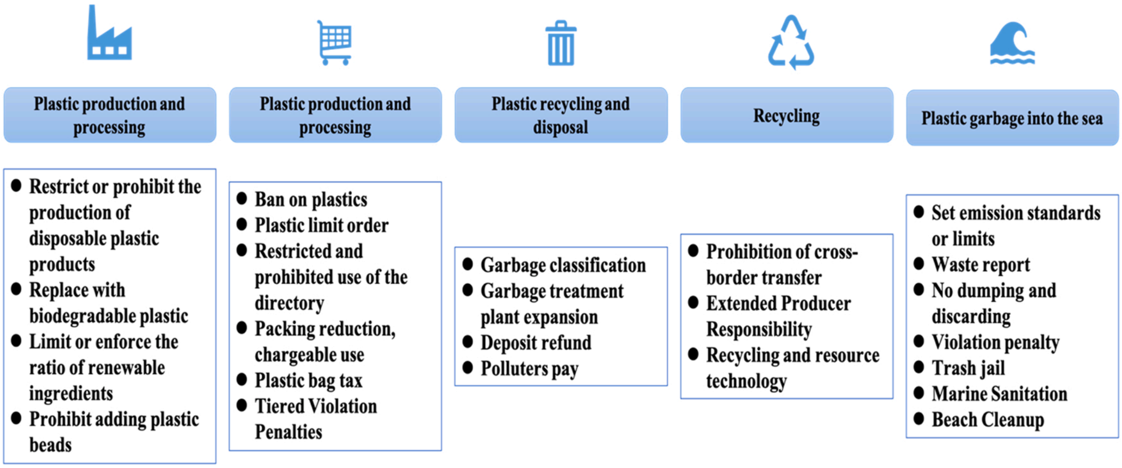

Fig. A3. Treatment measures for plastic waste and microplastics corresponding to different life cycles.

focus of research during this period, and despite the filtration of domestic and industrial wastewater by sewage treatment plants, the wastewater still contains a large amount of plastic particles that are transferred to the marine ecosystem.

4.2. Impacts of marine plastic pollution on living organisms

Before the outbreak, keywords such as "animals" and "fish" showed that the impact of marine plastic pollution on organisms was mostly focused on marine animals, birds, microorganisms and plants. After the outbreak, the COVID-19 epidemic as a public health event affecting the world has increased academic concern for the health of citizens[80]. The potential impact of marine plastic pollution on human health became the focus of scholarly research. Theoretical research frameworks and contexts are becoming clearer, and the dimensions of research are expanding from a single biological species to a more comprehensive field. Marine plastic pollution may affect human health along the food chain, primarily through the consumption of sea salt, aquatic products, livestock and poultry that feed on marine fishmeal. Biological and chemical contaminants are ingested by humans through adsorption to plastic surfaces and may lead to reproductive toxicity, carcinogenicity and mutagenicity.

4.3. Marine plastic pollution control

The management of plastic pollution in the ocean has always been one of the focuses of academic research. Fig. A3 shows the plastic pollution waste management strategies corresponding to different life cycles [81]. It can be seen that the control measures of marine plastic waste pollution follow the source reduction and process management. According to the idea of sea entry prevention and control and marine salvage, the full life cycle control of plastics is realized through production and consumption reduction, disposal process management and recycling. In the whole life cycle theory, the research before the epidemic mostly focused on the processing, consumption and disposal of plastic products, while the research on the recycling of plastic waste has not yet been developed.

In this section, a strategy map is used to describe the inter-linkages of clustered topics and the inter-linkages between different topics. Each node in the strategy graph represents a topic clustered by n keywords, and the number in the node is the amount of related literature on the topic. The vertical axis of is the density, which is used to measure the strength of association between keywords within the topic. The horizontal axis is the centrality, which measures the strength of the association between a topic and other topics in the research time zone.

In Fig. 10, timelice1 shows the keyword evolution over the period 2015–2019. First, there is only one keyword in motor themes: "marine environment", which has high density and centrality indicators, indicating that it has been well developed. In the development and isolated themes there are keywords "degraded", "mediterranean sea". This suggests that plastic degradation may become a research hotspot in the future stage. In emerging or declining themes, there is a keyword "particles", which means that research related to plastics has received a lot of attention and is well developed. Basic and transversal themes are "pollution", "debris", indicating that the issue of microplastic pollution requires further research.

Timelice 2 represents the evolution of keywords in 2020–2022. Comparing timeslice 1, “pollution” has shifted from basic and transversal themes to motor themes, suggesting that after the outbreak, the pollution problem has been more influenced by the academic community. There is a keyword "microplastics" in development and isolated themes, indicating a further increase in research on microplastics, which may become a research hotspot in the future. The new keyword "gastrointestinal tract" appears in emerging or declining themes, and the keyword "intake" appears in basic and transversal themes, indicating that biological reproduction and survival research present different hot trends.

It is worth noting that microplastics and plastic degradation, as the two main research directions in the future, are not completely independent. Since it is easy to produce microplastics during the process of plastic degradation, the microplastics in the ocean are not enough to support the metabolism of prokaryotes, and may not be degraded by microorganisms in any period related to human society. Therefore, the degradation of microplastics has become a key issue of global concern. Future research efforts should further identify key environmental parameters and properties that affect plastic degradation to predict the fate of plastics in different environments and facilitate the development of technologies to reduce plastic pollution [82–84].

5. Conclusion

This paper reviews the status of publications on marine plastic pollution during 2015–2019 and 2020–2022 by using the systematic literature review and latent semantic analysis. A detailed review of the national cooperation model, research hotspots, and research evolution before and after the epidemic is carried out. The main conclusions of this paper are as follows:

(1) From 2015–2022, the research on marine plastic pollution can be divided into three stages: initial stage, ascent stage, and exploration stage. After the outbreak of the COVID-19 epidemic cause a brief decline in publications, there was a sharp rise. This may be related to the epidemic prevention policies in the pre-epidemic and post-epidemic periods.
(2) In the exploration of regional research models, the degree of plastic pollution and knowledge output are positively correlated to a certain extent. The epidemic do not affect the knowledge output of the main publishing countries, including developing countries where waste management systems are severely affected during the outbreak. The regional cooperation model changes to a certain extent. After the outbreak of COVID-19, 4 main research groups emerge: Central European countries centered on Italy; Nordic countries centered on United Kingdom; Asian-African development countries; United States, China as the center of the Pacific Rim countries.
(3) In the analysis of the knowledge graph, before and after the COVID-19 epidemic, the clustering of keywords do not change significantly, which can be divided into four parts: ecosystem, spatial distribution, environmental governance and biodegradation. There are differences in the study of subcategories of keywords.
(4) In the analysis of the evolution of knowledge structure, the research on the origin and distribution of plastic pollution in the ocean is relatively mature, the knowledge system is relatively complete, and the number of relevant publications is large, but the research has not developed further after the epidemic. The impact of marine plastic on organisms and the governance of marine plastic pollution have become a branch of knowledge that has evolved rapidly after the epidemic. In the post-epidemic era, the study of microplastics in the ocean and the pollution of biodegradable plastics have become two major research hotspots.

The study leaves some gaps, and these limitations could be a future direction for researchers. First, in terms of data selection, due to the choice of database, some publications may be missed, which may affect our final analysis results. Second, some of the censorship studies used may lead to recall and response biases. Third, the authors’ productivity analysis, although using Lotka’s law, still uses other descriptive statistical methods. Finally, the impact of the pandemic on marine plastic pollution has changed over time, and the existing literature does not reflect this change in a timely manner. Although preprints and early versions of scientific articles represent a means of rapidly disseminating information, these articles are not used as our data source because they lack independent quality control.

CRediT authorship contribution statement

Qiang Wang: Conceptualization, Methodology, Software, Data curation, Writing – original draft, Supervision, Writing – review & editing. **Hui Huang:** Methodology, Software, Data curation, Investigation Writing – original draft, Writing – review & editing. **Rongrong Li:** Methodology, Data curation, Investigation Writing – original draft, Writing- Reviewing.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix

(See here appendix Figs. A1–A3).

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