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Review

Management of Used COVID-19 Personal Protective Equipment: A Bibliometric Analysis and Literature Review

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Abstract: Using a science mapping approach, we analyzed the exponential increase in the number of scientific documents about the negative environmental impacts produced by waste from personal protective equipment (PPE), especially face masks, used to reduce SARS-CoV-2 transmission worldwide. Our results revealed that India, China, and Canada are leaders in this research field, which is clearly related to environmental issues, but also the solutions developed from an engineering point of view. Our analysis of the most-relevant documents in the field uncovered the considerable negative effects of PPE waste in aquatic media, its contribution to greenhouse gas emissions, effects on wildlife, etc. To reduce the negative environmental impacts of PPE waste, we need to implement innovative ecodesign strategies for their green production, including their re-use as and the use of recycling materials, but also a collaboration with the population to reduce PPE waste at its source. Both action lines could be materialized by establishing a collective, extended producer responsibility system for PPE to ensure their sustainable production and consumption. These well-implemented strategies will contribute to maintaining progress towards achieving sustainable development goals.

Keywords: COVID-19; face mask; individual protection equipment; personal protective equipment; waste management

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1. Introduction

SARS-CoV-2 was detected for the first time in Wuhan (China) in late 2019. The ensuing pandemic was characterized by high rates of co-infection between humans, and the disease spread in several different ways, including short-range aerosol and airborne transmission [1,2]. With the objective of reducing its spread, governments worldwide implemented preventative measures, such as limitations to physical contact, in addition to disseminating information regarding hand hygiene and washing, disinfecting surfaces, the use of face masks in public spaces [1,3], etc. Consequently, the demand for and consumption of individual protection equipment (IPE), including gloves and face masks, as well as hygiene products, such as wipes and tissues, greatly increased [2–5]; furthermore, all of these different forms of equipment contain plastic in their composition [2].

As a result of the mandatory use of personal protective equipment (PPE) by populations in countries worldwide, their global production has considerably increased, especially in the case of face masks. For example, in April 2020, the Colombian plastic industry estimated an increase from 2 to 8–10 million in the monthly manufacture of face masks and from 60,000 to 100,000 in the case of N95 medical masks, as well as the country importing over two million gloves [6]. China increased its production of face masks by 450% in February 2020 [7], with 14.8 million units produced, and the demand for N95 masks grew from about 200,000 to 1.6 million [5]. In Japan, a milestone of over 600 million orders for face masks per month was reached as of April 2020 [8]. In South American countries, during the pandemic, the monthly production of face masks was estimated at 20 million [9].

The production of PPE consumes vast amounts of raw materials, and its carbon footprint is worsened by its disposal in landfill, with values between 22 and 59.5 g CO_2 per mask reported in different studies [10–13]; 60% of emissions came from production, especially from textile production (40%), while 40% was from disposal [10]. In addition to these negative environmental impacts, poor waste management practices have resulted in the disposal of face masks and gloves in public places and natural environments [3], especially in aquatic areas where they degrade into microplastics (MPs) and nanoplastics (NPs) [3,14], contributing to the release of potentially hazardous chemicals [3] or nanoparticles (ENPs) [15].

Thus, it is possible to confirm that COVID-19 has resulted in not only a public health problem, but also an increase in waste production from the consumption of plastic, with short- and long-term negative environmental implications [3,5,16,17], which have been addressed in numerous investigations. Some studies have analyzed the composition of different types of PPE used during the pandemic, such as single-use gloves, face shields, wet wipes, etc., but especially face masks, including disposable medical or single-use face masks, N95 masks, reusable-by-washing masks [16], and face masks with some fashionable properties [4] or with bactericidal, fungicidal, and antiviral properties [16]. Waste production from PPE and its disposal in the environment has been increasing in different regions and countries, such as Brazil, Canada, Morocco [16], Peru, Chile [18], Japan, and Kenya [19], highlighting poor waste management practices. The environmental impacts of PPE waste accumulated in terrestrial and aquatic areas have been also analyzed, specifically because of their plastic content [16,20–24]. The application of disinfection techniques has been researched to evaluate their effects on possible reuse, including, for example, the steam sterilization process [25], vaporized hydrogen peroxide (VHP) or ultraviolet (UVC) radiation [26], dry heat pasteurization [27], or water or medical-grade alcohol [28], among others. Finally, although in some countries, such as The Netherlands, no energy recovery takes place during the incineration of regulated medical waste [29], the use of thermo-chemical processing for the energy valorization of PPE has been also explored [30–32].

Despite the existence of studies that have addressed the environmental problems derived from the production of waste from PPE as a consequence of the COVID-19 pandemic, none of them used a science mapping approach, a tool that gives objective criteria for evaluating research [33], as well as a macroscopic overview of the scientific literature [34]. Therefore, the main objective of this paper was to analyze this research field's development since the outbreak of SARS-CoV-2 to quantify the production of personal protective equipment (PPE) waste by the general population, as well as to evaluate the environmental impact produced by PPE waste, providing an overview of the management of used COVID-19 PPE through a literature review supported by a bibliographic analysis. As result, this study will contribute to the existing body of knowledge of the management of used COVID-19 PPE by highlighting the trends and patterns in this field, establishing the most-significant research themes, mapping networks of researchers from various countries, and defining areas for future study.

Understanding how the knowledge base of this strategic field is disseminated in scientific sources, countries, and the communities of cooperating countries, in addition to discerning the most-relevant themes in the research field are fundamental to assist in designing strategies to prevent the environmental impacts related to the use of PPE as a means to mitigate disease transmission in possible future pandemics. Consequently, we sought to answer the following research questions:

RQ1: What are the most-relevant sources in the research field?
RQ2: What are the most-prolific countries in the research field?
RQ3: Who are the most-prolific authors in the research field?
RQ4: What are the major alliances between authors and countries in the research field?
RQ5: What are the most-influential works in the research field?

RQ6: What are the major themes in the research field?
RQ7: What is the status of the research field?

To answer these research questions, we retrieved papers in the field published from 2020 to June 2022 from the Scopus database and analyzed the resulting corpus by means of science mapping analysis, bibliographical networks, and themes' evolution to include a final overview that highlights the status of the research field. The remainder of this paper is organized as follows: First, the methodology used to carry out the study is explained; second, our most-considerable results are presented and described; next, we use a literature review of the most-relevant documents to show the status of the research field; finally, the conclusions and proposal for future research are described.

2. Methodology

This paper analyzed and summarizes the available literature on the waste management of used COVID-19 PPE using a science mapping approach. First, we chose documents from within the research field. Both Scopus and the Web of Science are objective, comprehensive, and successful databases for searching publications; however, in as much as the Scopus database has a broader bibliometric scope and more current data than the Web of Science, the data for the present evaluation were retrieved from Scopus [35,36]. The Scopus database was searched for bibliometric data on 15 June 2022 using the following search string: COVID-19 OR covid19 AND waste AND individual protection equipment OR IPE OR personal protective equipment OR PPE OR face mask.To exclude irrelevant records, data refinement approaches were employed in accordance with the PRISMA flowchart guidelines (Figure 1). Thus, the total number of primary searches for documents in Scopus was 416. After filtering documents for their title and abstract to remove documents that did not fall within the scope of the review and to limit the research to journals and conference documents in English, a total number of 406 relevant documents were finally selected.

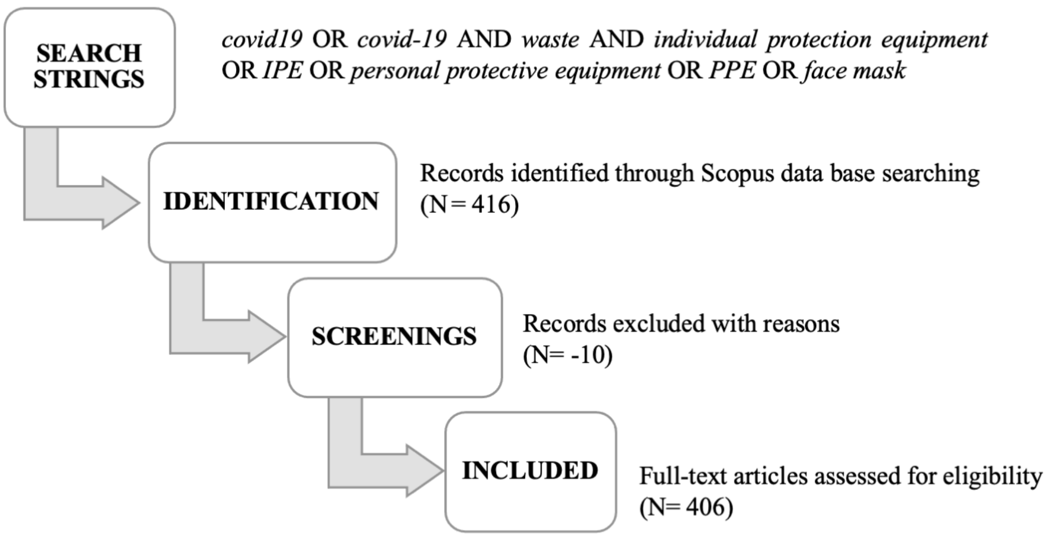

Figure 1. Steps followed to choose full-text included in bibliometric analysis in accordance with PRISMA flowchart guidelines.

The resulting papers were stored in two formats: comma-separated values (CSV) files and the format developed by research information systems (RIS). Further analysis of the retrieved data was performed using two open-source science mapping software tools: VOSviewer and Science Mapping Analysis Software Tool (SciMAT). VOSviewer is available for constructing and visualizing bibliometric networks and is commonly employed in a range of sectors [37]; on the other hand, SciMAT is based on a longitudinal science mapping approach and incorporates methods, algorithms, and measures for all the steps in a science mapping workflow, from preprocessing to visualizing the results [38].

The scientometric analysis of the documents included the following: (i) yearly publication trend; (ii) a science mapping of publication sources, countries, authors, and articles; (iii) the discussion of the themes of the research field by keyword analysis. SciMAT was used for the yearly publication trend and the generation of strategy diagrams. VOSviewer was used for the rest of the analysis. Finally, the most-considerable documents identified in the scientometric analysis were used for a literature review of used COVID-19 PPE management.

3. Scientometric Analysis: Results and Discussion

The results and discussion of the scientometric analysis were developed according to the sequence defined in the previous section. The more significant results are analyzed and discussed below.

3.1. Yearly Publication Trend

The number of publications and citations of articles in a research field depicts its development patterns. Hence, the yearly publication trend, including the cumulative number of papers during the time horizon for the defined search strings, is included in Figure 2. The first article was found in 2020, coinciding with the start of the COVID-19 pandemic; therefore, this study's time horizon was set to the period from 2020 to 15 June 2022. A preliminary analysis of Figure 2 shows a progressive increase in the number of publications, starting with 83 documents in 2020 and 197 in 2021. If the previous year's trend continues, taking into account the fact that, by mid-2022, the number of published documents had already reached 126, we expect that, by the end of the year, it will exceed the previous year's quantities.

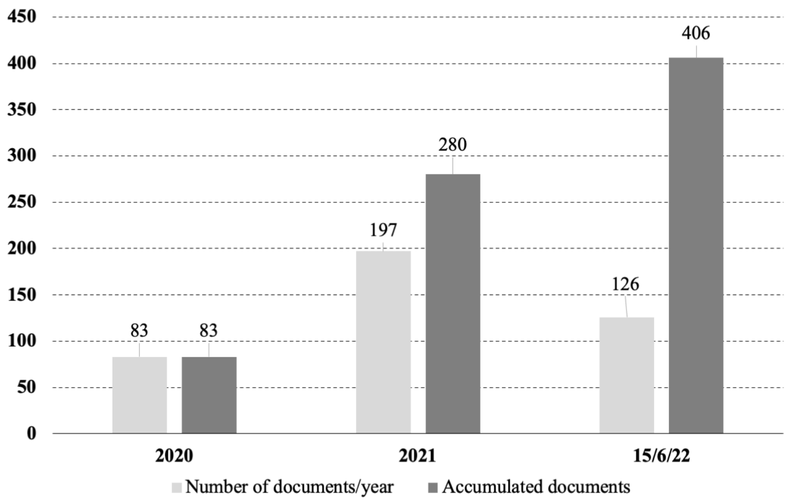

Figure 2. Number of documents per year and accumulated documents published in the time horizon (2020–15 June 2022).

3.2. Science Mapping

Science mapping can be used to evaluate the progress and innovation in a research field. Therefore, we used VOSviewer to map publication sources, countries, authors, and documents by performing a comprehensive quantitative analysis according to the number of documents and citations for each item, in addition to recording the value of the normalized citations, average year of publication, average number of citations, and average normalized citations [39]. Normalized citations are defined as the number of citations of all the articles within the same journal, or from the same author or country; the average year of publication determines when the articles were published; the average number of citations was obtained by calculating the total number of citations per article; the average normalized citations are defined as the total number of citations divided by the average number of citations published in the same year, which is used to correct for the fact that the old articles have more time for more citations than the new ones [39]. A simple visualization of this quantitative analysis was developed using VOSviewer, resulting in a set of figures in which the size of the node indicates the importance of the journal, author, document, and country, in terms of the number of documents, citations, or average normalized citations. The colors and thicknesses of the linking lines indicate the inter-connections between them [37]. The results are discussed below.

3.2.1. Mapping of Publication Sources

In our preliminary analysis, we included a total of 236 sources in the study. Figure 3 shows the relationship between the number of sources and documents published. The results showed a low concentration of documents per source, as well as a measure of the interest in the field; moreover, 185 sources (78.4%) published only one document in the field, while the highest number of documents per source was 46, followed by 12.

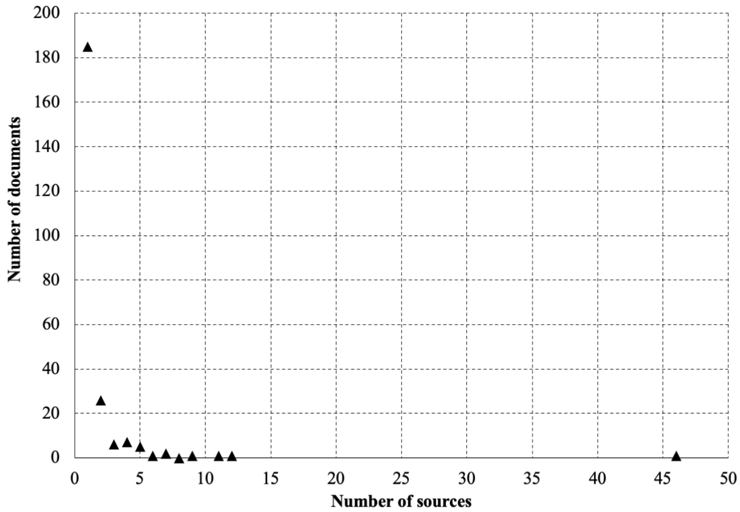

Figure 3. Relationship between number of sources and documents published.

To identify sources with more importance in the field, journals with a minimum of five documents and five citations of a source were identified, resulting in 12 sources, which are summarized in Table 1 in terms of publication count, total citations, and average normalized citations. The journal *Science of the Total Environment* clearly leads the ranking, with 46 documents and 1548 citations; on the other hand, the *Chemical Engineering Journal* leads the ranking in terms of average normalized citations, with only five documents published but 375 citations (the second position in this ranking) and 5.2879 average normalized citations. Only two of the journals included in the top five in terms of the number of documents are also included in the same ranking of the sources with a higher number of citations and average normal citations, namely *Science of the Total Environment* and the *Marine Pollution Bulletin*. The highest value of the average normal citations in the case of the *Chemical Engineering Journal*, *Journal of Hazardous Materials*, *Science of the Total Environment*, *Journal of Environmental Chemical Engineering*, and *Marine Pollution Bulletin* shows that, despite having a smaller number of documents, these journals received more citations than the others.

Table 1. Ranking of journals with more importance in the field in terms of total publication count, total citations, and average normalized citations.

A	B	C	D	E	F	G
			Publication count			
1	*Science of the Total Environment*	46	1548	121.78	33.65	2.64
2	*Environ. Sci. Pollut. Res.*	12	86	12.78	7.17	1.06
3	*Marine Pollution Bulletin*	11	214	24.11	19.45	2.19
4	*Sustainability* (Switzerland)	9	25	2.76	2.78	0.30
5	*Chemosphere*	7	118	11.73	16.86	1.67
6	*Journal of Hazardous Materials*	7	70	19.72	10.00	2.81
7	*Resour. Conserv. Recycl.*	6	141	9.54	23.50	1.58
8	*Chemical Engineering Journal*	5	375	26.44	75.00	5.28
9	*Environmental Pollution*	5	222	12.42	44.40	2.48
10	*J. Environ. Chem. Eng.*	5	107	9.38	21.40	1.87
11	*Plos One*	5	10	0.68	2.00	0.13
12	*Polymers*	5	66	3.75	13.20	0.74
			Total citations			
1	*Science of the Total Environment*	46	1548	121.78	33.65	2.64
2	*Chemical Engineering Journal*	5	375	26.43	75.00	5.28
3	*Environmental Pollution*	5	222	12.41	44.40	2.48
4	*Marine Pollution Bulletin*	11	214	24.11	19.45	2.19
5	*Resour. Conserv. Recycl.*	6	141	9.53	23.50	1.58
6	*Chemosphere*	7	118	11.72	16.85	1.67
7	*J. Environ. Chem. Eng.*	5	107	9.37	21.40	1.87
8	*Environ. Sci. Pollut. Res*	12	86	12.77	7.16	1.06
9	*Journal of Hazardous Materials*	7	70	19.72	10.00	2.81
10	*Polymers*	5	66	3.74	13.20	0.74
11	*Sustainability* (Switzerland)	9	25	2.76	2.77	0.30
12	*Plos One*	5	10	0.67	2.00	0.13
			Average normalized citations			
1	*Chemical Engineering Journal*	5	375	26.43	75.00	5.28
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11	*Sustainability* (Switzerland)	9	25	2.76	2.77	0.30
12	*Plos One*	5	10	0.67	2.00	0.13

(A) Position in rankings; (B) name of journal; (C) total number of documents published in the field; (D) total citations of documents published in the field; (E) normal citations: citation of all documents within same journal; (F) average citations: total citations per document in journal; (G) average normal citations: normalized number of citations of journal, which is equal to the total number of citations divided by the average number of citations published in the same year.

Table 2 summarizes the categories of the sources leading the rankings, showing that 8 of the 12 journals are included in the *Environmental Sciences* category, with 3 in *Engineering*, and 1 in environmental. In addition, *Marine Pollution Bulletin* is included in the category marine and freshwater biology, while *Sustainability* is in the category green and sustainable science and technology. These results emphasize the negative environmental effects of waste from PPE, especially marine pollution [4,17], and the need to provide solutions to them.

Table 2. Categories of sources leading the rankings.

Source	Journal's Category in Scopus							
	1	2	3	4	5	6	7	8
Science of the Total Environment	■							
Environmental Science and Pollution Research	■							
Marine Pollution Bulletin	■			■				
Sustainability (Switzerland)	■				■			
Chemosphere	■							
Journal of Hazardous Materials	■	■						
Resources, Conservation and Recycling	■	■						
Chemical Engineering Journal			■			■		
Environmental Pollution	■							
Journal of Environmental Chemical Engineering		■	■					
Plos One							■	
Polymers								■
Total	8	3	2	1	1	1	1	1

1. Environmental sciences. 2. Engineering, environmental. 3. Engineering, chemical. 4. Marine and freshwater biology. 5. Green and sustainable science and technology. 6. Biotechnology and applied microbiology. 7. Polymer science. 8. Multidisciplinary sciences.

Finally, Figure 4 provides a network visualization of the sources containing the 12 sources included in the ranking in terms of the number of documents. All of them are connected, and the size of a cluster indicates the contribution of that source to the publication count; a larger size implies greater influence. In this way, because *Science of the Total Environment* has larger circles compared with the other journals, this means that this journal has the highest impact on the research field in terms of the number of papers. Additionally, circles with the same color indicate the clusters of sources associated in terms of the scope of research outlets or the number of times they are co-cited [37]. Thus, five groups or clusters were identified by the clusters in red, green, blue, yellow, and purple, with three, three, three, two, and one journals in each one, respectively. Because *Science of the Total Environment* (Cluster 4 yellow) is close together with *Environmental Science and Policy* (Cluster 1 red) and *Marine Pollution Bulletin* (Cluster 5 purple), we identified a stronger connection between these sources in comparison with the others, whose frames are farther apart from each other.

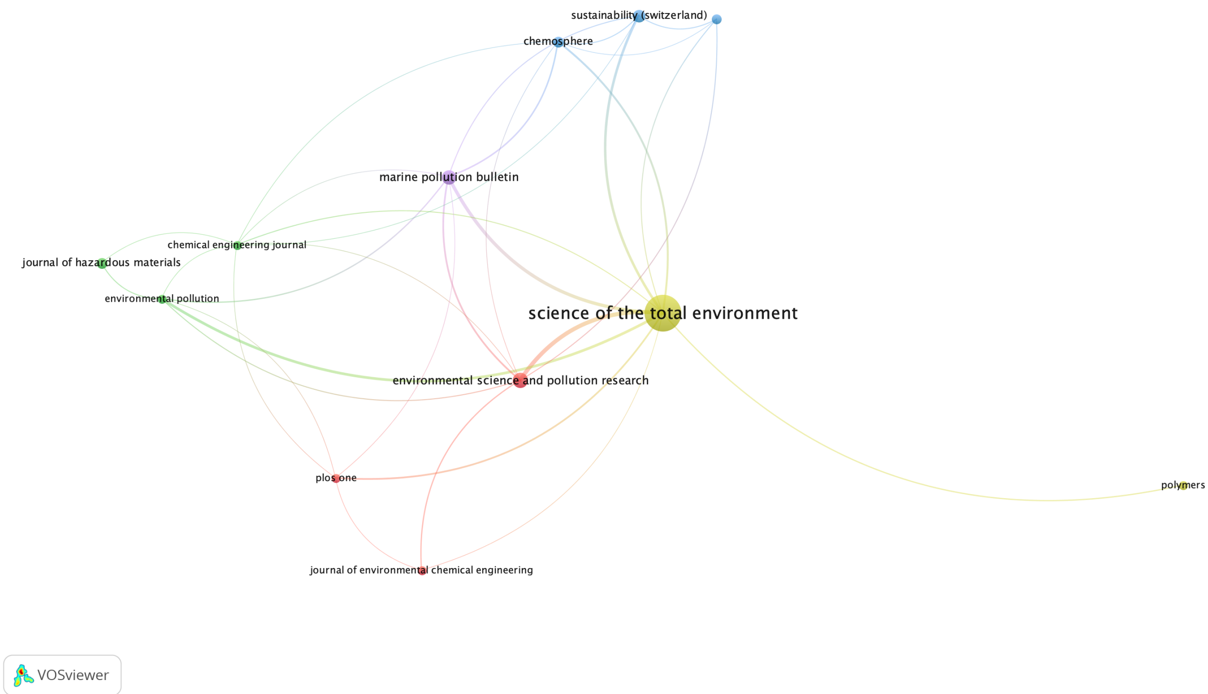

Figure 4. Network visualization of sources with more importance in the field, included in Table 1, in terms of the number of documents.

3.2.2. Mapping of Countries

In our preliminary analysis, we included a total of 87 countries in this study. Figure 5 shows the relationship between the number of countries and the number of documents published in the field. The results show a low concentration of documents per country; furthermore, 11 countries published only 1 document, followed by 18 countries with only 2 documents published; these countries represent 46% of the total sample.

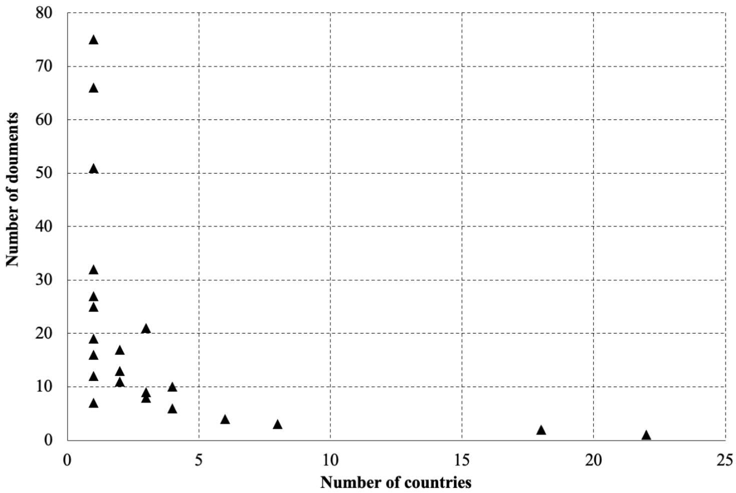

Figure 5. Relationship between the number of countries and the number of documents published.

To identify countries with greater importance in the field, journals with a minimum of five documents and five citations of a source were identified, resulting in 33 countries. The top 10 of these countries in terms of publication count, total citations, and average normalized citations are summarized in Figure 6. A total of 16 countries are included in the three top lists. India, China, and the United States lead the rankings in terms of the number of documents, with more than 50 publications; China, Canada, and Portugal lead for citation rankings; Portugal, Canada, and Peru lead in terms of average normalized citations. Three of the top lists (Bangladesh, Canada, China, and Spain) are included in the three rankings, so they could be considered the countries with the most influence in the research in the field; six countries (Australia, India, Italy, The United States, Portugal, and South Korea) are in two of them; eight of them are included in only one of the lists (Saudi Arabia, The United Kingdom, France, Iran, Malaysia, and Peru).

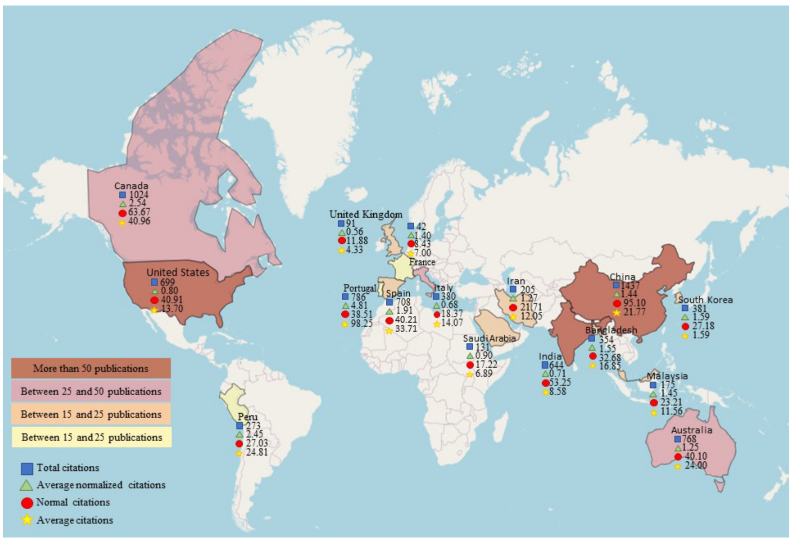

Figure 6. Countries with greater importance in the field, in terms of publication count, total citations, and average normalized citations.

Finally, Figure 7 presents the network visualization of the 16 countries included in the three top 10 lists in terms of total citations. All of them are linked based on citations, and the degree to which a country has contributed to the research in this field is indicated by the size of the box. Three groups or clusters were detected, denoted by distinct colors: red (Cluster 1), green (Cluster 2), and blue (Cluster 3), with seven, five, and four countries in each one, respectively. Based on the graphical description of the active countries, the large size of the circles of China makes clear the aforementioned leadership of this country in terms of total citations. Our analysis will support researchers working jointly in scientific collaborations to share approaches and ideas and produce papers.

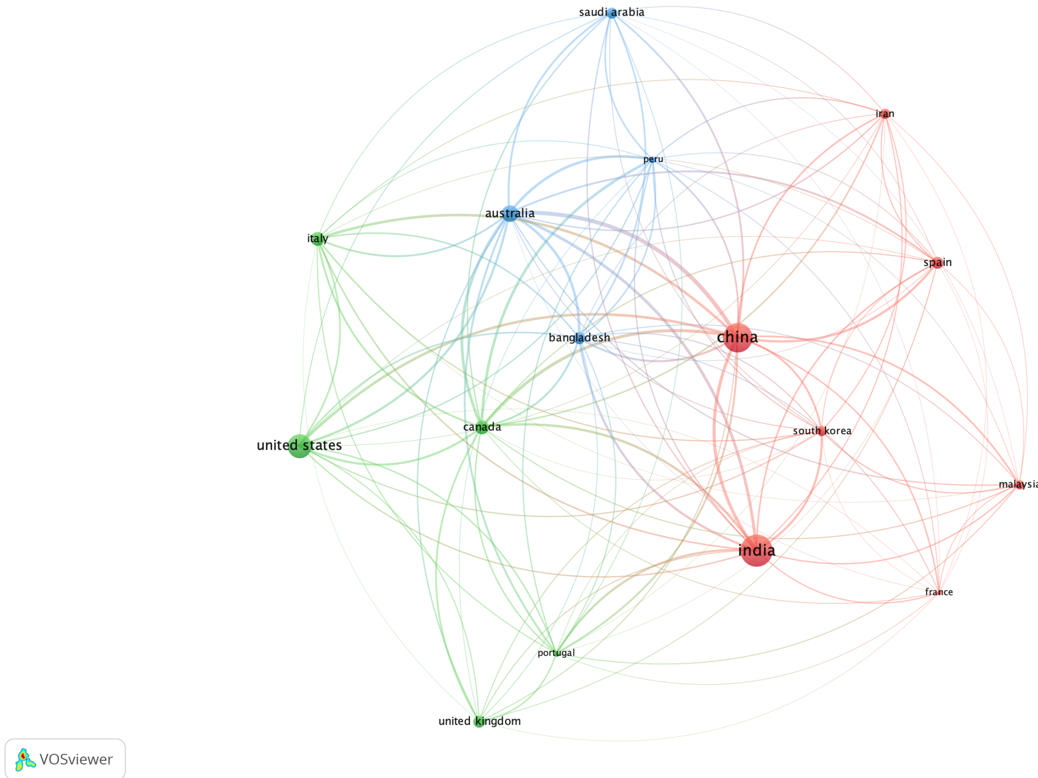

Figure 7. Network visualization of countries with greater importance in the field in terms of total citations.

3.2.3. Mapping of Authors

In our preliminary analysis, we identified a total of 974 authors. Figure 8 shows the relationship between the number of authors and the number of documents published in the field. There is a high dispersion in the production of papers, which could be explained by the novelty and interest of the field; moreover, the largest number of documents published per author is 10, followed by 7 and 6; in addition, 818 of the authors (making up 84% of the total) have published only 1 paper. As a result of the lower number of papers published per author, only seven authors have published five papers or more (Table 3). The ranking in terms of publication count is led by De la Torre G.E., with 10 documents published, followed by Li J., with 7 documents.

As the number of citations received by a researcher in a certain discipline is used to quantify his/her influence, we also analyzed the number of authors in terms of citations. Table 3 shows that 11 authors have more than 200 citations; in this case, the ranking is clearly led by Duarte A.C., Prata J.C., and Rocha-Santos T., all of them with 764 citations and only five documents, followed by Walker T.R. with the same number of documents and 745 citations. Positions 7 to 10 are occupied by authors with only 1 or 2 documents, but with a number of citations that varies between 261 and 284; the high number of citations reveals the great impact of these authors, especially when taking into account the short time horizon of this analysis. Finally, in the case of the average normalized citation ranking, the results include authors with only one document published, but with 177 to 282 citations. In all these cases, the average normalized citation index is higher than nine, which means that these authors with only one document have made a considerable contribution to the research field.

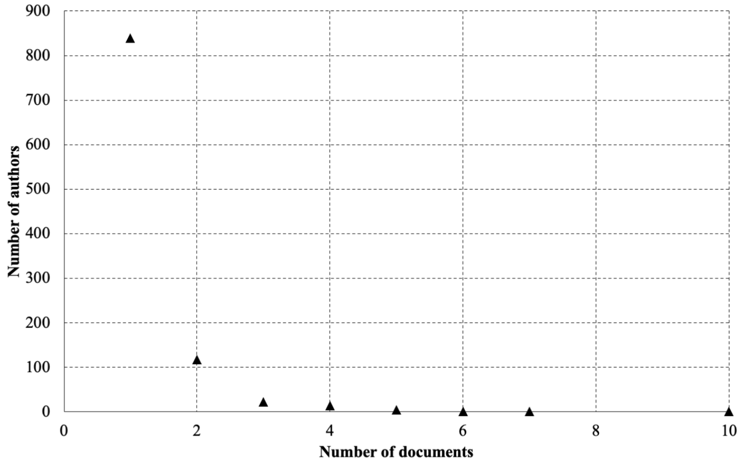

Figure 8. Relationship between the number of authors and the number of documents published.

Table 3. Ranking of authors with more importance in the field in terms of total publication count, total citations, and average normalized citations.

A	B	C	D	E	F	G
			Publication count			
1	De la Torre G.E.	10	244	25.29	24.4	2.52
2	Li J.	7	129	10.35	18.42	1.47
3	Liu Y.	6	85	8.2506	14.16	1.37
4	Walker T.R.	5	745	40.09	149	8.01
5	Duarte A.C.	5	764	36.95	152.8	7.39
6	Prata J.C.	5	764	36.95	152.8	7.39
7	Rocha-Santos T.	5	764	36.95	152.8	7.39
			Total citations			
1	Duarte A.C.	5	764	36.95	152.8	7.39
2	Prata J.C.	5	764	36.95	152.8	7.39
3	Rocha-Santos T.	5	764	36.95	152.8	7.39
4	Walker T.R.	5	745	40.09	149	8.01
5	Barceló D.	4	503	27.78	125.75	6.94
6	Patrício Silva A.L.	4	503	27.78	125.75	6.94
7	Okoffo E.D.	2	284	10.23	142	5.11
8	Ouyang W.	1	282	19.02	282	19.02
9	Fadare O.O.	1	276	9.69	276	9.69
10	Silva A.L.P.	1	261	9.17	261	9.17
11	De-La-Torre G.E.	10	244	25.29	24.4	2.52
			Average normalized citations			
1	Ouyang W.	1	282	19.02	282	19.02
2	Bhattacharya J.	1	177	11.93	177	11.93
3	Dubey B.K.	1	177	11.93	177	11.93
4	Goel S.	1	177	11.93	177	11.93
5	Ranjan V.P.	1	177	11.93	177	11.93
6	Samal B.	1	177	11.93	177	11.93
7	Sharma H.B.	1	177	11.93	177	11.93
8	Vanapalli K.R.	1	177	11.93	177	11.93
9	Fadare O.O.	1	276	9.69	276	9.69
10	Silva A.L.P.	1	261	9.17	261	9.17

(A) Position in rankings; (B) name of author; (C) total number of documents published in the field; (D) total citations of documents published in the field; (E) normal citations: citations of author with documents published in the field; (F) average citations: total citations per author of documents published in the field; (G) average normal citations: normalized number of citations of author, which is equal to the total number of citations divided by the average number of citations published in the same year.

With the objective of analyzing the collaboration between authors, we developed a mapping of co-authorship by author with a minimum of one document and 50 citations.

Figure 9 shows the high number of small collaboration groups in which the 119 identified authors are working. With the objective of identifying this collaboration in terms of countries, a mapping of co-authorship by country with a minimum of 10 documents (Figure 10) was developed, resulting in 22 countries that work together in the research field. Considerable collaborations between countries that include five scientific communities have been identified with red (Cluster 1), green (Cluster 2), blue (Cluster 3), yellow (Cluster 4), and purple (Cluster 5) colors; note that the one in red includes eight countries (Australia, Bangladesh, Brazil, Canada, Iran, Peru, Singapore, and The United States).

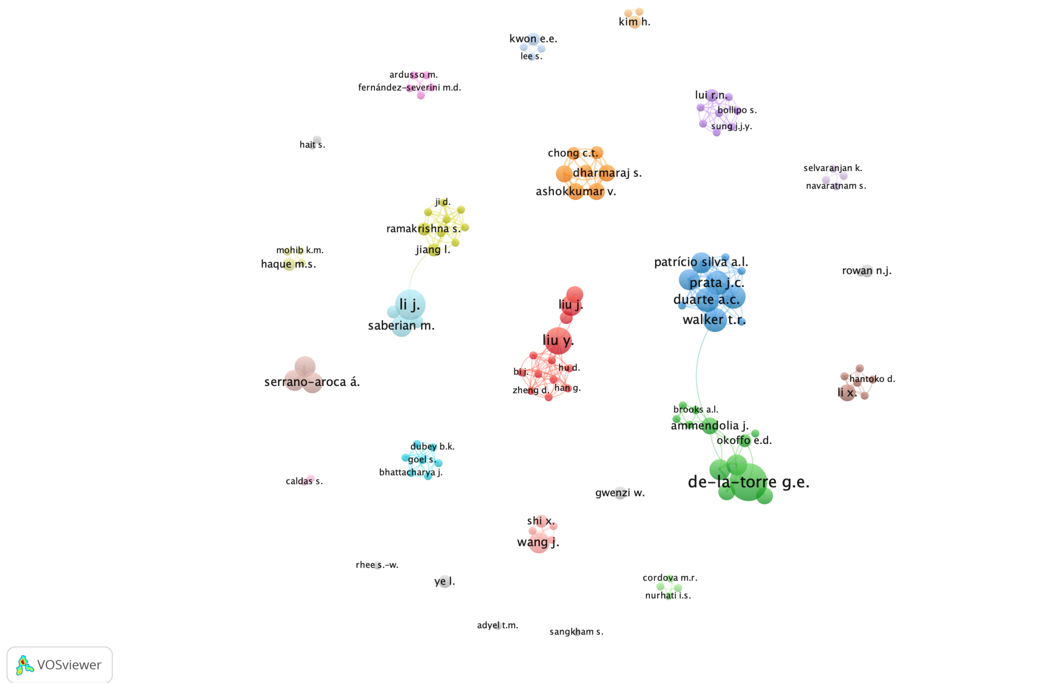

Figure 9. Author collaboration network visualization, including authors with a minimum of 50 citations.

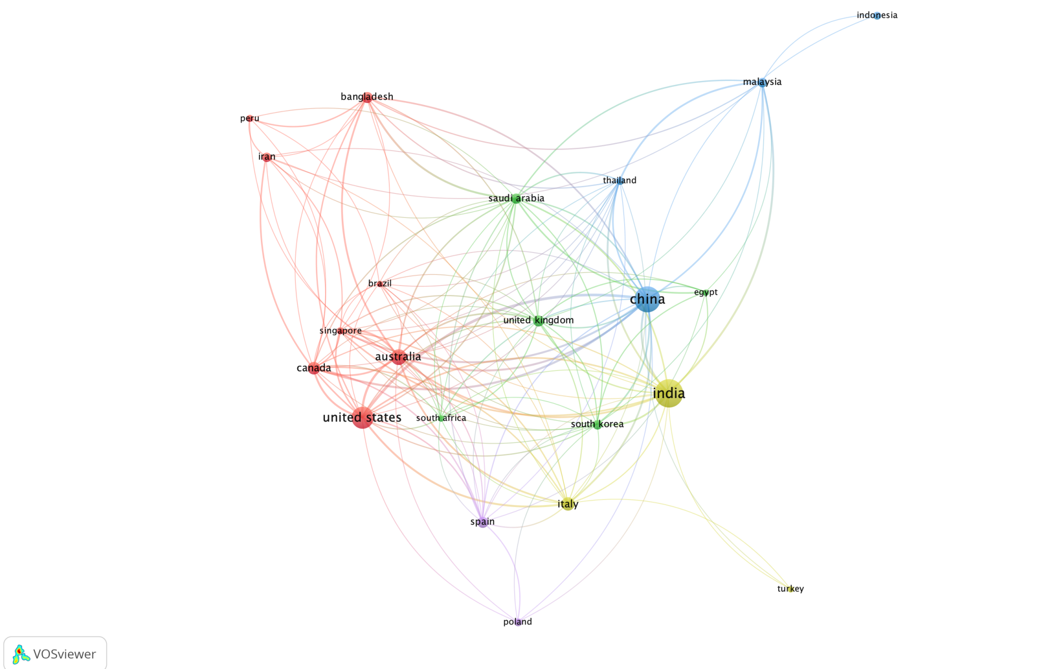

Figure 10. Country collaboration network visualization, including countries with a minimum of 10 documents in the field.

3.2.4. Document Mapping

A paper's citation density reflects its impact on the research field [37]. Table 4 summarizes the top 10 documents in terms of total citations and normalized citations, including a total of 13 documents in both lists. Seven of them are included in both lists, so they are considered the papers with the highest contribution to the research field. Only 2 documents are included in the top 10 in terms of total citations, with 3 for normalized citations. The titles of the documents show great concern regarding plastic pollution resulting from the COVID-19 pandemic, with special reference to its effects on surface water.

Table 4. List of most-relevant documents in the field in terms of total citations and normalized citations.

A	B	C	D	E	F	G	H
1	1	Increased Plastic Pollution due to COVID-19 Pandemic: Challenges and Recommendations	Ana L. Patricio Silva, Joana C. Prata, Tony R. Walker, Armando C. Duarte, Wei Ouyang, Damiá Barceló, Teresa Rocha-Santos	282	19.07	2021	*Chemical Engineering Journal*, 405, 126683
2	3	COVID-19 Face Masks: A Potential Source of Microplastic Fibers in the Environment	Oluniyi O. Fadarea, Elvis D. Okoffo	276	9.69	2020	*Science of The Total Environment*, 737, 140279
3	4	COVID-19 Pandemic Repercussions on the Use and Management of Plastics	Joana C. Prata, Ana L.P. Silva, Tony R. Walker, Armando C. Duarte, and Teresa Rocha-Santos	261	9.17	2020	*Environmental Science Technology*, 13, 7760–7765
4	6	Rethinking and Optimizing Plastic Waste Management under COVID-19 Pandemic: Policy Solutions Based on Redesign and Reduction of Single-use Plastics and Personal Protective Equipment	Ana L. Patricio Silva, Joana C. Prata, Tony R. Walker, Diana Campos, Armando C. Duarte, Amadeu M.V.M. Soares, Damiá Barcelò, Teresa Rocha-Santos	190	6.67	2020	*Science of The Total Environment*, 742, 10 140565
5	2	Challenges and Strategies for Effective Plastic Waste Management During and Post COVID-19 Pandemic	Kumar Raja Vanapalli, Hari Bhakta Sharm, Ved Prakash Ranjan, Biswajit Samal, Jayanta Bhattacharya, Brajesh K. Dubey, Sudha Goel	177	11.97	2021	*Science of The Total Environment*, 750, 141514
6	-	Disinfection Technology and Strategies for COVID-19 Hospital and Bio-medical Waste Management	Sadia Ilyas, Rajiv Ranjan Srivastava, Hyunjung Kim	130	4.56	2020	*Science of The Total Environment*, 749, 141652
7	-	Face mask and Medical Waste Disposal During the Novel COVID-19 Pandemic in Asia	Sarawut Sangkham	122	4.28	2020	*Case Studies in Chemical and Environmental Engineering*, 2, 100052
8	8	An Emerging Source of Plastic Pollution: Environmental Presence of Plastic Personal Protective Equipment (PPE) Debris Related to COVID-19 in a Metropolitan City	Justine Ammendolia, Jacquelyn Saturno, Amy L. Brooks, Shoshanah Jacobs, Jenna R. Jambeck	85	5.75	2021	*Environmental Pollution*, 269, 116160
9	9	Valorization of Disposable COVID-19 Mask through the Thermo-Chemical Process	Sungyup Jung, Sangyoon Lee, Xiaomin Dou, Eilhann E. Kwon	82	5.54	2021	*Chemical Engineering Journal* 405, 126658
10	-	Mask Use During COVID-19: A Risk-Adjusted Strategy	Jiao Wanga, Lijun Pan, SongTanga John S. Ji, Xiaoming Shi	80	2.81	2020	*Environmental Pollution* 266, Part 1, 2020, 115099
-	5	A Critical Synthesis of Current Peer-Reviewed Literature on the Environmental and Human Health Impacts of COVID-19 PPE Litter: New Findings and Next Steps	Gurusamy Kutralam-Muniasamy, FermÃn PÃ©rez-Guevara, V.C. Shruti	14	8.44	2022	*Journal of Hazardous Materials*, 422, 126945
-	7	Face Masks Related to COVID-19 in the Beaches of the Moroccan Mediterranean: An Emerging Source of Plastic Pollution	Bilal Mghili Mohamed, Analla, Mustapha Aksissou	11	6.63	2022	*Marine Pollution Bulletin*, 174, 113181
-	10	COVID-19 Pandemic Repercussions on Plastic and Antiviral Polymeric Textile Causing Pollution on Beaches and Coasts of South America	M. Ardusso, A.D. Forero-LÃ³pez, N.S. Buzzia, C.V. Spettera, M.D. FernÃ¡ndez-Severini	74	5.00	2021	*Science of The Total Environment*, 763, 144365

(A) Position of document per total citations; (B) position of document per normal citations; (C) title of document; (D) authors of document; (E) total citations of document; (F) normalized citations of document; (G) publication year; (H) publication journal data.

3.3. Keyword Analysis

As the keywords of a document present its main content within the relevant domain of a research field [40], their analysis is a way to obtain knowledge of the themes included in the paper [37]. In this case, we developed the keyword analysis with VOSviewer, in terms of the keywords' co-occurrence, and SciMAT to analyze the evolution of themes using an overlay graph, as well as strategic and thematic diagrams. The results are summarized and discussed below.

3.3.1. Keywords' Co-Occurrence

The co-occurrences of keywords was used to identify the relationships between documents. The co-occurrence of the authors' keywords (which take into account synonyms, various spellings, and plurals), full counting method (which means that each co-occurrence link has the same weight), and a minimum of five occurrences were used for the keyword analysis. Figure 11 shows the resulting 34 keywords included in six clusters in the colors red (Cluster 1), green (Cluster 2), blue (Cluster 3), yellow (Cluster 4), purple (Cluster 5), and black (Cluster 6). In addition, Figure 12 shows an overlay visualization in terms of average citations, showing that plastic waste, waste, and single-use plastic are included in the group with a higher value; in addition to these words, those relating to microplastic, polypropylene, waste, and masks are included in the group with a higher average normal citation map.

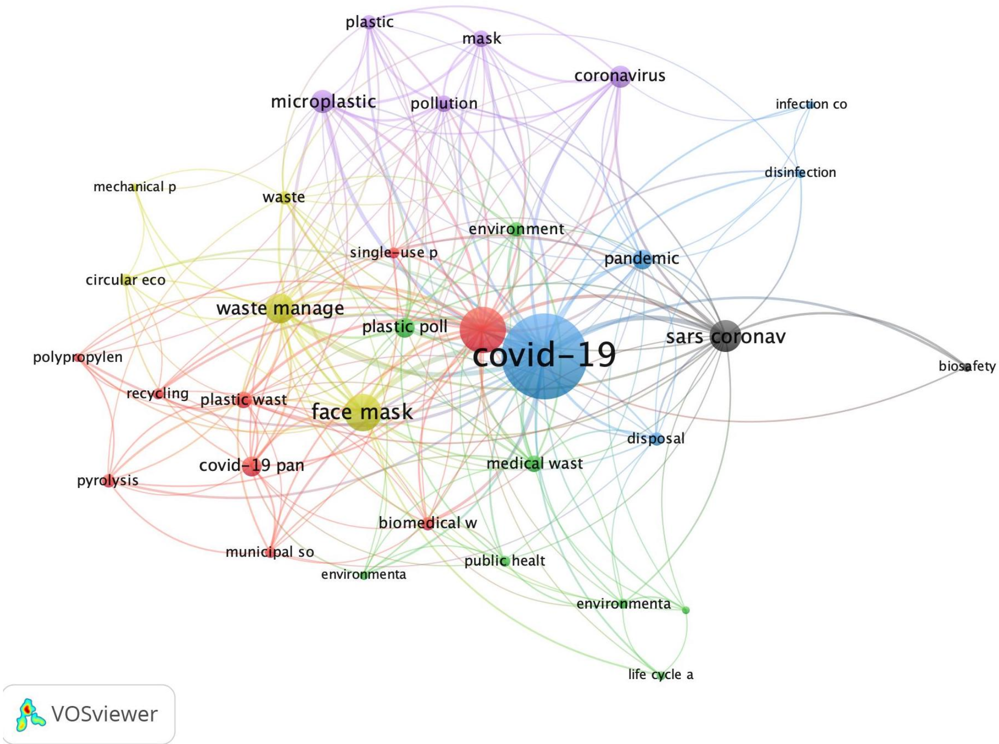

Figure 11. Network co-occurrences of author keywords' visualization with a minimum of 5 occurrences.

Table 5 summarizes the clusters' most-significant characteristics in terms of influential keywords, assigned theme, and the average normal citation of each cluster. To find that, first, the terms with the highest average normal citation in each cluster were selected; then, the clusters were classified considering the principal theme according to the keywords included in them; finally, the average year of publication and average normalized citation of each cluster were determined. The results showed that the most-considerable clusters are 1 (red) and 5 (purple), whose assigned themes are plastic waste management and pollution from plastic waste, respectively. Cluster 1 has the highest number of keywords, as well as the highest value for the average normal citation; Cluster 5 has the highest value of the average normal citation (1.7769), closely followed by Cluster 1 (1.6845). Hence, both clusters are considered the most significant. Because the COVID-19 pandemic has increased the use of PPE and packaging based on plastic composition, it is clearly contributing to aggravating the environmental crisis derived from the wasteful use and consumption of single-use plastics [5,7].

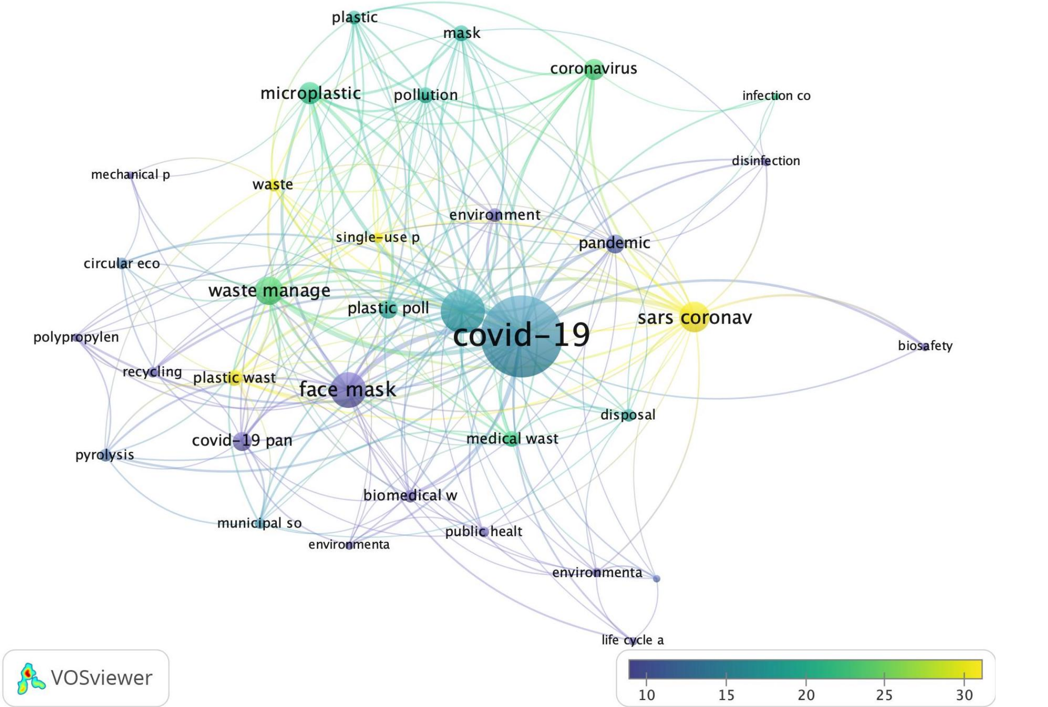

Figure 12. Overlay visualization, in terms of average citations, of network co-occurrences of authors' keywords with a minimum of 5 occurrences.

Table 5. Most-significant characteristics of clusters of influential keywords in the field.

A	B	C	D	E	F	G
1	Red	9	Single-use plastic	62.55	Plastic waste management	1.68
2	Green	8	Medical waste	22.00	Environmental effect of medical waste	1.00
3	Blue	5	Infection control	21.80	Infection control of pandemic	0.89
4	Yellow	5	Waste	29.25	Waste management	1.23
5	Purple	5	Coronavirus	22.84	Pollution of plastic waste	1.77
6	Black	2	SARS Coronavirus	32.40	SARS Coronavirus and biosafety	1.03

(A) Cluster number; (B) color of cluster in Figure 9a; (C) number of keywords in cluster; (D) most-influential keyword in cluster; (E) average normal citations of the most-influential keyword in cluster; (F) assigned theme to cluster; (G) average normalized citations of cluster.

3.3.2. Evolution of Themes

The evolution of the topics over time in the research field was studied using an overlay graph, a thematic evolution map, and strategic diagrams, all generated by SciMAT.

Figure 13a shows the overlay graph. It represents the stability of the keywords between two consecutive subperiods and measures the number of keywords shared by successive subperiods [38]. The analysis of the overlay graph shows a high number of keywords of the first year, as well as its increase in 2021, which has doubled. Taking into account the evolution during the first half of 2022, it is expected that the number of keywords in 2022 will reach 3000, a lower increase than that of the previous year, implying a tendency towards the stabilization of the research field. In addition, the analysis of the horizontal arrow, which represents the number of keywords shared by both periods, and the upper-incoming and -outcoming arrows of Periods 1 and 2, which represent the number of new keywords in each period, show the considerable renewal of terms related to the novelty of the field: the number of new keywords in 2021 was 1702, which represents 80% of those included in this year. In addition, the number of this year's keywords that will be replaced by 15 June 2022 reached 1592, a value that represents 75% of all keywords.

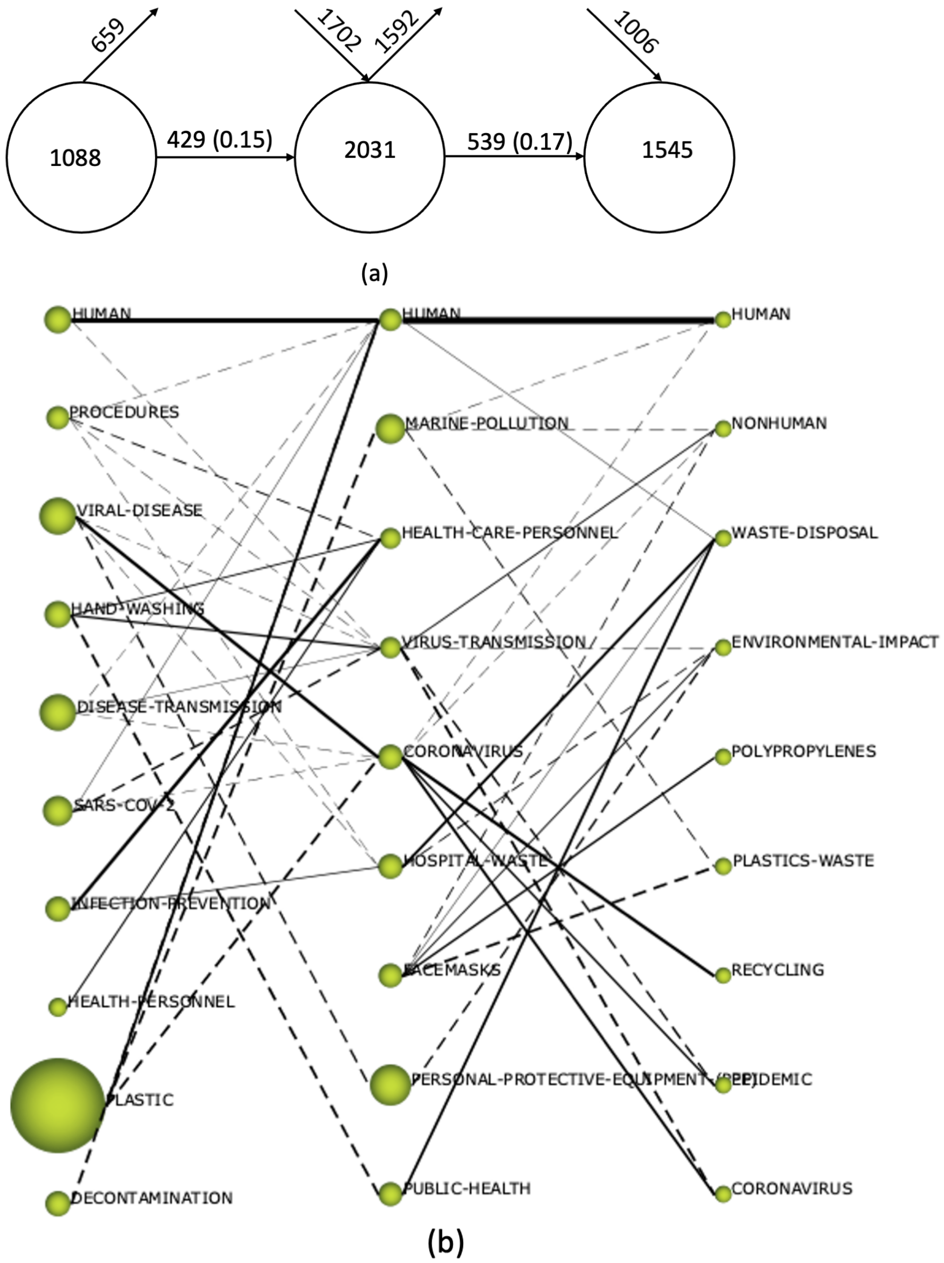

Figure 13. Representation of the evolution of topics over time in the research field using overlay graph (**a**); thematic evolution map in terms of average citations (**b**).

Figure 13b shows the thematic evolution maps of the research field in terms of the average citations. Our analysis indicated the following:

- In general terms, in each year, the themes are not the same, showing that new themes with their associated keywords appear, while others disappear, as was discussed concerning the overlay graph. Only the HUMAN theme appears in all three years. However, COVID appears in the three years, first as SARS-COV-2 in 2020and then under the denomination of Coronavirus in 2021;

- Because the identified themes are connected with a line in a previous year, the research into the management of used COVID-19 PEE is very cohesive. In addition, the thickness of most of the edges is high, meaning that such an edge is a considerable thematic nexus [38]. In the case of solid lines, they link themes that shared the same name; this means that both themes are labeled with the same keywords or the label of one theme is part of the other, which is the case with themes such as infection prevention and health care personnel, plastic and human, or viral disease and Coronavirus and recycling. The dotted lines link themes that share elements that are not the name of the themes; this is the case, for example, for plastic and marine pollution and plastic waste;
- Human, Coronavirus, viral disease, disease transmission, plastic, and marine pollution are the themes whose spheres have the largest volumes (such a volume is proportional to the average citations), showing both an interest in the transmission of the virus and the use of plastic materials to prevent its spread, which produce problems, such as marine pollution, after being discarded [4,7,17];
- The predominance of themes related to the transmission of the virus and its prevention is clear in 2020 and 2021. However, in the first half of 2022, the themes stress the environmental relevance, with a predominance of terms related to plastic or waste management, namely waste disposal, environmental impact, polypropylenes, plastic waste, and recycling. This shows that, after overcoming the pandemic, the interest in knowing the environmental impact resulting from the use of PPE has been increasing [5,7,16].

SciMAT was used to produce a strategy diagram for each year to show the evolution of research topics in terms of the number of documents published. These diagrams are included in Figure 14. Table 6 contains some quantitative and impact measures to analyze each one. In the case of the strategy diagrams, they are divided into four quadrants showing the following four types of research topics [38]. The number of transversals to the scientific field and highly developed and isolated themes, located in the lower-right and upper-left quadrants, respectively, is very low and related to the novelty of the research field. In the case of transversal themes, disease transmission appears in the first year of the pandemic with hand washing, which is just on the border with motor themes, and polypropylenes appears as a keyword in 2022; on the other hand, only two themes are classified as emerging, namely health personnel and plastic waste in 2021 and 2022, respectively, while viral disease in 2020 is just on the border with motor themes. Motor themes, the upper-right quadrant, show well-developed and essential themes in the field and include humans along the entire time horizon of the analysis. In addition, themes related to the virus and the infection, such as SARS-CoV-2, virus transmission, health personnel, and Coronavirus, were identified in 2020 and 2021. Last, interest in the environmental impact of PPE waste is clear with the motor theme in 2021, marine pollution, and two in 2022, environmental impact and waste disposal. The lower-left quadrant includes emerging or declining research topics that lack development and importance, although they may evolve and become more considerable or disappear entirely. In this sense, plastic, which appears in the first year, evolved to be classified as highly developed in 2022. In the case of Coronavirus, which in 2021 was classified as a motor theme, it appears in the lower-left quadrant in 2022, probably because it is heading towards disappearance. Nevertheless, the short time horizon of the study prevents a better interpretation of the results.

A higher value of centrality (Table 6) shows the importance of a theme in the development of the entire research field [41]. The human theme occupies the top position in the three subperiods, with centrality values of 1301.08, 735.48, and 722.83. This theme is followed by procedures, Coronavirus, and nonhuman, with 555.38, 242.28, and 317.76 in 2020, 2021, and 2022, respectively. On the other hand, according to the concept of density, human is the theme with the most-considerable internal ties between all keywords identified in the research field, implying that it has the highest level of development [41]. These results are related to the high number of global Coronavirus disease cases and the precautionary measures taken against the pandemic [15].

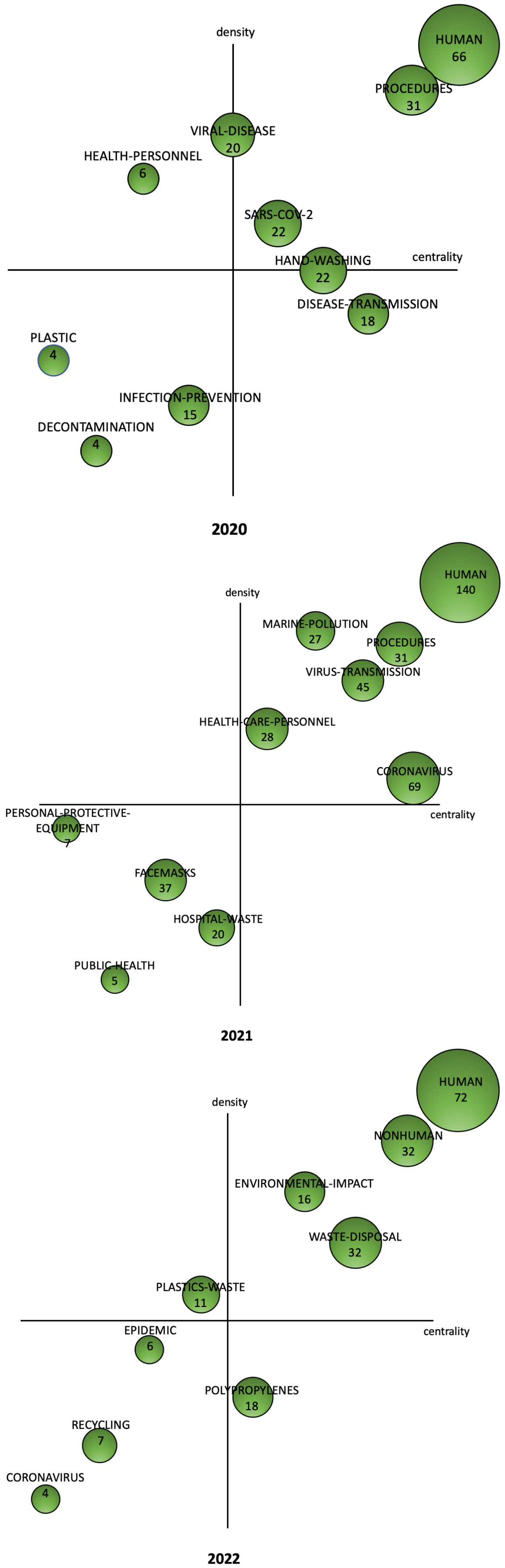

Figure 14. Representation of the evolution of topics over time in the research field using strategy diagrams in terms of the number of documents published.

Table 6. Performance measures for themes for subperiods of the time horizon.

A	B	C	D	E	F	G
2020						
Human	66	21	30.56	2017	1301.08	313.97
Procedures	31	12	20.35	631	555.38	80.22
Viral disease	20	14	56.9	1138	244.77	79.46
Hand washing	22	11	29.27	644	276	29.3
Disease transmission	18	9	55.39	997	299.33	25.52
SARS-CoV-2	22	12	37.91	834	275.34	30.72
Infection prevention	15	8	25.47	382	195.32	19.38
Health personnel	6	4	8.33	50	88.41	39.74
Plastic	4	4	209.75	839	25.57	23.81
Decontamination	4	3	25.5	102	45	12.19
2021						
Human	140	28	17.9	2506	735.48	154.01
Marine pollution	27	18	37.3	1007	175.66	51.75
Health care personnel	28	8	13.82	387	139.3	27.38
Virus transmission	45	15	14.64	659	212.48	44.65
Coronavirus	69	25	24.42	1685	242.28	27.01
Hospital waste	20	12	24.4	488	125.99	9.7
Face masks	37	19	22.41	829	117.54	11.32
Personal protective equipment (PPE)	7	5	67.57	473	27.82	13.11
Public health	5	4	21.6	108	35.71	8.62
Until 15 June 2022						
Human	72	7	2.28	164	722.83	176.15
Nonhuman	32	6	3.25	104	317.76	36.15
Waste disposal	32	6	2.81	90	243.23	26.04
Environmental impact	16	4	3.19	51	145.79	32.63
Polypropylenes	18	4	2.67	48	120.63	13.35
Plastic waste	11	4	4.36	48	78.07	23.5
Recycling	7	1	1.14	8	54.37	12.69
Epidemic	6	2	3	18	64.61	14.62
Coronavirus	4	2	3.25	13	17.96	12.5

(A) Theme name; (B) number of documents including the theme; (C) theme h-index; (D) theme average citations; (E) theme number of citations; (F) theme centrality: considered as theme's importance in overall development of the scientific field analyzed; (G) theme density: considered as theme's degree of internal cohesion.

4. Findings and Discussion

A scientometric evaluation of published documents about the management of used COVID-19 PPE was carried out to isolate the main sources of publications, authors, countries, and documents. The most-considerable documents in terms of citations and average normal citations, as well as others cited in them, were used to carry out a literature review about the management of used COVID-19 PPE.

In general terms, the literature predicts a worsening of the effects of plastic on the environment resulting from the increase in the quantity of plastic waste (including micro- and nano-sized plastics) aggravated by the excessive use and consumption of single-use plastics due to the COVID-19 pandemic. This increase was related to both the use of PPE and the higher demand for food packaging as a result of consumers worrying about hygiene. Thus, our literature review focused on waste from PPE. Our results are organized in terms of: (i) type and composition; (ii) quantification of waste; (iii) management of waste; (iv) environmental impact produced. The results are discussed below.

4.1. Type and Composition

Nonpharmaceutical interventions to physically cut off COVID-19 contagion by wearing PPE include the use of face masks, gloves, wet wipes, face shields, safety glasses, shoes, gowns, and aprons, all of them containing a substantial proportion of plastic [2]. For example, in the case of face masks, different polymers and materials, including polypropylene, polyacrylonitrile, and/or polyurethane, are used, with latex, synthetic polymers, vinyl, and/or nitrile being used in the case of disposable gloves. An interest in the contribution of PPE to plastic production was revealed in our science mapping analysis that identified plastic as the term with the highest average citation value, followed by polypropylenes and plastic waste (Figures 13b and 14).

The use of medical gloves, surgical face masks, face shields, safety glasses, shoes, gowns, and aprons has been recommended for healthcare service staff [42,43]. However, face masks, gloves, and wet wipes have also been recommended for wide use in the general population. Specifically, wearing face masks has been considered as the most-effective method to interrupt disease transmission for the general population [15]. Additionally, in many cases, their use has been mandated [42,43]: in 2020, in over 50 countries, the use of face masks by the population was mandatory in public places [5].

Different types of face masks have been used, including disposable medical or single-use face masks and N95 masks, as well as cotton gowns and sponges, which are reusable after washing [16].Single-use face masks are produced from polymers and polymer fibers, such as polyethylene, polypropylene, polyvinyl chloride, polyurethane, polyacrylonitrile (PAN), polystyrene, and polycarbonate, among others [3,14,44]. They consist of three layers [14]: an inner layer made of soft fibers; a middle layer, which is the main filtering layer; and a water-resistant outer layer, usually colored and made of nonwoven fibers [44]. In the case of N95 masks, they are made of plastics, such as polypropylene and polyethylene terephthalate [5]. In the case of reusable and washable face masks, they are usually manufactured with commercial synthetic textiles, including polymers or mixes of polymers and natural fibers [4], such as polyether or nylon, among others [45,46].

Finally, in addition to the growing increase in PPE, there have been some advances in avoiding contagion, such as the production of face masks with bactericidal, fungicidal, and antiviral properties, as well as the use of sprays and gels with Ag and Cu. There have also been some enhancements of their fashionable properties, such as fragrances [3,4].

4.2. Quantification of Waste

Considerable demand for PPE and single-use plastic has resulted in an increase in waste production. A study about the spatial distribution of PPE debris has demonstrated that the most-abundant debris items have been disposable gloves (44%), followed by face masks (31%) and disinfectant wipes (25%) [1]. Furthermore, the monthly number of face masks has been reported to have increased from 10 [47] to 129 million masks [48]. Other studies reported that more than 85 million face masks are disposed of each day in Brazil [16], with 65 billion gloves consumed monthly [1].

The increased production of waste related to PPE has been accompanied by an increased use of other medical waste and single-use plastics [3]; there has been increases of 350% and 370% in the amount of medical waste in regions such as Catalonia (Spain) and China, respectively [49]. Moreover, consumers prefer fresh food acquisitions in plastic packages to prevent infections, and restaurants have implemented pick-up services, increasing the production of waste plastic [2,7].

This increase in the use of single-use plastics goes against environmental sustainability, as well as the objectives included in different international agreements [5]: (i) the first circular economy action plan adopted by the European Commission in 2015, which identified plastics as a key priority and resulted in the European Strategy for Plastics in a Circular Economy; (ii) the Basel Convention and its amendment in 2019 to regulate transboundary movements of plastic waste; (iii) the United Nations Convention on the Law of the Sea to control the pollution of the marine environment produced by plastics; (iv) the United Nations Global Partnership on Marine Litter, a multi-stakeholder association created to define strategies to reinforce a reduction in plastics in the marine environment based on innovation for sustainable and green plastic solutions and to achieve an ocean free of macroplastic and microplastic pollution.

4.3. Management of Waste

In healthcare contexts, PPE waste has been included in the medical waste category; therefore, it is expected to be properly disposed of through incineration followed by the landfill of residual ash or the use of disinfection techniques, such as microwave or chemical disinfectants, all of which are widely used to protect public health [3,50]. However, the extensive use of PPE has overwhelmed the available waste management infrastructures, for example incinerators, which have operated beyond their capacity. For example, the increase in medical waste in Wuhan (China) forced the use of mobile incinerators, whereas in the case of The United Kingdom, municipal waste incinerators were given permission to process medical waste [51].

In the case of PPE used by the population, guidelines during the pandemic recommended that waste generated by home-quarantined patients should be stored in dedicated containers after the application of a disinfectant spray [50]. However, currently, PPE used at home is disposed of with municipal waste, which means it is being disposed of by the public in an incorrect manner. Some studies have reported the poor waste management practices and a lack of environmental awareness among the population during the pandemic, concluding that the density of the use of disposable face masks varies from one region to others, increasing in the tourist season and touristic regions [1,4,16,17], as well as in coastal areas [7]. Thus, face masks have been found on the beaches of Lima, Peru, the Chilean coast [18], Soko island in Japan, and on the Kenyan coast [19] and the Persian Gulf [52] areas, among others. PPE density varies by different regions of the world, from 1.13×10^{-5} PPE/m^2 along the Moroccan shoreline to 6.29×10^{-3} PPE/m^2 in the case of the Peruvian coast, increasing in the summer, or between 0 and 8.22×10^{-3} to 5.6×10^{-2} in the case of Canadian and Kenyan streets, respectively [16]. Consequently, we found that studies on PPE waste disposal in landfills or their improper disposal in the environment [53] evidenced that around 75% of PPE waste plastic ended up in landfills, public places, urban environments, and natural environments, such as beaches and ocean beds [3,51].

One of the pillars of the circular economy is the hierarchy in waste management defined by the Waste Framework Directive to prevent and reduce the negative impact caused by the generation and management of waste and to improve resource use efficiency. To ensure that, new challenges for municipal solid waste management and disposal have arisen, including the separate collection of used face masks at the source [20,54,55] to avoid infection and cross-contamination [56]; however, some options described below have been explored according to the cited directive hierarchy:

- Although single-use masks have a higher effectiveness in preventing the transmission of bacteria and viruses, studies have shown that reusable masks could have adequate performance after a decontamination process [13]. This solution has a lower environmental and economic impact, preventing waste production. As such, some possibilities have been explored to re-use disposable masks in order to prevent excessive waste generation during the pandemic. For example, a study showed that dry heat at 70 °C for 1, 2, and 3 h could successfully inactivate the H1N1 indicator virus in N95 respirators and surgical face masks without changing their shape, components, or filtering efficiency of bacterial aerosol [27]. N95 respirators have been decontaminated using vaporized hydrogen peroxide (VHP) or ultraviolet (254 nm wavelength; UVC) radiation, maintaining their integrity [26]. In another study, single-use FFP2 masks were sterilized by a 15 min procedure at 121 °C using a dry sterilization process, which could be adjusted in standard autoclaves in hospitals, showing the effectiveness of these processes to inactivate the Coronavirus without influencing the functionality of the tested masks [25]. Liquids such as alcohol solutions, chlorine-based solutions, or soaps should not be used to clean the respirator, as this will lead to a degradation in the static charge that is necessary for the filtering facepiece respirator (FFR) to meet the N95 standard [28], whereas the application of spray-on alcohol-based solutions containing disinfectants on the top surface of masks does not result in a measurable loss of mask filter performance [57]. In addition, efforts to develop green and degradable materials for PPE should be applied to reduce the environmental impact of PPE waste, for example a novel self-sanitizing mask prototype that reduces unnecessary waste has been developed [58];

- Recycling should be the best solution for face mask waste. However, this is not easily achieved because of the difficulty in properly separating materials [59] and the their bio-hazardous potential [21]. Nevertheless, some studies have opened opportunities in this field. For example, biochar production through the co-carbonization of disposable face masks and waste biomass has been investigated, indicating the possibility of using the biochar as an adsorbent and to increase soil fertility [60]. Some alternatives explored the use of PPE waste to produce concrete for construction [61,62] or the recovery of plastic particles from decomposed PPE [20];
- Finally, thermo-chemical processing offers a reliable treatment route for PPE to valorize face masks and other PPE using waste-to-energy technologies [30], including combustion [31,63], gasification [64], and pyrolysis [32]. The incineration of single-use face mask waste could generate an estimated 32.65 and 6.03 million kWh/day of electricity in Asia and Africa, respectively, although the potential risk of acidification makes necessary the provision of air pollution control devices in incineration plants [65]. The plasma gasification technology produces both synthesis gas, which can be utilized to run compression ignition engines, but also byproducts, which can be further utilized as valuable inputs in other industries, strengthening the circular economy concept; for example, vitrified slag can be used for building aggregates, tiles, or bricks [64]. The gasification and pyrolysis processes can be applied to recover Zn and Fe from nonrecyclable steel-making byproduct dusts and waste plastic material, such as face masks [66]. The refuse-derived fuel (RDF) pyrolysis process from protective masks produces a high calorific value for pyrolysis gas, amounting to approximately 47.7 MJ/m3. This process has been also applied to the polypropylene (PP) powder derived from COVID-19 isolation gown waste to yield char briquettes [32]. In any case, all these processes encourage PPE waste management towards energy recovery.

All these solutions are necessarily related to both the increase in public awareness for the sake of the collection and segregation of PPE waste at its source, but also the application of ecodesign practices in face mask production, such as the Extended Producer Responsibility (EPR) defined in Directive 98/2008 [67]. The EPR is an environmental protection strategy aimed at decreasing the total environmental impact of a product and its packaging by ensuring that the product's producers take responsibility for its entire lifecycle, especially through the take-back, recycling, and final disposal of their products [68]. It is included in Article 8 of Directive 98/2008, which directs Member States to take measures to ensure that any natural or legal person who professionally develops, manufactures, processes, treats, sells, or imports products has extended producer responsibility [67]. Such measures may include an acceptance of returned products and of the waste that remains after those products have been used, as well as the subsequent management of waste and financial responsibility for such activities. Taking into account the huge influence of Collective Extended Producer Responsibility Systems in Europe regarding different types of waste, such as packaging, used tires, electric and electronic waste, etc., the development of a comparable system for PPE could be a challenge for the suitable management of medical waste.

4.4. Environmental Impact Produced

In addition to the carbon footprint for each material composing the PPE, the incorrect disposal of used gloves, wipes, and masks produces considerable negative impacts. Thus, the low biodegradability of this waste leads to its accumulation in terrestrial and aquatic areas, affecting natural biota and tourism, as well as human health [69]. In addition, given the low density of the polymers used to produce them, they are easily carried by wind and water courses, traveling long distances [3,16] and spreading their negative effects across the globe. Some of the negative effects of PPE in the environment have been discussed in terms of: (i) carbon footprint; (ii) disease transmission; (iii) physical and physico-chemical degradation; (iv) effects on wildlife.

4.4.1. Carbon Footprint

The production, treatment, and disposal of PPE implies a carbon footprint (CF); moreover, the total carbon footprint for surgical masks used from March 2020 to December 2021 was calculated to be approximately 240 kton [70]. Some studies used life cycle assessment (LCA) techniques to determine the CF of PPE. For example, a study on disposable medical face masks revealed a CF of 21.5 g CO_2-eq, of which the main contributor was the raw material supply (40.5%), followed by packaging (30.0%) and production (15.5%) [71]. Other studies reported CF values between 22 and 59.5 g CO_2 per mask [10–13], attributing 60% to PPE production, especially textile production (40%), with the remaining 40% linked to disposal [10]. A computational model estimated that the use of each disposable surgical mask and embedded filtration layer (EFL) reusable face mask produced between 18.7 g CO_2-eq and 0.338 kg CO_2-eq [72]. On the other hand, reusable cotton masks have a total carbon footprint of 285.484 kg CO_2-eq/FU, which implies that they reverse the trend and become more environmentally friendly after 17 washes [72]. Studies that determined greenhouse gas emissions during the production, transport, sterilization, and end-of-life processes of FFP2 face masks showed that the CF was 58% in the case of face masks that were reused five times after a sterilization process compared with new single-use face masks [29]. In any case, all these studies revealed the relation between the composition of face masks and the CF, as well as the reduction in the CF of reused masks; therefore, future research on developing environmentally friendly PPE should focus on innovative materials that are easily washable, disinfectable, or susceptible to recycling.

4.4.2. Disease Transmission

Our science mapping analysis revealed many studies on the human-to-human transmissions of the COVID-19 virus, identifying terms such as human, viral disease, disease transmission, virus transmission, and epidemic (Figures 13b and 14). Studies have revealed that the disease is transmitted via exposure to respiratory fluids carrying infectious virus. The epidemiological evidence for the dominance of the airborne spread of COVID-19 via droplets and aerosol is increasing [73]. The two principal ways of exposure are the (1) inhalation of droplets and aerosol particles or (2) the deposition of droplets and particles on exposed mucous membranes in the mouth, nose, or eye. Nevertheless, studies have revealed the persistence of COVID-19 on inanimate surfaces; for example, the virus can survive for 6.8 and 5.6 h on plastics and stainless steel, respectively [74]. Therefore, it is possible for people to be infected by touching their mucous membranes with their hands if they have touched surfaces or objects (fomites) with virus on them; however, the risk is generally considered to be low. In any case, cleaning by using soap or detergent and disinfection, using a product or process designed to inactivate the virus, can reduce the risk of fomite transmission.

Consequently, efforts to prevent disease transmission have been centered on reducing exposure to droplets and aerosol particles by effective ventilation and air disinfection systems [75], as well as the use of PPE, especially face masks, which reduce the emission and spread of respiratory viruses through airborne droplets and aerosols and reduce the inhalation of airborne respiratory viruses [76]. In this sense, terms such as face masks, personal protective equipment, or health care personnel are represented in our science mapping analysis (Figure 13b). However, after their use, face masks can present contamination. One study reported a virus survival time of 7 days on the surface of PPE waste, such as face masks [50,77], resulting in considerable health risks associated with the possibility of

COVID-19 virus transmission by handling PPE litter [16] or uncontrolled dumping in landfills [78]. Consequently, we must cautiously manage the enormous amount of PPE waste generated during and after the pandemic to avoid the risk of the secondary transmission of the virus.

In the case of waste produced in sanitary facilities, their classification as biomedical waste promotes their being handled in accordance with safety measures. However, public participation in the separate and timely collection of face masks is one of the key factors in the effective management of this type of waste [50].

4.4.3. Physical and Physico-Chemical Degradation

Because the composition of PPE is based on plastic [2], the interactions of waste in open environments lead to their physical and physico-chemical degradation [79]. PPE waste will slowly degrade into microplastics (MPs) (5 mm–1 μm) and nanoplastics (NPs) (<1 μm) due to physicochemical (e.g., UV radiation, wind, currents) and biochemical (enzymatic activity) processes [3,14], contributing to the mounting problem of MP and NP pollution [16], in addition to leachable inorganic and organic chemicals' production, which are associated with textiles and plastic additives that have an adverse impact on human health and the environment [80], especially in marine water, resulting in the popularity of the terms marine pollution and environmental impact in our thematic maps (Figures 13b and 14).

To combat the negative consequences of MP and NP production, some studies tested the degradation of face masks and wipes into microplastics and nanoplastics under different aging and environmental conditions [20–24,80–83]. They found concentrations varying from 2.6×10^3 to 6.0×10^9 items per face mask [16], including polypropylene (PP) and polyethylene terephthalate (PET) microplastics with different colors. Comparing the types of face mask, the middle melt-blown layer of surgical face masks discharges a greater quantity of MPs and NPs than the outer and inner layers [20,21]. Hence, the amount of microplastics produced by these face masks is higher than in the case of nonwoven examples. In addition, some studies showed that the use of face masks and wipes comprises new routes for the exposure of humans to plastic particles. Thus, the use of face masks for a prolonged time produces MPs and NPs that can be inhaled. A study reported 2.6 ± 0.4–10.6 ± 2.3 particles of microplastics in adults' nasal mucus secretion [21], and in the case of using wipes for hands, a concentration of 180–200 particles per sheet was reported [23].

Concerning harmful chemical and organic pollutant production, the use of antiviral and antibacterial barriers in face masks and dye compounds, as well as the enhancement of some fashionable properties, such as fragrances and colors, generate nanoparticles classified as emerging contaminants [4], which are expected to contribute to the release of potentially hazardous chemicals [3]. Heavy metals such as Pb, Cd, and Cu are commonly used as chemical additives during plastic manufacture [84], and they were identified by [80] in amounts ranging from 0.01 to 6.79, 0.01 to 1.92, and 0.85 to 4.17 g/L, respectively; Sb with levels ranging from 111 to 393 μg/L has been mainly associated with colored novelty face masks [80]. In the case of using antibacterial barriers based on Ag and Cu, they produce synthetic or engineered nanoparticles (ENPs). ENPs are particles whose sizes range between 1 and 100 μm and are made up of many atoms or molecules bonded with each other [15]. All these components have a long-term effect as a potential pollutant in water mass, with extreme danger for aquatic organisms [85,86]. Finally, evidence of added chemicals in the production of polymer-based face masks is only now emerging [80,87,88], indicating that they could also be a source of environmental chemical pollution [16].

Cloth masks manufactured with commercial synthetic textiles are washable and cost-effective and have improved environmental performance [45,46]. One study reported an 85% reduction in waste due to the use of these reusable masks, with a 3.39-times lower impact on climate change and being 3.7-times less expensive than disposable masks [89]. However, some criticalities, such as the use of fossil-based or impactful materials, as well as an open-loop end-of-life stage, have been identified; therefore, they cannot be considered sustainable [90]. Furthermore, because of the presence of fiber in their composition, they may also produce MPs during domestic washing, which are released into wastewater and later reach the surface water due to the inability of wastewater treatment plants (WWTPs) to remove them with current treatment technologies [4,16].

4.4.4. Effect on Wildlife

Plastics can have considerable direct or indirect negative effects on animals [91], which can be produced by both higher and smaller size fractions. Smaller-sized fractions of plastics or macroplastics (>5 mm) have significant negative effects on wildlife via ingestion and entanglement, limiting feeding ability and mobility [92,93]. The ingestion of plastic debris by birds, even of relatively low quantities, affects their morphometrics and levels of uric acid, cholesterol, and amylase [94], as well as their reproduction, due to chemical body burdens [95]. The immobilization of animals by plastic litter results in their death by suffocation, drowning, or strangulation. It also produces infections or causes amputations, possibly even causing the animal to stop eating to the point of starvation [92,96].

As with other sources of plastic pollution, both masks and gloves pose a risk of entanglement, entrapment, and ingestion. In fact, several cases of wildlife species entangled in disposable face masks [91], including seagulls, peregrine falcons, and hedgehogs, among others, as well as the death of an adult Magellanic penguin because of the ingestion of an FFP2 face mask [97], have been reported.

In addition to ingestion and entanglement, the negative effects of face masks or other PPE are still unexplored.Finally, the use of PPE for the construction of common coot nests has been reported in The Netherlands [91], which could compromise both the nutritional requirements and development of the chicks [98], such as their reproductive success, because of its effect on the thermal and drainage properties of the nests [99].

5. Conclusions

Research trends in the management of used COVID-19 personal protective equipment (PPE) have been analyzed since the outbreak of the pandemic in 2020. The high levels of PPE waste production, especially for face masks, have been the result of their huge demand by the public as a way to reduce disease transmission. This has translated into an exponential increase in the number of scientific documents in this research field; however, this field has not yet reached maturity because of its novelty, resulting in a low number of transversals to other scientific fields. Moreover, we identified highly developed and isolated themes with a high level of coherence in our study.

Although countries such as India, China, and Canada lead the rankings and leading journals are included in environmental and engineering categories, a low concentration of documents per source, country, and author was observed. The production and poor management practices of COVID-19 PPE waste, especially face masks, contribute to greenhouse gas emissions and produce considerable environmental problems, chiefly in aquatic media, where face masks of different compositions, including antiviral and antibacterial barriers, produce macroplastics, microplastics, and nanoplastics, resulting in potentially hazardous chemical pollution, which is contrary to environmental sustainability and the objectives included in international agreements, as well as regional and national policies. The popularity of this topic in the research field is clear from the keyword clusters, as well as the predominance of the motors and emerging themes related to plastics and environmental effects and to disease and its transmission.

As a consequence, and in accordance with the hierarchy in waste management, it is necessary to reduce PPE waste, applying reusing, recycling, and valorization alternatives to landfill disposal. In this sense, innovations in ecodesign are needed for the re-use of PPE, as well as the development of easily washable and disinfectable material, in addition to new green materials for their production that make waste recycling easier according to the EPR principle; however, it is also necessary to educate the population to reduce their contributions to PPE waste and improve separate collections at the source. Both action lines could be materialized in the creation of a collective EPR system for PPE to contribute to their sustainable production and consumption. These well-implemented strategies will contribute to maintaining progress towards achieving Sustainable Development Goals 3, 6, 8, 12, and 13, which relate to good health and well-being, clean water and sanitation, decent work and economic growth, responsible consumption and production, and climate action, respectively.

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