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RESEARCH ARTICLE

Plastic pollution induced by the COVID-19: Environmental challenges and outlook

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Abstract
The COVID-19 pandemic has also caused an environmental challenge, especially plastic pollution. This study is aimed to provide a systematic review of the current status and outlook of research on plastic pollution caused by the COVID-19 pandemic using a bibliometrics approach. The results indicate developed countries were the first to pay attention to the impact of plastics on the ocean and ecological environment during COVID-19 and conducted related research, and then developing countries followed up and started research. Research in developed countries is absolutely dominant in plastic pollution induced by the COVID-19, although the plastic pollution faced by developing countries is also very serious. The author's co-occurrence analysis shows the Matthew effect. Keyword clustering shows that plastics have a harsh chain-like impact on the ecological environment from land to ocean to atmosphere. The non-degradable components of plastic bring a serious impact the ocean ecosystems, and then pose a serious threat to the entire ecosystem environment.

Keywords COVID-19 · Plastic pollution · Environmental challenges · Bibliometrics · Visual analysis

Introduction

The pollution of plastic waste has attracted the attention of governments all over the world, related actions have been launched to combat the threat of plastic waste to the environment (Jie et al. 2020; MacLeod et al. 2021; Sahlol et al. 2020). Based on the data, 8.3 billion tons of plastics had been produced globally until mid-2017, about 6.3 billion tons of plastic waste have been generated, of which about 9% has been recycled, 12% has been incinerated, 79% has accumulated in landfills or the natural environment until 2017 (Brooks et al. 2018). The United Nations declared that plastic waste pollution was seen as a global crisis that should drive global adjustment of relevant strategies to prepare for sustainable economic development (Borrelle et al. 2020; Islam et al. 2021; von Schuckmann et al. 2020; W. Yuan & Chang 2021).

However, the COVID-19 pandemic has made the treatment of plastic pollution more complicated (March et al. 2021). In December 2019, the world was affected by a pandemic caused by a virus called "SARS-CoV-2" this virus causes a serious respiratory disease called COVID-19, which is easily spread through air, respiratory droplets and other channels (Huang et al. 2020; Liu et al. 2021). Common signs of coronavirus infection in humans include respiratory symptoms, fever, cough, shortness of breath and difficulty breathing. In March 11, 2022, WHO considers the current outbreak of pneumonia to be a global pandemic. Severe transmission of the new coronavirus COVID-19 pandemic causes physical damage to humans

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Highlights
- A systematic survey of marine environmental challenges and outlook caused by plastic pollution induced by COVID-19.
- Developed countries is dominant in the research on plastic pollution induced by COVID-19.
- The author's co-occurrence analysis shows the Matthew effect.
- Plastics have a harsh chain-like impact on the ecological environment from the land to ocean.

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and animals, its complications can lead to death (Sahlol et al. 2020). In response to this major public health incident, countries and regions have adopted a series of preventive and control measures, including closed management models, restricting social contact and social distance, reducing the mobility of goods and passengers, economic activities to a minimum to prevent the further spread of COVID-19 (Acter et al. 2020; Das Gupta & Wong 2020; Guan et al. 2020; Long et al. 2020; Zhu et al. 2020). Second, people must have PPE (masks, gloves and other personal protective equipment) to enter public places during severe outbreaks. The demand for disposable PPE by doctors and other defense workers is also increasing, which has significantly increased the consumption of plastic products such as masks and medical equipment (Celis et al. 2021; Herron et al. 2020). In addition, people are particularly conscious of personal health and hygiene during outbreaks, most industries and suppliers prefer to use single-use plastic products to address customer concerns and ensure their safety (Patrício Silva et al. 2021; Sassanelli et al. 2019). Finally, the blockade and isolation measures that people face during the epidemic have driven the operation of e-commerce platforms, the proportion of the population who consumes daily necessities online has greatly increased. This preference has led to a sharp increase in the production of multilayer plastic film and foam (Chen et al. 2020). It can be seen that the contribution of plastic materials during the prevention and control of the COVID-19 epidemic is undeniable, especially for frontline workers.

Therefore, the health crisis brought about by COVID-19 has gradually aggravated the environmental challenge of plastic waste (Kvale et al. 2021; Saadat et al. 2020). COVID-19 is a major public health event, it has affected all aspects of people's lives (Wang et al. 2021). Government agencies, research institutions, society and the public are first to pay close attention to public health issues, but underestimate the impact of plastic waste on the environment. First of all, what we can see is the durability, water resistance and flexibility of plastics (Risch 2009). They play an important role in protecting the health of front-line workers and the public (Kampf et al. 2020). However, the refractory and long-lived characteristics of the material components in most plastics make plastic waste more difficult to handle (Mallick et al. 2021; Mensah et al. 2022). During the epidemic, the manufacturing industry increased and expanded fossil fuel virgin plastic production, the closure of most waste treatment plants, the shortage of employees, resulting in a shortage of funds for the recycling industry, exacerbating the irrational disposal of plastic waste, which will lead to the problem of plastic pollution of the ecological environment (Benson et al. 2021; Dong et al. 2021a, b; Dong et al. 2021a, b). In addition, beaches are considered to be an important natural resource in coastal areas. They are the source of land, sand and fishing grounds that coastal communities depend on (Dharmaraj et al. 2021). The blockade implemented by many countries due to COVID-19 has reduced the movement of people in coastal areas and surrounding areas, led to clean beaches and waters in the surrounding areas, but ignored the serious pollution of most beaches caused by plastic waste during the epidemic (Zambrano-Monserrate et al. 2020). Nearly 90% of marine debris is composed of plastic, foam, food and packaging materials (Dharmaraj et al. 2021). It is estimated that by 2020, approximately 1.56 billion masks (approximately 5.66 million tons of plastic) will eventually enter the ocean (X. Yuan et al. 2021a). Large pieces of plastic waste (including masks) can be broken down into microplastics (Yuan et al. 2021b). Inadequate plastic waste management has severely led to an alarming accumulation of plastic in aquatic ecosystems, these effects may subsequently affect the economy and ocean (Bennett et al. 2021; March et al. 2021). Then we see the "visual pollution" caused by rampant plastic waste and realize that we are realizing the value of plastic at the expense of the environment. Therefore, there is an urgent need to understand "potential contamination" of the environment caused by plastics and make changes to address these challenges (Patrício Silva et al. 2021).

Currently, bibliometrics can determine the basic structure, research hotspots and development trends of the research field through systematic reviews (Gössling et al. 2021; Newman 2001; Wang and Huang 2021). It is playing an increasingly important role in responding to international public health emergencies (Rodriguez and Laio 2014). This study uses bibliometric methods and scientific knowledge graph software to comprehensively analyze the basic characteristics of the scientific literature of related research by constructing author cooperation networks, national cooperation networks, institutional cooperation networks, timeline views and keyword co-occurrence networks. In addition, we have discussed in depth the use of plastics and the chain impact of plastic waste on the ecosystem during COVID-19. Recently published documents have not yet fully clarified these issues. This study also identified the marine environmental challenges posed by plastic waste during COVID-19 and discussed mitigation measures to overcome these challenges for the reference of policy makers.

The main content of this article includes five chapters. The "Methods and data sources" section describes the methodological framework and data sources of this research. The results of the "The condition of plastic waste during COVID-19" section show the main research results of bibliometric analysis and scientific map analysis. The "Conclusions and future research" section describes the environmental challenges and future development prospects of plastics during COVID-19. The last part is a summary of the full text.

Methods and data sources

Data collection

Scopus has comprehensive academic information in multiple research fields, it can provide higher standards of literature data, and improve data processing efficiency. We screened the keywords and obtained "covid-19" "covid19" "2019 novel coronavirus disease" "2019 novel coronavirus" "COVID19" "COVID-19" "COVID-19 pandemic" "COVID-19 virus disease" "SARS-CoV-2" "coronavirus disease-19" "coronavirus disease19" "coronavirus disease 2019" "coronavirus disease2019" "2019-nCoV disease" "2019 novel-cov" "2019-nCov" "2019 novel coronavirus" "plastic" "plastics" "plastic pollution" "plastic contamination" "marine" "environment" "marine environment" etc., through a large literature case base and press materials. We also used the operators "AND" "OR" "NOT" "*" operators to match the selected keywords, which avoided subjective keyword selection and ensured the objectivity and comprehensiveness of the literature search results. Since the COVID-19 outbreak occurred in December 2019, we restricted the time frame to December 2019 to September 2021 to ensure the timeliness and relevance of the articles. After obtaining a large amount of literature, we reviewed the titles of each article and initially selected articles with high relevance to "plastics" and "environment". We reviewed the abstracts of the selected papers in detail and removed those that were not related to plastic waste and ecosystem pollution, resulting in a total of 123 papers, which were exported as data sources for bibliometric analysis and scientific atlas analysis.

Data analysis

CiteSpace and VOSviewer are Java applications. They are powerful visual data analysis platforms and widely used in bibliometric analysis (Hu et al. 2019). CiteSpace and VOSviewer can assist manual operation to analyze data and reduce errors caused by manual analysis, thereby improving the accuracy and reliability of the results. They can produce complete analysis graphs for visual analysis in scientific literature. Therefore, this study will use the knowledge map software CiteSpace and VOSviewer software for visual analysis. The visualization process mainly includes three main steps, standardized processing, clustering and visualization methods.

Standardization processing

The standardized processing of similar data is the basis of data visualization analysis. In order to obtain ideal data results and better highlight the relationship between the data, preprocessing must be performed to improve the quality of the data. Dice is one of CiteSpace's standardized algorithms. The Dice similarity coefficient can calculate the similarity of two strings.

$$\text{Dice} = \frac{2 \times comm(S_1, S_2)}{leng(S_1) + leng(S_2)} \quad (1)$$

In formula (1), $comm(S_1, S_2)$ is the number of the same characters in S_1 and S_2, and $leng(S_1)$ and $leng(S_2)$ are the lengths of the character strings S_1 and S_2.

Clustering

Clustering is divided into multiple clusters according to different data. The principle is to agree that the data objects in the cluster have good similarity, but the data of different clusters are different. The clusters menu contains algorithms that can be selected during the clustering process, including Clustering algorithms, LLR algorithms and MI algorithms. The Clustering algorithm belongs to the inter-class distance algorithm in the hierarchical clustering algorithm.

$$\mathrm{D}^2_{pq} = \frac{1}{n_p n_q} \sum_{\vec{x_j} \in \omega_q, \ \vec{x_i} \in \omega_p,} d^2_{ij} \quad (2)$$

In the formula (2), p and q are two clusters. The distance between them is determined by the average distance between the units i, j. Likelihood ratio (LLR) clustering algorithm:

$$LLR = log \frac{p(C_j \backslash V_{ij})}{p(-C_j \backslash V_{ij})} \quad (3)$$

In the formula (3), it is assumed that for the category C_j, the frequency, concentration, and dispersion of the word W_i constitute a vector V_{ij}. LLR is the log-likelihood ratio of the word W_i to the category C_j. $p(C_j|V_{ij})$ and $p(-C_j \backslash V_{ij})$ are the density functions of W_i in category C_j and $-C_j$, respectively. MI (mutual information) clustering algorithm:

$$MI(\mathrm{w,c}) = \sum_{w,c} p(w,c)log\frac{p(w,c)}{p(w)p(c)} \tag{4}$$

In the formula (4), $p(w,c)$ is the co-occurrence probability of w and c; $p(w)$ and $p(c)$ are the probability of occurrence of w and c respectively.

Visual analysis

In the graph-based visualization method, the relationship between nodes is connected by lines, the connection between nodes can clearly reflect the connection between two objects. The size of the nodes in the network graph indicates the frequency of each keyword, the connections between nodes indicate the strength of co-occurrence (Goh and See 2021). Large-scale networks can be separated by time slicing. The time series visualization method is mainly to detect the change trend of the subject over time, to detect the variant words in the literature combined with the clustering algorithm. It is used to detect and visualize the trends and changes over a period of time, further predict the development trend of the subject matter.

Research design

This article adopts the bibliometric analysis method and follows the standard scientific drawing process (Gao et al. 2020; Qin et al. 2014; Wang et al. 2021). The analysis is divided into four stages (The specific analysis process can be seen in Fig. 1).

- Determine the research problem and purpose. This stage is mainly to determine the description of the research problem and research purpose of this article.
- Determine the research method. This stage continues the previous stage, which mainly introduces the bibliometric methods used in this research, determines the database, limited time range, geographic area selected by this research.
- Identify keywords. Collect commonly used keywords related to the content of this research from various channels such as journal literature, news materials and case libraries, summarize these keywords. Screen the obtained keywords to avoid repetitive keywords and include them in the database for literature screening.
- Visual network analysis. This part follows the principle of bibliometric analysis methods to visually analyze the obtained literature data, conduct data mining from different perspectives to obtain the most comprehensive research hotspots and trends in this field.

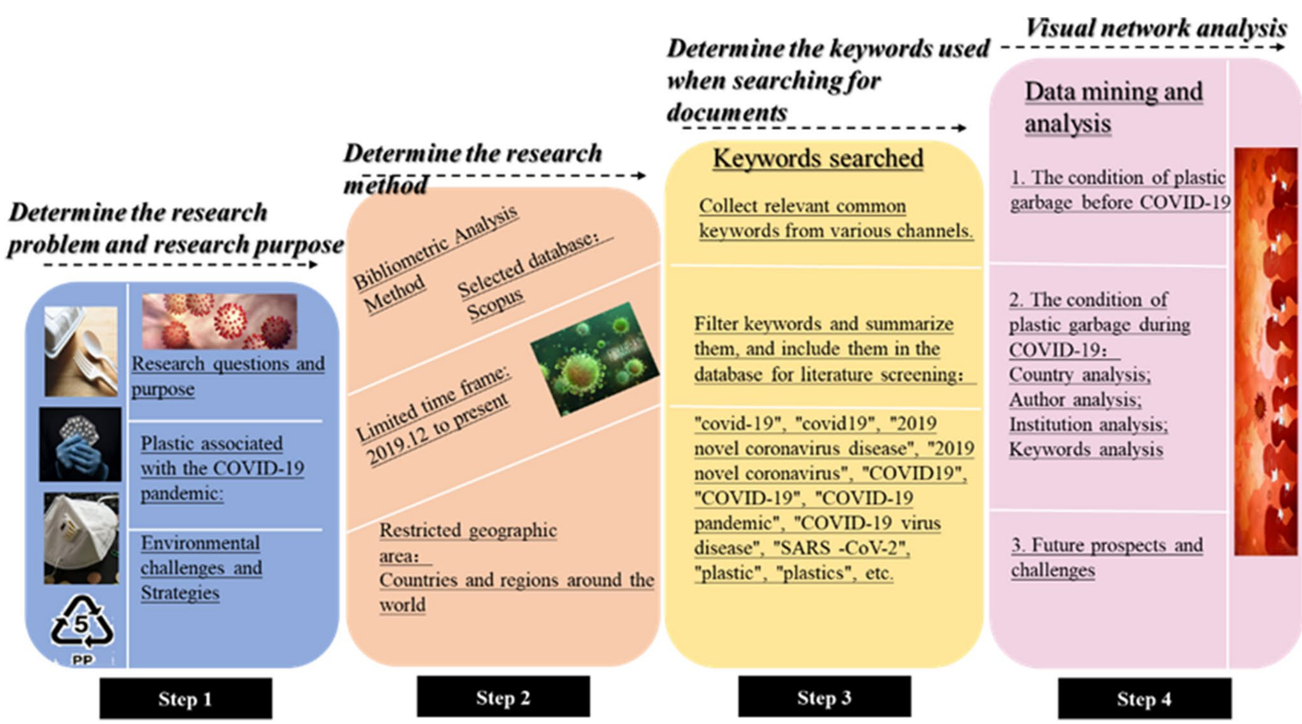
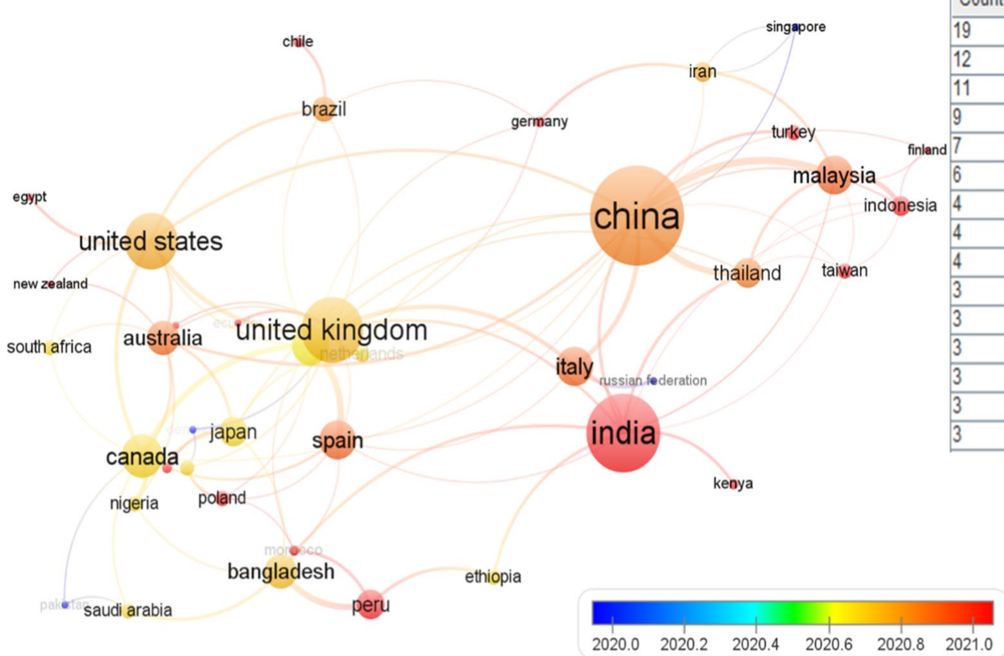


Fig. 1 The specific steps of research



Count	Centrality	Year	Countries
19	0.14	2020	UNITED STATES
12	0.00	2020	CHINA
11	0.00	2021	INDIA
9	0.01	2020	UNITED KINGDOM
7	0.00	2020	SPAIN
6	0.00	2020	AUSTRALIA
4	0.00	2021	ITALY
4	0.00	2020	CANADA
4	0.02	2020	BANGLADESH
3	0.00	2021	TURKEY
3	0.00	2020	PORTUGAL
3	0.00	2020	BRAZIL
3	0.00	2021	THAILAND
3	0.00	2021	IRAN
3	0.00	2020	SOUTH KOREA

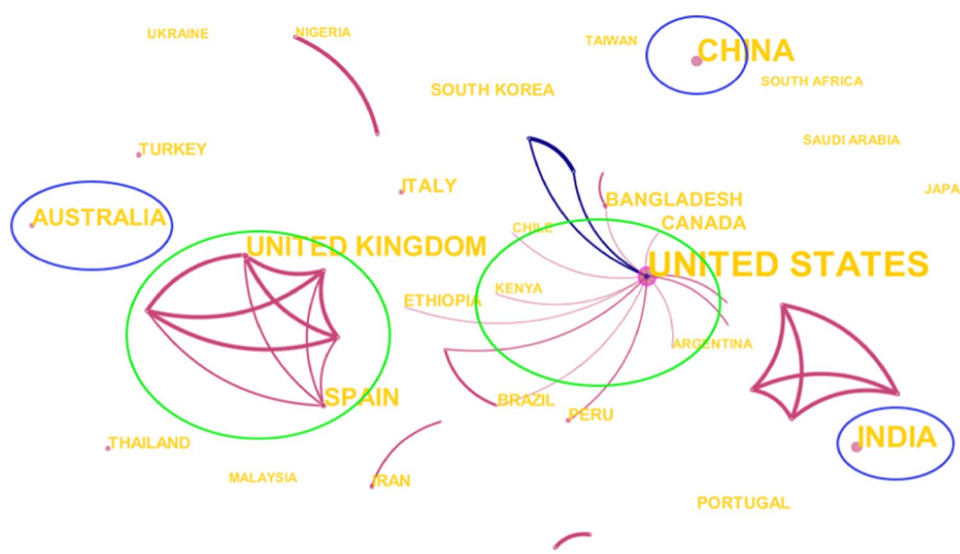
Fig. 2 The time schedule network for countries

The condition of plastic waste during COVID-19

The analysis of country cooperation networks

This section traces the relevant information recorded in the scientific literature, finds that more than 50 countries or regions around the world have participated in investigations and studies on the impact of plastics on the environment during COVID-19. In Fig. 2, the top eight countries with a high number of occurrences were the USA, China, India, the United Kingdom, Spain, Australia, Italy and Canada. The USA has the highest number of occurrences in the country collaborative network analysis on the ecosystem impacts of plastic waste during COVID-19 with 19 occurrences. The analysis of the country cooperation network in Fig. 2 shows that the number of developed countries accounts for three-quarters of the total, only two countries among developing

Fig. 3 The bibliographic coupling of country/region



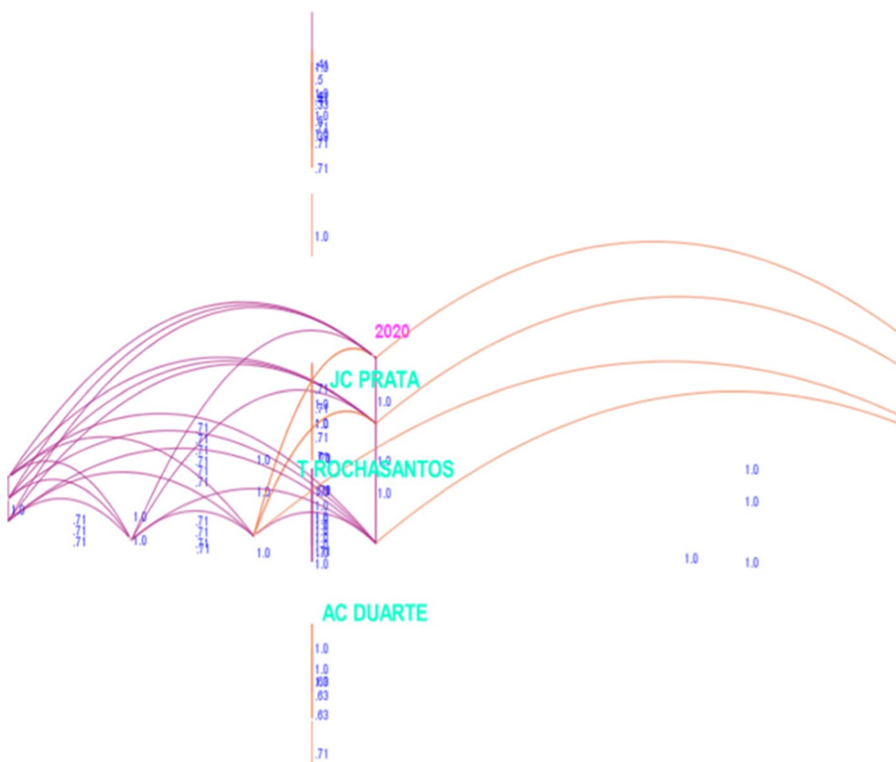
countries are China and India. The chronological order shows that during COVID-19, most developed countries such as Canada, the UK and the USA took the lead in conducting research on the impact of plastics on environmental sustainability, followed by developing countries such as China, India and Indonesia. Thus, most studies on the environmental impacts of plastics during COVID-19 was done in the developed countries. Figure 3 shows the degree of interrelationship among countries in the investigation of the environmental impact of plastics during COVID-19. Green circles represent countries with more collaborative exchanges, while blue circles represent countries with few collaborative exchanges. As can be seen from Fig. 3, research on the environmental impacts of plastics during COVID-19 has formed a major research network led by the USA and the United Kingdom. Among the countries or regions with high publication quality, the USA formed the larger research network, with the United Kingdom and Spain in second place, they also cooperated with some countries in research. In addition, most developed countries, such as Canada, have carried out relevant exchanges and cooperation. However, China, India and Australia rarely collaborated with other countries to investigate the environmental impacts of plastics during COVID-19.

These data highlight the fact that developed countries are the mainstay of research on the environmental sustainability of plastics, but developing countries have less environmental resistance during the epidemic. Therefore, developing countries should pay attention to their reliance on plastic products such as masks, gloves and medical devices during COVID-19, the environmental impacts of plastic products, and strengthen relevant research studies. While leading research on the environmental impact of plastic products during the epidemic, developed countries should strengthen communication and cooperation with developing countries to promote sustainable development of the global environment.

The "Matthew effect" in author's co-occurrence analysis

Co-citation analysis refers to the analysis of the reference list in which two articles appear together in the third cited document, and the two articles form a co-citation relationship. The content of this section is mainly to analyze the co-citation of the authors of the paper. Figure 4 is a diagram of the author's co-citation analysis. The size of the green font indicates the reduction in the number of co-cited articles by the author, the yellow and brown lines indicate the connection between the authors, the change of color indicates the distance and the nearness of the year. From Fig. 4, GE DELATORRE, JC PRATA, T ROCHASANTOS, AC DUARTE, J LIU and Y WANG are the six most cited authors from Peru, Portugal, the USA and China, mostly from developed countries. In addition, the analysis revealed the researchers' research in the impact of plastics on the environment during COVID-19. Some of the authors in the picture cooperate closely and form obvious cooperative groups, but the cooperation is mostly carried out within the group, there are few connections between multiple groups. Due to the suddenness of the epidemic, researchers in this field have not yet formed a relatively stable scientific research cooperation group, which is not conducive to the exchange and sharing of knowledge. Robert Morton summarized the "Matthew Effect" as any individual, group or region that succeeds and advances in a particular area will have a cumulative advantage and more opportunities to achieve greater success and

Fig. 4 The bibliographic coupling of authors

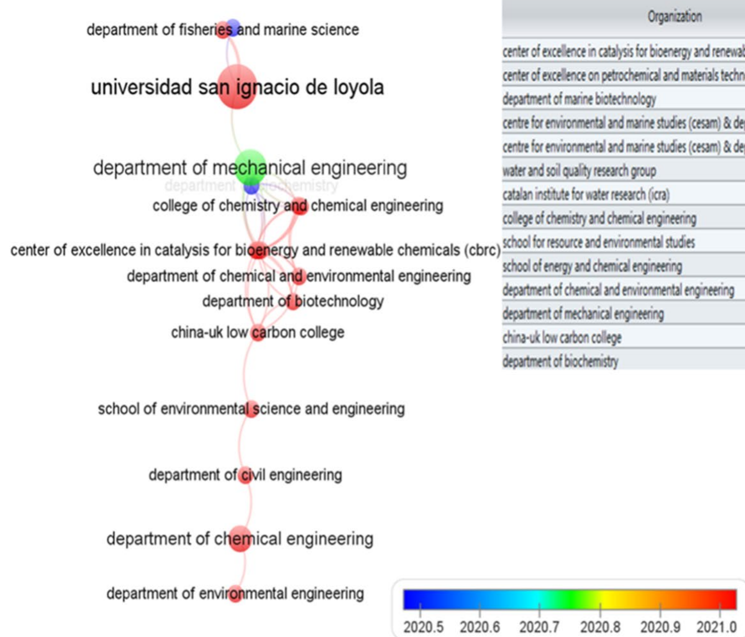


Count	Centrality	Year	Authors
5	0.00	2021	GE DELATORRE
4	0.00	2020	AC DUARTE
4	0.00	2020	JC PRATA
4	0.00	2020	T ROCHASANTOS
3	0.00	2020	D BARCELÓ
3	0.00	2021	J LIU
3	0.00	2021	Q LIU
3	0.00	2021	Y WANG
2	0.00	2021	C NGAMCHARUSSRIVICHAI
2	0.00	2021	CI PIZARROORTEGA
2	0.00	2021	DC DIOSESSALINAS
2	0.00	2021	DE BASSEY
2	0.00	2021	G MORGANTI
2	0.00	2021	H XU
2	0.00	2021	KW CHEW

Fig. 5 The time schedule network for authors

progress (Perc 2014). From the author's co-occurrence analysis, the research status of the researchers is in line with the "Matthew effect". Therefore, researchers should increase their multi-angle exploration in this field, so as to generate an accumulated advantage, the research in this field can sufficiently support the needs of reality.

In addition, Fig. 5 shows that many researchers' scientific literature has been cited since 2020. This shows that



Organization	Documents	Total link strength
center of excellence in catalysis for bioenergy and renewable chemicals (cbrc)	2	11
center of excellence on petrochemical and materials technology (petromat)	2	11
department of marine biotechnology	2	11
centre for environmental and marine studies (cesam) & department of biology	3	10
centre for environmental and marine studies (cesam) & department of chemistry	3	10
water and soil quality research group	3	10
catalan institute for water research (icra)	2	8
college of chemistry and chemical engineering	2	8
school for resource and environmental studies	3	8
school of energy and chemical engineering	2	8
department of chemical and environmental engineering	2	7
department of mechanical engineering	4	7
china-uk low carbon college	2	6
department of biochemistry	2	6

Fig. 6 The cooperation network of institutions (Red clusters include "COVID-19" "Medical Waste" "Plastic Pollution" "Solid Waste" and "Waste Management". Yellow clusters include "Prevalent Plastics" and "Air Pollution". Blue and purple clusters include "Plastics" "Mouthpieces" "Microplastics" "Water Pollution" and "Marine Pollution". The green cluster includes "personal protective equipment" "masks" and "protective clothing". "Public Health" in the public sector, "Waste Treatment" and "Pollution Control" in the environmental sector)

most researchers have been concerned about the increase in plastic dependence during the COVID-19 period since the outbreak, and have began to explore the various impacts of plastics on the sustainable development of the environment.

The cooperation networks of research institutions analysis

The number of publications and the frequency of citations of scientific literature of research institutions reflect to a certain extent the research scale and research capabilities of the field. This section analyzes the research development trends in this field from the perspective of research institutions. Figure 6 reveals the number, time and centrality of publications of various research institutions. From the perspective of the types of institutions, the main research is universities, and foundations etc. account for only a small proportion. Colleges and universities have gradually become the main research force in this field, subject knowledge has been well inherited and disseminated in colleges and universities. Moreover, we can see from the figure that these research institutions are highly central, they are representative research groups. These groups reflect the characteristics of the current cooperation of research institutions. The exchanges and cooperation between research institutions are not restricted by geographical location. In addition, different types of research institutions have conducted extensive cooperation, which has increased the diversification and comprehensiveness of research in this field.

The challenges of plastic to environment

Keywords contain the core information of the article. Keyword analysis can identify valuable information in documents, intuitively reflect the research hotspots, analytical perspectives and research methods of specific fields in different time series, reveal the inherent knowledge of the research field (Gao et al. 2020; Qin et al. 2014). We use keyword analysis to determine the main research directions and hotspots of the impact of plastics on environmental sustainability during the epidemic, make judgments on research trends in this field. In Fig. 7, there are five colors, keywords corresponding

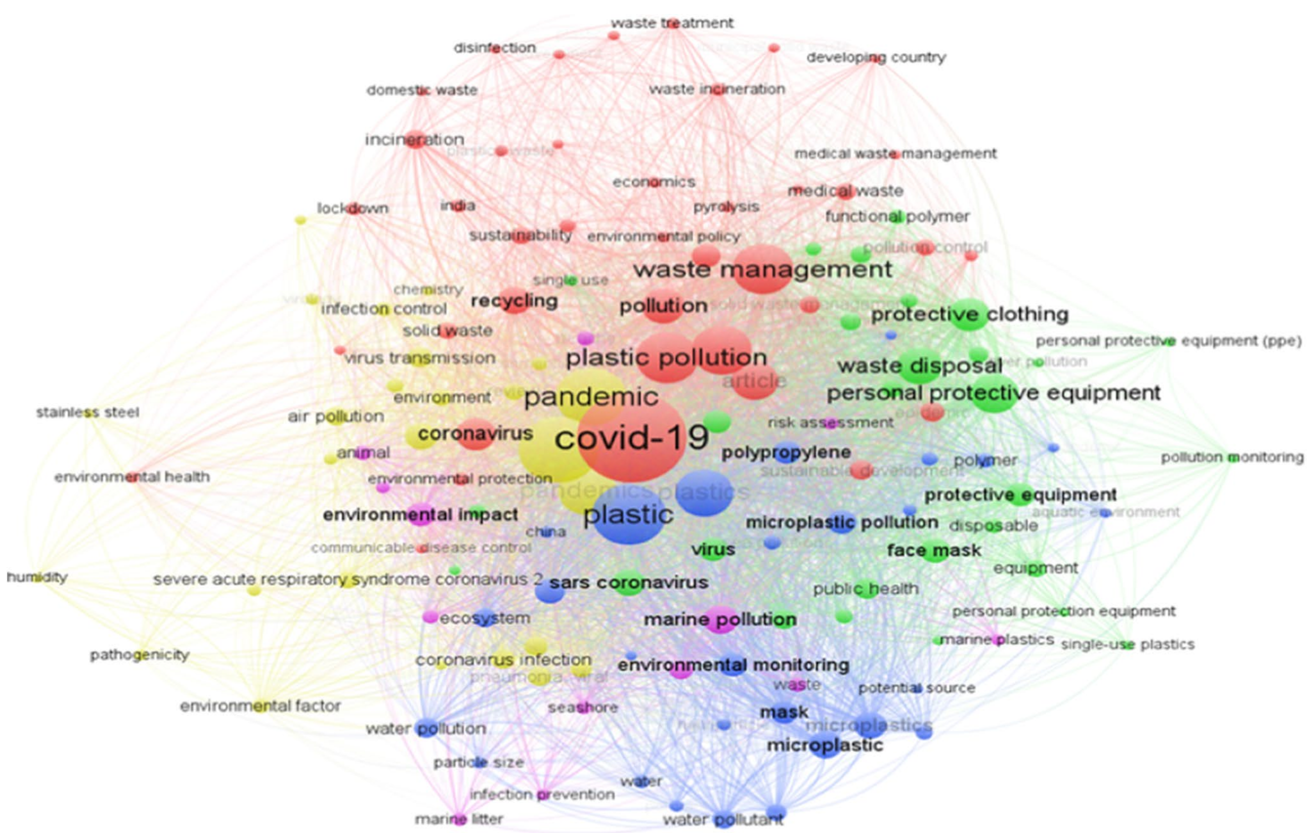


Fig. 7 Network diagram of the keyword analysis. We further refine the use of plastics during the COVID-19 period mentioned in the above section, the impact of plastics on the three main bodies of ecological sustainability (terrestrial ecosystem, marine ecosystem and atmospheric environment) (refer to Fig. 8 for details)

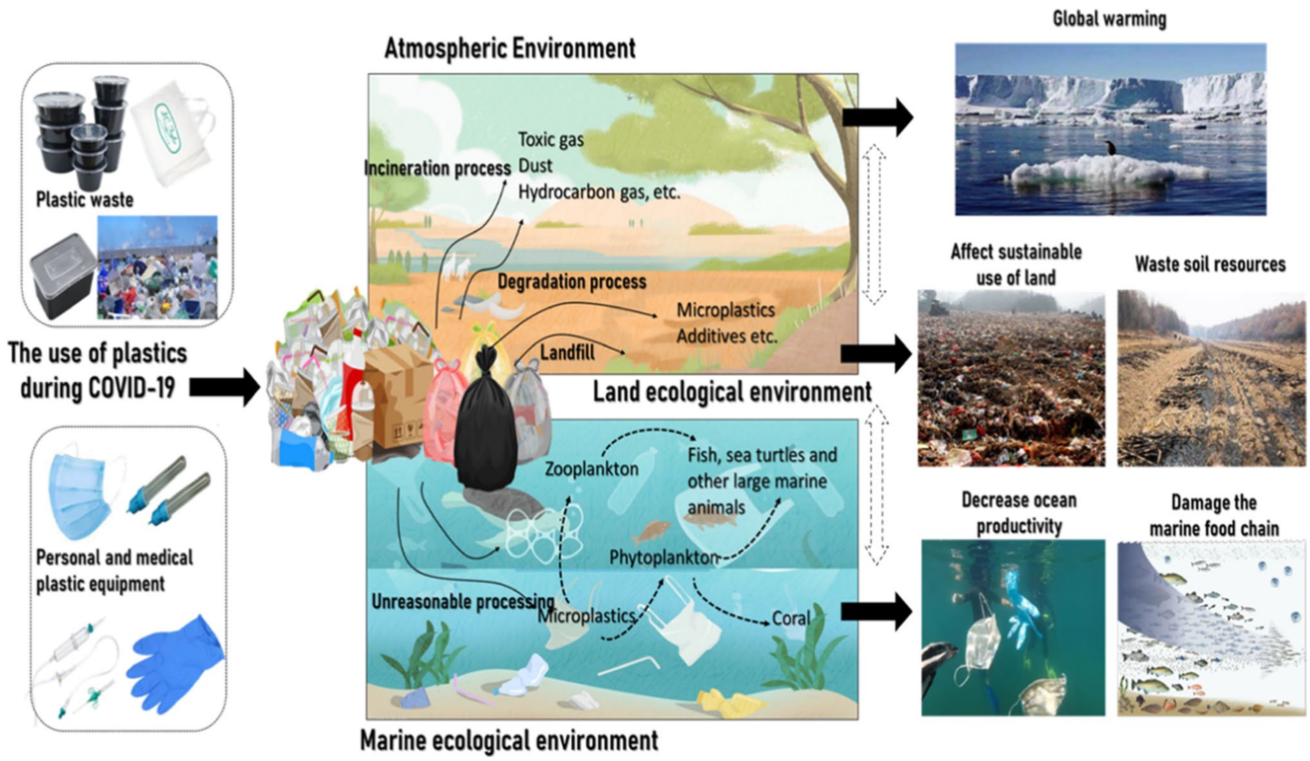


Fig. 8 The impact of plastic waste on the ecological environment

to the same color belong to the same category. The red clusters, this part of the scientific literature mainly found that a large number of plastic waste were consumed and utilized due to a series of measures to control the epidemic during the COVID-19 period. "Developing country" appeared in the cluster, only the word "India" about the country appeared. Since the outbreak of COVID-19, it has rapidly spread to most developing countries around the world. Their dependence on plastic products and the poor control during the epidemic poses a serious threat to environmental sustainability (Bashir et al. 2020). In the yellow clusters, the keywords

Table 1 Several commonly used plastics

Plastic type	Application	Environmental characteristics
Polyethylene (PE)	A wide range of inexpensive uses including supermarket bags and plastic bottles	When exposed to ambient solar radiation the plastic produces two greenhouse gases, methane and ethylene; biodegradability; toxicity
Polypropylene (PP)	Bottle caps, drinking straws, yogurt containers, appliances, car fenders and bumpers, and plastic pressure pipe systems	
Polyethylene terephthalate (PET)	Carbonated drink bottles, peanut butter jars, plastic film, and microwavable packaging	
Polyvinyl chloride (PVC)	Plumbing pipes and guttering, electrical wire/cable insulation, shower curtains, window frames, and flooring	
Polystyrene (PS)	Foam peanuts, food containers, plastic tableware, disposable cups, plates, cutlery, compact disc (CD), and cassette boxes	
Polyester (PES)	Fibers and textiles	
Low-density polyethylene (LDPE)	Outdoor furniture, siding, floor tiles, shower curtains, and clamshell packaging	

belong to the air pollution caused by the unreasonable disposal of plastic waste during the epidemic. The blue and purple clusters have more intersections, it focuses on the threats to the marine environment and marine life caused by plastic materials such as masks and microplastics. The keywords of the green cluster involve more fields and overlap with public and environmental.

The Coronavirus disease 2019 (COVID-19) pandemic on a global scale has caused serious loss of life (Wang et al. 2022a, b). The COVID-19 pandemic has led to large-scale consumption and use of personal protective equipment such as masks, face masks, gloves and medical supplies, most of which are made of plastic materials. Plastic is a synthetic or semi-synthetic material with polymer as the main component. The weight of plastic is very light and can be used repeatedly (Randall Curlee 1986). Plastic materials are divided into many types in industrial production, their main uses and environmental characteristics can refer to Table 1.

During the COVID-19 pandemic, the consumption of single-use plastics is increasing. First, to avoid the spread of an outbreak, everyone chooses to wear adequate personal protective equipment. Masks, face masks, disposable gloves and other protective equipment are highly protective for everyone, especially medical personnel (Patrício Silva et al. 2021). In addition, COVID-19 has promoted the operation of e-commerce platforms, the proportion of people who consume daily necessities online has greatly increased. Data shows that the proportion of people buying food and daily necessities online has increased by 92.5% and 44.5% respectively (Vanapalli et al. 2021). Increased consumption of food and products have led to a dramatic rise in the production of multi-layer plastic films and foams.

Therefore, we will realize the benefits of plastics to human society during COVID-19. We should also pay attention to the losses caused by plastic waste to the sustainable development of the environment.

Land ecological environment

Plastic materials have contributed greatly to the control of the epidemic during COVID-19 and have brought a lot of convenience to our human society. However, with the consumption and a large number of medical supplies, masks, gloves and disposable packaging supplies, improper handling and abuse of plastic waste have emerged.

First, the used masks are discarded anywhere in the public area without processing (Olatayo et al. 2021). Increased waste of plastic packaging (Dharmaraj et al. 2021). The waste plastic products used in laboratory research will aggravate the production of plastic waste. These plastic products are not only scattered on both sides of highways and railroads in city streets, causing visual pollution, but are also potentially harmful.

Secondly, most plastics have the disadvantages of being difficult to degrade and low melting point, the chemical molecules in the internal structure of the plastic make it difficult to corrode and rot (Potrykus et al. 2021). Due to these characteristics of plastics, if we do not dispose of them in a timely and good manner after using plastic products, plastic waste will pose a threat to the ecological environment of the land. The best way to deal with plastic waste is the recycling method, but this method is not suitable for all plastics, but for most plastics with weaker overall structure. During the COVID-19 period, due to the implementation of a series of lockdown measures. The shortage of funds for workers and recycling industry in some factories, the greatly reduced management level of enterprises have increased the unreasonable recycling and disposal of plastic waste, causing serious environmental damage (Ferronato et al. 2021). Moreover, most plastic waste will eventually be sent to landfills. Landfill will encroach on limited arable land and seriously waste resources. According to statistics, there are approximately 125,000 to 500,000 landfills in Europe, more than 260–13.1 million tons of waste have been landfilled in the past two decades (Canopoli et al. 2018).

In addition, the garbage buried in the soil may be degraded in biological and non-biological processes, a large amount of microplastics and additives will be produced during the degradation process, which will lead to irresistible pollution of the soil, making the occupied land unrecoverable for a long time, affecting the sustainable use of the land. Some scholars analyzed waste samples from landfills and found that the samples contained more different types of microplastics, the concentrations were higher (Alimi et al. 2018). In addition, compared with the landfill site, the new landfill site contains a higher concentration of plastic, which may be related to the different characteristics of different plastic products (Park and Kim 2019).

Atmospheric environment

Many plastic products will be landfilled or incinerated when they are processed. Incineration of most plastic products will reduce air quality and damage the atmospheric environment. Some environmental protection experts pointed out that foamed plastic contains a very toxic compound, which is a thousand times more toxic than potassium cyanide, is known as the most toxic poison on the planet. Incineration of the same plastic such as plastic lunch boxes will emit this toxic substance (Chen et al. 2020), this not only causes serious pollution to air quality but also threatens human health.

In addition, due to the problems of unreasonable design or imperfect management of certain plastic products, secondary pollution will be caused in the process of oily waste plastics. In this process, the poorly sealed packaging of plastic products will cause dust to diffuse in the air during plastic transportation and dust removal, causing air pollution. When waste plastics are processed at high temperatures, hydrocarbon gases leak during the process. Rising carbon emissions are detrimental to environmental quality and the achievement of carbon neutrality goals (Dong et al. 2022; Wang et al. 2023). This part of the gas is very easy to explode. At the same time, when coal, gasoline and other fuels are burned, it is very easy to produce sulfur dioxide and pollute the atmosphere (Kvale et al. 2021).

In summary, we can see that improper disposal of discarded plastic waste will not only cause the "Visual pollution" problem that people have strongly reacted to, but the most serious is the deep-seated "long-term harm" caused by plastic waste (Benson et al. 2021).

Marine ecological environment

According to statistics, during the COVID-19 period, a large amount of plastic waste was produced globally, a high proportion of plastic waste entered the ocean, the proportion of marine waste increased, which caused long-term pollution to the marine ecological environment.

First, beaches are considered an important natural resource in coastal areas. They are the source of land, sand and fishing grounds that coastal communities depend on. As far as the government is concerned, beaches are a good source of income for the tourism industry. The blockade imposed by many countries due to COVID-19 has reduced the movement of people in coastal areas and surrounding areas, resulting in clean beaches and waters in the surrounding areas. However, the unreasonable treatment of plastic products (masks, medical equipment, etc.) caused a large amount of plastic garbage to accumulate on the beach (Chowdhury et al. 2021; Zambrano-Monserrate et al. 2020). Currently, many disposable plastic products are very light and small, easily transported by wind and water. They flow into the ocean and accumulate in the ocean or float on the coast, which pollutes the marine environment. This will change the chemical, physical and biological characteristics of coastal and marine areas, threaten marine diversity and affect marine productivity (Chowdhury et al. 2021; Otero et al. 2021).

Secondly, nearly 300 species worldwide are affected by plastic, of which 86% are sea turtles, 44% are seabirds and 43% are marine mammals. For larger marine organisms such as sea turtles, dolphins and seals, some plastic products such as plastic bags will entangle and strangle them tightly or damage the stomach capacity of marine species and hinder their growth. In addition, large pieces of plastic will float to new habitats, harming ecologically and commercially important species, such as corals (W. Yuan & Chang 2021). It is estimated that 11.1 billion plastic waste is entangled on coral reefs in the Asia–Pacific region, this number is expected to increase by 40% by 2025 (Lamb et al. 2018). Plastic waste flowing through coral reefs may cause physical damage to coral reefs and introduce foreign pathogens. Improper disposal of plastic waste and disposal of the ocean will threaten the health of aquatic animals such as sea turtles, corals and whales, thereby disrupting the marine ecosystem.

In addition, a new type of plastic pollutant called "microplastic" spreads from land to sea and the rest of the world. Microplastics are most widely distributed on the surface of the ocean, with the North Atlantic and the Pacific Ocean being the sites of microplastic accumulation. Microplastics are light and small, their distribution is easily influenced by monsoons and ocean currents. It has a small volume and a particle size of less than 5 mm. According to the source, it can be divided into primary microplastics and secondary microplastics (Chamas et al. 2020). "Microplastics" have a survival period of up to 3 years and can remain intact. Due to its small size, it has a huge impact on the physics and biology of the marine environment and food chain (Klemeš et al. 2020; Laskar and Kumar 2019). They are easily washed into the sewer and wastewater treatment plant, but there is no filter fine enough to completely remove these particles, so that they are discharged into the river or the ocean together (Saadat et al. 2020; Woodward et al. 2021). Many zooplankton will swallow it into their bodies and store them in their tissues. Microplastics will also stick to the cell walls of phytoplankton, causing their chlorophyll absorption to decrease. As we all know, zooplankton are primary consumers in the aquatic food chain. Corals and fishes also feed on plankton, microplastics also show adverse effects on corals, fish and other organisms (Dharmaraj et al. 2021). Microplastics are found in many parts of the world and have various impacts on marine ecosystems, which can be potentially harmful to humans through biosphere transfer and enrichment effects. The rise of microplastics in the marine food chain has aroused great human attention, because humans are the main consumers of seafood, but its adverse effects on human health are still difficult to assess. Therefore, during the COVID-19 period, a large number of personal protective equipment and medical protective equipment are made of bioplastic materials, which can be decomposed into microplastics and pose a threat to the environment. The large amount of plastic waste has a huge impact on the food chain of the marine environment (Kvale et al. 2021).

Future prospects and challenges

In order to ameliorate the environmental damage caused by plastic waste during the epidemic, government, society and individuals must make appropriate improvements.

- Government departments should not only raise public awareness of single-use plastic applications, but also strengthen cooperation with external sectors in order to further reduce plastic use and enhance the efficiency of plastic use.
- It is impossible to ban the use of plastic completely, but we can choose some materials to replace plastic. More encourage the use of reusable paper bags, cloth bags and some bioplastics, in the industrial replacement of traditional plastics need further research.
- Education plays an important role in the process of reducing plastic use. For children in habit formation, educational awareness can have a particularly important impact on their peers and even on the next generation. Schools and other educational institutions need to strengthen the organization of activities that can significantly increase students' awareness of plastic waste reduction and knowledge of the environmental impacts of plastic through different forms of activities.
- Research and development of technology should be strengthened to convert plastic waste into value-added products, such as advanced technologies for converting plastic waste into fuel. Government departments should drive investment in technologies that convert plastic waste into value-added products, which will not only benefit human society but also contribute to sustainable development of the environment.
- The government should improve the corresponding rules and regulations, reward the industrial enterprises with good efficiency in plastic waste recycling, motivate and encourage the public through publicity.
- Companies involved in plastic waste recycling, landfill and incineration need to strengthen their management to promote the proper management of plastic waste and do their part for the sustainable development of the environment.

Conclusions and future research

Conclusions

We systematically analyzed recent publications on studies of the environmental impact of plastics during the COVID-19 pandemic, mainly using bibliometric methods and scientific mapping analysis, obtained the following conclusions.

- During the COVID-19 period, research hotspots on the impact of plastics on the environment have gradually increased. From the point of view of country distribution, developed countries occupy a dominant position, developing countries need to further develop research on the impact of plastics on the environment. The order of time shows that most developed countries such as Canada, the United Kingdom and the USA took the lead in conducting research on the impact of plastics on the ocean and the entire ecosystem environment during COVID-19, developing countries such as China, India and Indonesia conducted related research. Developed countries are the first to pay attention to the impact of plastics on the environment during COVID-19 and conduct related research, they have an absolute advantage in the quality of literature. It can be seen from the visual map that although several research groups have been formed, the cooperation between developed and developing countries is not very close.
- As the epidemic gradually spread from the region to the world, a series of protective measures have led to the massive consumption of plastic products, plastic waste has caused "Visual pollution". From the perspective of the number of publications, this has led more researchers to pay attention to the "Long-term pollution" caused by plastic prod-

ucts on the entire ecosystem environment. Some authors cooperate closely and form obvious cooperative groups, but most of the cooperation is carried out within the group, there are fewer connections between multiple groups, there is a “Matthew effect”. Due to the suddenness of the epidemic, researchers in this field have not yet formed a relatively stable scientific research cooperation group, which is not conducive to the exchange and sharing of knowledge.
- From the perspective of the types of institutions, the main body of research is universities, foundations, etc. account for only a small proportion. Colleges and universities have gradually become the main research force in this field, subject knowledge has been well inherited and disseminated in colleges and universities. The exchanges and cooperation between research institutions of different departments are not restricted by geographical location. In addition, research institutions of different types have carried out extensive cooperation, which has increased the diversity and comprehensiveness of research in this field.
- Bibliometric analysis of keywords was carried out, the corresponding scientific atlas was obtained, revealing the challenges brought by plastics to the environment during COVID-19 and the future research trends in this field. First of all, countries and regions have adopted a series of measures to control the further spread of the epidemic. Among them, plastic products have been widely used. At the same time, these have also caused plastic waste to bring huge challenges to the environment. In addition, plastic waste will have a chain-like adverse effect on the ecological environment. Among them, unreasonable disposal of a large amount of plastic waste during COVID-19 will seriously affect the availability of ocean, leave difficult-to-degrade ingredients in the soil and ocean. Animals and plants can be infected or even die when they come into contact with plastic waste, plastic waste can pose a serious threat to the survival of the entire ecosystem environment.

Future research

Based on the above research results, we make the following relevant suggestions for the future development of scientific research in this field.

- Developing countries should pay attention to our dependence on plastic products during COVID-19, the impact of plastic products on the entire environment, strengthen investigation and research in this field. Developing countries can take advantage of the technological advantages of developed countries in the field of artificial intelligence and big data, learn from the experience and resources of developed countries in the field of research. Developed countries should strengthen exchanges and cooperation with developing countries while studying in this field, so as to promote the sustainable development of the global environment together.
- Researchers and research institutions must not only cooperate and contact within the various cooperative groups of scientific research in this field, but also cooperate and contact between groups, carry out multi-faceted and multi-angle investigations, so that knowledge can be exchanged and shared fluently, a relatively stable scientific research cooperation group can be formed.
- After conducting a keyword analysis of scientific literature, we found that plastic products are widely used while causing chain damage to the marine ecological environment, which threatens the survival of the entire ecosystem environment. Among them, “Microplastics” play an important role. However, the impact of "Microplastics" on ecosystems has not been analyzed in a multi-faceted and comprehensive manner. In the future, our scientific research should pay more attention to the long-term effects of “Microplastics” on the ecosystem and provide adequate theoretical guidance to address the environmental challenges posed by plastics.

This study also has certain limitations. First of all, we may lose some publications in the selection of the case library, which may affect the results of our analysis. Secondly, with the accelerating pace of the times, the impact of plastics on the environment is constantly changing with time and technological progress. The existing literature does not reflect this change. Therefore, the above may be the research direction of relevant researchers in the future.

Appendix

Table 2 Top ten countries' information

Countries	Number	Year	Citing article	Authors	
United States	1	2020	Reusable masks for COVID-19: a missing piece of the microplastic problem during the global health crisis	Shruti, VC	Shruti V.C.,Pérez-Guevara Fermín,Elizalde-Martínez I.,Kutralam-Muniasamy Gurusamy. Reusable masks for COVID-19: a missing piece of the microplastic problem during the global health crisis[J]. Marine Pollution Bulletin,2020,161(PB)
	2	2020	Increasing temperature and relative humidity accelerates inactivation of SARS-COV-2 on surfaces	Biryukov, J	Jennifer Biryukov,Jeremy A. Boydston,Rebecca A. Dunning,John J. Yeager,Stewart Wood,Amy L. Reese,Allison Ferris,David Miller,Wade Weaver,Nathalie E. Zeitouni,Aaron Phillips,Denise Freeburger,Idris Hooper,Shanna Ratnesar Shumate,Jason Yolitz,Melissa Krause,Gregory Williams,David G. Dawson,Artemas Herzog,Paul Dabisch,Victoria Wahl,Michael C. Hevey,Louis A. Altamura. Increasing temperature and relative humidity accelerates inactivation of SARS-CoV-2 on surfaces[J]. mSphere,2020,5(4)
	3	2021	Macroplastic accumulation in roadside ditches of New York State's Finger Lakes region (USA) across land uses and the COVID-19 pandemic	Pietz, O	Pietz Olivia,Augenstein Mary,Georgakakos Christine B,Singh Kanishka,McDonald Miles,Walter M Todd. Macroplastic accumulation in roadside ditches of New York State's Finger Lakes region (USA) across land uses and the COVID-19 pandemic.[J]. Journal of environmental management,2021,298
	4	2021	The impacts of COVID-19 pandemic on marine litter pollution along the Kenyan Coast: a synthesis after 100 days following the first reported case in Kenya	Okuku, E	Okuku Eric,Kiteresi Linet,Owato Gilbert,Otieno Kenneth,Mwalugha Catherine,Mbuche Mary,Gwada Brenda,Nelson Annette,Chepkemboi Purity,Achieng Quinter,Wanjeri Veronica,Ndwiga Joey,Mulupi Lilian,Omire Jill. The impacts of COVID-19 pandemic on marine litter pollution along the Kenyan Coast: a synthesis after 100 days following the first reported case in Kenya[J]. Marine Pollution Bulletin,2020,162(prepublish)
	5	2020	Single-use plastics and COVID-19: scientific evidence and environmental regulations	Hale, RC	Hale R C,Song B. Single-use plastics and COVID-19: scientific evidence and environmental regulations.[J]. Environmental science & technology,2020,54(12)
	6	2021	Personal protective equipment (PPE) pollution driven by the COVID-19 pandemic in Cox's Bazar, the longest natural beach in the world	Rakib, MRJ	Rakib Md. Refat Jahan,De la Torre Gabriel E.,Pizarro Ortega Carlos Ivan,Dioses Salinas Diana Carolina,Al Nahian Sultan. Personal protective equipment (PPE) pollution driven by the COVID-19 pandemic in Cox's Bazar, the longest natural beach in the world[J]. Marine Pollution Bulletin,2021,169(prepublish)
	7	2021	Challenges and practices on waste management and disposal during COVID-19 pandemic	Hantoko, D	Hantoko Dwi,Li Xiaodong,Pariatamby Agamuthu,Yoshikawa Kunio,Horttanainen Mika,Yan Mi. Challenges and practices on waste management and disposal during COVID-19 pandemic[J]. Journal of Environmental Management,2021,286

Table 2 (continued)

Countries	Number	Year	Citing article	Authors	
	8	2021	Assessing threats, regulations, and strategies to abate plastic pollution in LAC beaches during COVID-19 pandemic	Alfonso, MB	Alfonso María B.,Arias Andrés H.,Menéndez María C.,Ronda Ana C.,Harte Agustín,Piccolo María C.,Marcovecchio Jorge E.. Assessing threats, regulations, and strategies to abate plastic pollution in LAC beaches during COVID-19 pandemic[J]. Ocean and Coastal Management,2021,208
	9	2021	Drinking water pollutants may affect the immune system: concerns regarding COVID-19 health effects	Quinete, N	Quinete Natalia,HauserDavis Rachel Ann. Drinking water pollutants may affect the immune system: concerns regarding COVID-19 health effects.[J]. Environmental science and pollution research international,2020,28(1)
	10	2021	Medical waste: current challenges and future opportunities for sustainable management	Singh, N	Singh Narendra,Ogunseitan Oladele A.,Tang Yuanyuan. Medical waste: current challenges and future opportunities for sustainable management[J]. Critical Reviews in Environmental Science and Technology,2022,52(11)
	11	2021	An emerging source of plastic pollution: environmental presence of plastic personal protective equipment (PPE) debris related to COVID-19 in a metropolitan city	Ammendolia, J	Ammendolia Justine,Saturno Jacquelyn,Brooks Amy L.,Jacobs Shoshanah,Jambeck Jenna R.. An emerging source of plastic pollution: environmental presence of plastic personal protective equipment (PPE) debris related to COVID-19 in a metropolitan city[J]. Environmental Pollution,2021,269
	12	2021	Photocatalytic rejuvenation enabled self-sanitizing, reusable, and biodegradable masks against COVID-19	Li, Q	i Qiang,Yin Yongchao,Cao Daxian,Wang Ying,Luan Pengcheng,Sun Xiao,Liang Wentao,Zhu Hongli. Photocatalytic rejuvenation enabled self-sanitizing, reusable, and biodegradable masks against COVID-19.[J]. ACS nano,2021
	13	2021	Conservation physiology and the COVID-19 pandemic	Cooke, SJ	Cooke Steven J,Cramp Rebecca L,Madliger Christine L,Bergman Jordanna N,Reeve Connor,Rummer Jodie L,Hultine Kevin R,Fuller Andrea,French Susannah S,Franklin Craig E. Conservation physiology and the COVID-19 pandemic[J]. Conservation Physiology,2021,9(1)
	14	2021	Occurrence of personal protective equipment (PPE) associated with the COVID-19 pandemic along the coast of Lima, Peru	De-la-Torre, GE	De-la-Torre Gabriel E.,Rakib Md. Refat Jahan,Pizarro-Ortega Carlos Ivan,Dioses-Salinas Diana Carolina. Occurrence of personal protective equipment (PPE) associated with the COVID-19 pandemic along the coast of Lima, Peru[J]. Science of the Total Environment,2021,774
	15	2021	Plastic residues produced with confirmatory testing for COVID-19: classification, quantification, fate, and impacts on human health	Celis, JE	Celis José E.,Espejo Winfred,Paredes-Osses Esteban,Contreras Sonia A.,Chiang Gustavo,Bahamonde Paulina. Plastic residues produced with confirmatory testing for COVID-19: classification, quantification, fate, and impacts on human health[J]. Science of the Total Environment,2021,760
	16	2021	Stability of SARS-CoV-2 and other coronaviruses in the environment and on common touch surfaces and the influence of climatic conditions: a review	Aboubakr, HA	Aboubakr Hamada A,Sharafeldin Tamer A,Goyal Sagar M. Stability of SARS-CoV-2 and other coronaviruses in the environment and on common touch surfaces and the influence of climatic conditions: a review.[J]. Transboundary and emerging diseases,2020,68(prepublish)

Table 2 (continued)

Countries	Number	Year	Citing article	Authors	
	17	2021	Personal protective equipment (PPE) pollution associated with the COVID-19 pandemic along the coastline of Agadir, Morocco	Haddad, MB	Haddad Mohamed Ben,DelaTorre Gabriel E,Abelouah Mohamed Rida,Hajji Sara,Alla Aicha Ait. Personal protective equipment (PPE) pollution associated with the COVID-19 pandemic along the coastline of Agadir, Morocco.[J]. The Science of the total environment,2021,798
	18	2021	Face mask waste generation and management during the COVID-19 pandemic: an overview and the Peruvian case	Torres, FG	Torres Fernando G.,De-la-Torre Gabriel E.. Face mask waste generation and management during the COVID-19 pandemic: an overview and the Peruvian case[J]. Science of the Total Environment,2021,786
China	1	2021	Used disposable face masks are significant sources of microplastics to environment	Chen, X	Chen Xianchuan,Chen Xiaofei,Liu Qian,Zhao Qichao,Xiong Xiong,Wu Chenxi. Used disposable face masks are significant sources of microplastics to environment.[J]. Environmental pollution (Barking, Essex: 1987),2021,285
	2	2021	A high-resolution typical pollution source emission inventory and pollution source changes during the COVID-19 lockdown in a megacity, China	Hu, X	Hu Xue,Liu Qizhen,Fu Qingyan,Xu Hao,Shen Yin,Liu Dengguo,Wang Yue,Jia Haohao,Cheng Jinping. A high-resolution typical pollution source emission inventory and pollution source changes during the COVID-19 lockdown in a megacity, China.[J]. Environmental science and pollution research international,2021,28(33)
	3	2020	COVID-19 waste management: effective and successful measures in Wuhan, China	Singh, N	Narendra Singh,Yuanyuan Tang,Zuotai Zhang,Chunmiao Zheng. COVID-19 waste management: effective and successful measures in Wuhan, China[J]. Resources, Conservation & Recycling,2020,163
	4	2021	Face masks as a source of nanoplastics and microplastics in the environment: quantification, characterization, and potential for bioaccumulation	Ma, J	Ma Jie,Chen Fengyuan,Xu Huo,Jiang Hao,Liu Jingli,Li Ping,Chen Ciara Chun,Pan Ke. Face masks as a source of nanoplastics and microplastics in the environment: quantification, characterization, and potential for bioaccumulation[J]. Environmental Pollution,2021,288
	5	2021	Neglected microplastics pollution in global COVID-19: disposable surgical masks	Shen, M	Shen Maocai,Zeng Zhuotong,Song Biao,Yi Huan,Hu Tong,Zhang Yaxin,Zeng Guangming,Xiao Rong. Neglected microplastics pollution in global COVID-19: disposable surgical masks[J]. Science of the Total Environment,2021,790
	6	2020	Thermoplastic polyurethane nanofiber membrane based air filters for efficient removal of ultrafine particulate matter PM0.1	Chen, R	Chen Ruowang,Zhang Han,Wang Mingyuan,Zhang Xiaowei,Gan Zhixing. Thermoplastic polyurethane nanofiber membrane based air filters for efficient removal of ultrafine particulate matter PM0.1[J]. ACS APPLIED NANO MATERIALS,2021,4(1)
	7	2021	An environmental dilemma for China during the COVID-19 pandemic: the explosion of disposable plastic wastes	Liu, J	Jianli Liu,A. Dick Vethaak,Lihui An,Qiang Liu,Yunfei Yang,Jiannan Ding. An environmental dilemma for China during the COVID-19 pandemic: the explosion of disposable plastic wastes[J]. Bulletin of Environmental Contamination and Toxicology,2021,106(2)

Table 2 (continued)

Countries	Number	Year	Citing article	Authors	
	8	2021	The implications of COVID-19 in the ambient environment and psychological conditions	Wang, Y	Wang Yan,Xue Qingwang. The implications of COVID-19 in the ambient environment and psychological conditions[J]. NanoImpact,2021,21(prepublish) [37]Hatton Grace. COVID-19 and clean air: an opportunity for radical change[J]. The Lancet Planetary Health,2021,5(1)
	9	2021	Protective equipment and health education program could benefit students from dust pollution	Chiang, Y-C	Yi-Chen Chiang,Xian Li,Chun-Yang Lee,Jia Rui,Chiung-Wen Hu,Hao-Jan Yang,Szu-Chieh Chen,Tianmu Chen,Yanhua Su,Chung-Yih Kuo,Shao-Chieh Hsueh. Protective equipment and health education program could benefit students from dust pollution.[J]. Air quality, atmosphere, & health,2020(prepublish)
	10	2021	Plastic waste associated with the COVID-19 pandemic: crisis or opportunity?	Khoo, KS	Khoo Kuan Shiong,Ho Lih Yiing,Lim Hooi Ren,Leong Hui Yi,Chew Kit Wayne. Plastic waste associated with the COVID-19 pandemic: crisis or opportunity?[J]. Journal of hazardous materials,2021,417
India	1	2021	From cosmetics to innovative cosmeceuticals—non-woven tissues as new biodegradable carriers	Morganti, P	Morganti Pierfrancesco,Morganti Gianluca,Gagliardini Alessandro,Lohani Alka. From cosmetics to innovative cosmeceuticals—non-woven tissues as new biodegradable carriers[J]. Cosmetics,2021,8(3)
	2	2021	Effect of microplastics in water and aquatic systems	Issac, MN	Issac Merlin N,Kandasubramanian Balasubramanian. Effect of microplastics in water and aquatic systems.[J]. Environmental science and pollution research international,2021,28(16)
	3	2021	Microplastic pollution in aquatic environments with special emphasis on riverine systems: current understanding and way forward	Vaid, M	Vaid Mansi,Sarma Kiranmay,Gupta Anshu. Microplastic pollution in aquatic environments with special emphasis on riverine systems: current understanding and way forward.[J]. Journal of environmental management,2021,293
	4	2021	Recycling of medical plastics	Joseph, B	Joseph Blessy,James Jemy,Kalarikkal Nandakumar,Thomas Sabu. Recycling of medical plastics[J]. Advanced Industrial and Engineering Polymer Research,2021(prepublish)
	5	2021	COVID-19 restrictions and their influences on ambient air, surface water and plastic waste in a coastal megacity, Chennai, India	Robin, RS	Robin R.S.,Purvaja R.,Ganguly D.,Hariharan G.,Paneerselvam A.,Sundari R.T.,Karthik R.,Neethu C.S.,Saravanakumar C.,Semanti P.,Prasad M.H.K.,Mugilarasan M.,Rohan S.,Arumugam K.,Samuel V.D.,Ramesh R.. COVID-19 restrictions and their influences on ambient air, surface water and plastic waste in a coastal megacity, Chennai, India[J]. Marine Pollution Bulletin,2021,171
	6	2021	Framework for PESTEL dimensions of sustainable healthcare waste management: learnings from COVID-19 outbreak	Thakur, V	Thakur Vikas. Framework for PESTEL dimensions of sustainable healthcare waste management: learnings from COVID-19 outbreak[J]. Journal of Cleaner Production,2021,287

Table 2 (continued)

Countries	Number	Year	Citing article	Authors	
	7	2021	The escalating biomedical waste management to control the environmental transmission of COVID-19 pandemic: a perspective from two South Asian countries	Shammi, M	Shammi Mashura,Behal Arvind,Tareq Shafi M. The escalating biomedical waste management to control the environmental transmission of COVID-19 pandemic: a perspective from two South Asian countries.[J]. Environmental science & technology,2021,55(7)
	8	2021	Biomedical applications of environmental friendly poly-hydroxyalkanoates	Ansari, S	Ansari Sabbir,Sami Neha,Yasin Durdana,Ahmad Nazia,Fatma Tasneem. Biomedical applications of environmental friendly poly-hydroxyalkanoates[J]. International Journal of Biological Macromolecules,2021,183
	9	2021	Air pollutants during covid-19 lockdown period in India	Vignesh, KS	Vignesh K. S.,Padma Venkatasubramanian. Air pollutants during COVID-19 lockdown period in India: special issue on COVID-19 and historical pandemics[J]. Journal of Disaster Research,2021,16(1)
United Kingdom	1	2021	Plastic waste footprint in the context of COVID-19: reduction challenges and policy recommendations towards sustainable development goals	Mallick, SK	Mallick Suraj K,Pramanik Malay,Maity Biswajit,Das Pritiranjan,Sahana Mehebub. Plastic waste footprint in the context of COVID-19: reduction challenges and policy recommendations towards sustainable development goals.[J]. The Science of the total environment,2021,796
	2	2021	Experimental analysis of structures for trapping sars-cov-2-related floating waste in rivers	Roy, D	Roy Deep,Pagliara Simone,Palermo Michele. Experimental analysis of structures for trapping SARS-CoV-2-related floating waste in rivers[J]. Water,2021,13(6)
	3	2021	An investigation into the leaching of micro and nano particles and chemical pollutants from disposable face masks—linked to the COVID-19 pandemic	Sullivan, GL	Sullivan G.L.,Delgado-Gallardo J.,Watson T.M.,Sarp S.. An investigation into the leaching of micro and nano particles and chemical pollutants from disposable face masks—linked to the COVID-19 pandemic[J]. Water Research,2021,196
	4	2020	COVID-19 and clean air: an opportunity for radical change	Hatton, G	Hatton Grace. COVID-19 and clean air: an opportunity for radical change[J]. The Lancet Planetary Health,2021,5(1)
	5	2021	Are controlled release scientists doing enough for our environment?	Park, K	Park Kinam,Mrsny Randall. Are controlled release scientists doing enough for our environment?[J]. Journal of Controlled Release,2021,332(prepublish)
	6	2020	Unmasking the hidden pandemic: sustainability in the setting of the COVID-19 pandemic	Ahmadifard, A	Ahmadifard Arefeh. Unmasking the hidden pandemic: sustainability in the setting of the COVID-19 pandemic.[J]. British dental journal,2020,229(6)
	7	2020	Effects of the COVID-19 pandemic on environmental sustainability in anaesthesia	White, SM	White Stuart M.,Shelton Clifford L.. Effects of the COVID-19 pandemic on environmental sustainability in anaesthesia. Comment on Br J Anaesth 2020; 125: 680–92[J]. British Journal of Anaesthesia,2020(prepublish)
	8	2020	COVID-19 impacts on beaches and coastal water pollution at selected sites in Ecuador, and management proposals post-pandemic	Ormaza-Gonzaìlez, FI	Ormaza Gonzaìlez Franklin I.,Castro Rodas Divar,Statham Peter J.. COVID-19 impacts on beaches and coastal water pollution at selected sites in Ecuador, and management proposals post-pandemic

Table 2 (continued)

Countries	Number	Year	Citing article	Authors	
	9	2020	Where is the evidence that human exposure to microplastics is safe?	Leslie, HA	H.A. Leslie,M.H. Depledge. Where is the evidence that human exposure to microplastics is safe?[J]. Environment International,2020,142(C)
Spain	1	2021	Twitter data analysis to assess the interest of citizens on the impact of marine plastic pollution	Otero, P	Otero P.,Gago J.,Quintas P.. Twitter data analysis to assess the interest of citizens on the impact of marine plastic pollution[J]. Marine Pollution Bulletin,2021,170
	2	2020	Rethinking and optimising plastic waste management under COVID-19 pandemic: policy solutions based on redesign and reduction of single-use plastics and personal protective equipment	Patrício, Silva	Ana L. Patrício Silva,Joana C. Prata,Tony R. Walker,Diana Campos,Armando C. Duarte,Amadeu M.V.M. Soares,Damià Barcelò,Teresa Rocha-Santos. Rethinking and optimising plastic waste management under COVID-19 pandemic: policy solutions based on redesign and reduction of single-use plastics and personal protective equipment[J]. Science of the Total Environment,2020,742
	3	2021	Increased plastic pollution due to COVID-19 pandemic: challenges and recommendations	Patrício, Silva	Ana L. Patrício Silva,Joana C. Prata,Tony R. Walker,Armando C. Duarte,Wei Ouyang,Damià Barcelò,Teresa Rocha-Santos. Increased plastic pollution due to COVID-19 pandemic: challenges and recommendations[J]. Chemical Engineering Journal,2021,405
	4	2021	COVID-19 face masks: a new source of human and environmental exposure to organophosphate esters	Fernández-Arribas, J	Fernández Arribas J.,Moreno T.,Bartroli R.,Eljarrat E.. COVID-19 face masks: a new source of human and environmental exposure to organophosphate esters[J]. Environment International,2021,15 4(prepublish)
	5	2021	SARS-CoV-2 and other pathogenic microorganisms in the environment	Núñez-Delgado, A	NúñezDelgado Avelino,Bontempi Elza,Coccia Mario,Kumar Manish,Farkas Kata,Domingo José L. SARS-CoV-2 and other pathogenic microorganisms in the environment.[J]. Environmental research,2021,201
	6	2021	Study of recycling potential of FFP2 face masks and characterization of the plastic mix-material obtained. A way of reducing waste in times of Covid-19	Crespo, C	Cristina Crespo,Gemma Ibarz,Carlos Sáenz,Pablo Gonzalez,Sandra Roche. Study of recycling potential of FFP2 face masks and characterization of the plastic mix-material obtained. A way of reducing waste in times of Covid-19[J]. Waste and Biomass Valorization,2021,12(12)
	7	2021	An urgent call to think globally and act locally on landfill disposable plastics under and after covid-19 pandemic: pollution prevention and technological (Bio) remediation solutions	Patrício, Silva	Patrício Silva Ana L.,Prata Joana C.,Duarte Armando C.,Barcelò Damià,Rocha-Santos Teresa. An urgent call to think globally and act locally on landfill disposable plastics under and after covid-19 pandemic: pollution prevention and technological (Bio) remediation solutions[J]. Chemical Engineering Journal,2021,426
Australia	1	2020	Environmental sustainability in anaesthesia and critical care	Sherman, JD	Sherman Jodi D.,Sulbaek Andersen Mads P.,Renwick James,McGain Forbes. Environmental sustainability in anaesthesia and critical care. Response to Br J Anaesth[J]. British Journal of Anaesthesia,2021,126(6)

Table 2 (continued)

Countries	Number	Year	Citing article	Authors	
	2	2021	Protecting the environment from plastic PPE	Zhang, EJ	Zhang Elissa J,Aitchison Lucy P,Phillips Nicole,Shaban Ramon Z,Kam Andrew W. Protecting the environment from plastic PPE.[J]. BMJ (Clinical research ed.),2021,372
	3	2021	COVID pollution: impact of COVID-19 pandemic on global plastic waste footprint	Benson, NU	Benson Nsikak U.,Bassey David E.,Palanisami Thavamani. COVID pollution: impact of COVID-19 pandemic on global plastic waste footprint[J]. Heliyon,2021,7(2)
	4	2020	Covid-19 face masks: a potential source of microplastic fibers in the environment	Fadare, OO	Fernández Arribas J.,Moreno T.,Bartroli R.,Eljarrat E.. COVID-19 face masks: a new source of human and environmental exposure to organophosphate esters[J]. Environment International,2021,154(prepublish)

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Declarations

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