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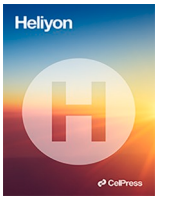

Review article

Unveiling the data: An analysis of plastic waste with emphasis on the countries of the E^{3}UDRES^2 alliance

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A B S T R A C T

This paper offers an examination of the current plastic waste landscape, with emphasis on the nine countries of the European University Alliance E^{3}UDRES^2, based on both the literature and official numbers, to verify the alignment of practical waste management practices with scientific tendencies and advancements. The paper includes a bibliometric analysis focusing on the overall plastic waste literature and the plastic waste literature of the E^{3}UDRES^2 countries. Additionally, a mass balance was calculated regarding the domestic waste management of each of the alliance countries in 2021. The main goal is to assess how scientific research in the field of plastic waste management is being implemented in practice, particularly in the context of the E^{3}UDRES^2 countries. Bibliometric results reveal significant growth in publications since 2006, with China, the USA, and India leading. Key themes reveal evident clusters around behavior and technology, encompassing both the properties of plastics and societal attitudes toward waste management policy measures. Mass balance results reveal that, in the nine countries of the alliance, Latvia and Finland exhibited high plastic recycling rates (85% and 49%, respectively), and Germany, despite its high population, generated less waste per capita and incinerated 64% of its plastic waste. Despite progress, the results highlight ongoing challenges in implementing comprehensive circular economy-focused policies for waste management in Europe yet reveal a growing commitment to improving waste treatment systems, leading to lower environmental impacts of plastic waste.

1. Introduction

Plastics are widely used in a wide array of applications due to their unique properties, such as light weight, durability, and low production costs. They are part of our daily lives, from the packaging used for storing food or drinks to the interiors of our vehicles. There has been a huge growth in the consumption and manufacture of these materials over the last few years which raises an important question: What happens to these plastics once they have reached the end of their useful life? Unfortunately, much of this plastic waste is either consigned to landfills or left untreated, which can be defined as improper disposal, as opposite to proper disposal, in which plastic is reused and recycled avoiding its accumulation in natural habitats. Plastic accumulation is due to its high durability [1], and happens substantially in rivers and oceans, causing a serious marine litter problem. The consequence of this is profound, encompassing contamination of groundwater and the ingestion of plastics by organisms. These phenomena have cascading effects that substantially harm both ecosystems and human health [2], enlightening the pressing need for robust waste management strategies and a collective shift towards sustainability.

Since most plastics used daily are short-lived products that are disposed of within a year of manufacture, adopting the circular

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economy model becomes extremely crucial to minimize the pollution and environmental impact of these materials. This economic model aims to reduce waste and optimize resource utilization by creating a closed loop. Within this system, products, raw materials, and resources are reused, repaired, refurbished, or recycled to extend their life cycle [3]. Such a shift not only alleviates pressure on the environment but also fosters sustainability, encouraging a more responsible and thoughtful approach to consumption and production.

By analyzing the data provided by Geyer et al. [4] regarding global production and plastic waste, we came across some concerning findings.

i. As of 2015, a staggering 6,300 million metric tons (Mt) of plastic waste had been generated worldwide. Out of this total, approximately 9% was recycled, 12% was incinerated, and a concerning 79% either ended up in landfills or the natural environment.
ii. If the current trends in production and waste management persist, it is estimated that by 2050, around 12,000 Mt of plastic waste will accumulate in landfills or the natural environment.
iii. By the end of 2015, the cumulative plastic waste generated from primary plastics (i.e., plastics made from raw materials that have not been processed or recycled before) had reached 5,800 Mt.
iv. Alarmingly, approximately 4,900 Mt, which accounts for 60% of all plastics ever produced, were improperly discarded, and are now accumulating in landfills or the natural environment.

Improper disposal of post-consumer plastics often leads to their presence in various bodies of water. Plastics found in water bodies are categorized as *human-made waste materials*, resulting from human activities, and are regarded as persistent pollutants [5]. Plastics enter marine environments through several pathways, including transportation via rivers and the atmosphere, littering on beaches, and direct introduction through aquaculture, shipping, and fishing practices. Inadequate waste management practices are the primary contributor to plastic accumulation in oceans. Land-based sources account for 80% of plastic debris found in the marine environment, particularly in densely populated areas and/or near industrial regions. The remaining 20% of plastic debris is attributed to ocean-based sources [6]. Most plastic debris encountered in water comprises packaging materials and household items [7]. Marine ecosystems exhibit the presence of plastic debris in various environments, including water columns, shorelines, seabeds, and the sea surface.

Waste management is a crucial component of implementing the circular economy, playing a vital role in a sustainable future. It encompasses the collection, transportation, processing, and disposal of waste, all conducted in an environmentally responsible manner.

The Waste Framework Directive (WFD) published on November 19, 2008 through the Directive 2008/98/EC of the European Parliament and of the Council of European Union, regulated waste management through landfilling limitation and innovative waste collection and recycling [8], using a strategy that focuses on a hierarchy of management options. In this hierarchy, reduction is the most desirable option, followed by reuse, recycling, recovery, and finally disposal as the least desirable option.

Zhang et al. [9] suggest a different hierarchy where energy recovery follows reduction, reuse, and recycling, while incineration without energy recovery and landfilling are the least desirable options. Note that, depending on the process employed, incineration of one ton of post-consumer plastic waste can produce 1–4 tons of carbon dioxide, while its recovery and recycling generates new plastic products, which corresponds to 10% of the total carbon dioxide otherwise burned from virgin naphtha [10]. This strategic advantage has led to an improvement in the percentage of recycled plastic waste [11,12] through the combination of the more usual mechanical recycling with chemical recycling. Currently, these hierarchical schemes are becoming more rigorous, with reduction being preceded by refusal, and the right to repair emerging as a part of them. However, the problem of plastic waste cannot be seen only by the issue of emissions, since large amounts of microplastics are formed by mechanical recycling, and during the recycling process there is degradation of the polymers, so recycling itself is also limited, with a solution to the problem of plastic waste, but it undoubtedly constitutes a good contribution.

Another important milestone of the WFD was setting out the minimum requirements for extended producer responsibility schemes by extending manufacturers' responsibilities for their products throughout their life cycle, including disposal.

By integrating circular economy principles into waste management practices [13,14], the amount of waste that is landfilled [15], and the quantity of natural resources used can be reduced [16]. This strategy not only offers benefits for the environment but also generates economic opportunities, such as employment creation, increasing the efficiency of resources [17], and energy production [18], being perfectly framed within the Sustainable Development Goals of the United Nations [19]. Nonetheless, the generation of economic opportunities cannot be regarded as the sole motive for change. If so, many problems may be generated. For instance, it is known that employment opportunities arising from the processing of plastic waste often involve vulnerable communities and pose serious health risks. It is also known that plastic waste is exported from rich countries to economically vulnerable countries. This way, environmental justice, human rights protection, and anti-waste-colonialism are perspectives that must transpire in regulations of waste-related economics. Governments, businesses, and people play an essential role in transitioning to a paradigm of development and well-being that can be applied to the entire Earth.

In effective terms, the countries of the European Union have committed, in the scope of the European Green Deal, through one of its building blocks, the Circular Economy Action Plan, to accelerate the transition to a circular economic model. This way, the European Commission has presented a package of proposals that aim to make sustainable products the norm in the union.

From a sectoral point of view, although there are other solutions, bio-based polymers are already used in a wide range of sectors, from construction and coatings to medicine and electronics, thanks to their biocompatibility and carbon neutrality. However, high production costs and limited yields, which prevent them from being mass-produced, prevent them from entering the market and becoming mainstream [20]. Also, the incorporation of plastic waste into other materials has received a great deal of interest due to its

ability to give this waste a second life. For example, the use of plastic waste in the construction and paving of roads is an exploring alternative. However, this method is limited by the compatibility between the plastic waste and the asphalt, as the different types of waste present different properties when they are incorporated into the asphalt [21]. Moreover, it is crucial to conduct further investigations into the potential risks of microplastics and chemicals associated with this method.

This paper provides an understanding of the current state of plastic waste management, using literature data and governmental data. For that, in the first stage, a bibliometric analysis of 23,299 articles available in the Web of Science Core Collection was carried out. Bibliometric analysis is a powerful tool to provide an overview and synthesize results of a given subject, theme, or field of study using quantitative methods of analysis of the available literature including trends, information on authors, sources, citations, and journals among others. This analysis allows the evaluation of scientific production using the publications data as well as the relationships between them through patterns such as the co-occurrence network that allows an evaluation and visualization of the relationship between the keywords used by the authors in the scientific publications [22].

Then, the bibliometric analysis focussed on the nine countries of the E^3UDRES^2 alliance. E^3UDRES^2, a European University Alliance, is a collaborative network of higher education institutions spanning nine countries: Austria, Belgium, Finland, Germany, Hungary, Latvia, the Netherlands, Portugal, and Romania.

Finally, a search was carried out in statistical databases or other sources of the countries under analysis and a mass balance was established to calculate values that are not available, to determine the alignment of scientific advancements with practical waste management practices.

2. Methodology

The bibliometric analysis was performed using performance analysis and science mapping [23]. Performance analysis techniques were used to identify the most productive and influential countries, authors, and journals and scientific mapping was carried out to identify the relationships between the keywords most used by authors, highlighting two clusters then explored in more detail.

Data was retrieved from the Web of Science Core Collection database. The query performed considered the following keywords: "TS=plastic* and (TS=reu* or TS=recycle or TS=reduce or TS=landfill or TS=incinerate* or TS=burn* or TS=energy) and (TS=waste or TS=garbage or TS=resid*)" which resulted in the selection of 23,299 documents on June 4, 2023. The search resulted in most articles (18,845), followed by proceedings articles (3,289) and review articles (1,742) among other document types such as book chapters (21).

These data were exported in batches of 500 in .txt files to be converted into a zip file for further analysis using the R-tool called Bibliometrix, which provides a reliable analysis of the information obtained [24]. Biblioshiny is built on top of Bibliometrix, providing a more accessible web interface way to utilize Bibliometrix capabilities without needing to delve into programming in R.

Using the collected data, a multifaceted analysis was conducted to explore several aspects of the subject: the chronological evolution of publications, the country's leading in both the number of publications and citations, the predominant journals that frequently publish articles on this topic, the standout articles that have been most cited, the authors who have made significant contributions, and the development and interconnectedness of keywords through a co-occurrence network.

Following the broad bibliometric analysis, the attention shifted to the E^3UDRES^2 alliance,. In this part of the study, the number of articles about plastic waste for the member countries was analyzed. To achieve this, a target search methodology in the Web of Science, for each country using the term "TS=Country name." was carried out. This refined approach yielded a total of 321 relevant articles, which were studied. This was also individually done to each country of the alliance. Retrieved articles that did not involve plastic waste or were not related to the countries in question were erased from the bibliometric analysis.

An analysis of the final destinations of domestic plastic waste in each country of the alliance in 2021 was also conducted. For this purpose, information was gathered on the domestic waste management of each country – values of the quantities of urban plastic waste generated, recycled, incinerated, and landfilled. The sources of information were diverse. In fact, in some countries there are available waste management reports from different governmental institutions, in other cases the information is available in national statistical institutes or only reported to European databases such as Eurostat.

For the countries that did not have values for the year in analysis (i.e., 2021) or did not have information on the quantities of recycled plastic waste, presenting only values for recovered plastic waste including the amount incinerated, it was necessary to make some approximations based on the data available in Eurostat. Some data such as quantities or percentages were collected allowing to establish a mass balance for calculating the missing values.

3. Results and discussion

3.1. Bibliometric analysis of the plastic waste literature

The collected database from the Web of Science Core Collection has published articles dating back to 1967 on the plastic and elastic characteristics of polycrystals, although these were not considered as part of our research this article has not been considered. As such, the first article on the topic is from 1972 and is entitled "Potential for reuse of plastics recovered from solid waste" [25] which reveals for the first time an awareness that plastics have the potential to be recovered and recycled for another use. Even then, people were thinking about what to do with the solid plastic waste that still haunts us decades later.

Fig. 1 shows the evolution of published articles in this field in the last two decades (i.e., 1992–2022). It is visible that since 2006 there has been an exponential growth in the number of articles published related to the awareness of the population about the risks of

plastics in the oceans and the marine environment. On the other hand, the analysis revealed that 146 countries have contributed to the scientific knowledge about plastic waste.

Fig. 2 shows the top 10 countries that have made the greatest scientific contribution to this subject. Out of the 23,299 articles analyzed, 9,978 were from China (ca. 43%), which reveals a great concern for this problem on the part of one of the world's most influential and populous countries. Followed by the USA with 6,992 papers (ca. 30%) and India with 3,214 (ca. 14%). In the European Union, Italy stands out with 2,068 published articles (ca. 9%), followed by Germany with 2,053 (ca. 9%) and Spain with 1,641 (ca. 7%). The UK is one of the major contributors to this study with 2,217 publications (ca. 10%). The grey countries in the map represent which countries have no publications.

Table 1 indicates the countries ranked by total citations on plastics recycling and waste which agrees with what was presented in Fig. 3. At the top of the list is the USA with 88,544 citations, followed by China with 73,399, and the UK with 42,073. European Union countries appear in fourth place with Germany with 24,818 citations, followed by Italy in sixth place with 22,151 citations, and finally by Spain with 18,068 in eighth place on the list.

Table 1 shows that the country with the highest average article citations is the UK with an average of 44.80 citations per article. This value reveals a great interest in UK publications since it is the fourth country with more published articles and the third with more citations. Even with five times as many articles published and almost twice as many citations, China has an average of 17.40 citations per article. Despite having more citations, the USA is the second country in the world with more published articles in this field, which leads to an average number of citations per article of 31.10, which is still much higher than China.

Table 2 presents the top ten journals with the most published articles on plastics recycling and waste. The journal that publishes the most papers on this topic is Waste Management with a total number of articles of 617, a total number of citations of 26,836, and an h-index of 79. Next is the Journal of Cleaner Production with 485 published articles, 14,198 citations as well as an h-index of 59. Tenth on the list is the Journal of Hazardous Materials with 189 articles and 8,608 citations.

Waste Management became the leading journal in terms of the number of publications in 2008, having overtaken Resources Conservation and Recycling. Over the last 20 years, the top 10 most published journals have evolved similarly, increasing their scientific output over the years.

In Scopus, the h-index is not a static value; it is calculated in real-time based on a set of results every time it is queried. This index is based on the set of the scientist's most cited articles and the number of citations he or she has received in other publications. More recently, the index has been applied to the productivity and impact of an academic journal, as well as to a group of scientists, such as a department, a university, or a country.

In these ten journals, the year in which the first article on this subject was published can be verified. In 1991 the first article on plastics recycling and waste was published in the journal Resources Conservation and Recycling, entitled "Identifying and assessing targets of opportunity for plastics recycling" [26]. This article explores several possible scenarios concerning the evolution of plastic waste production as well as a projection of the percentage of each plastic in the environment in 2000. In this study, we can verify that, as predicted, waste from plastic products has increased dramatically, especially in packaging plastics, which currently continue to be a major part of the most marketed plastics and associated waste.

Meanwhile, the Journal of Cleaner Production published its first article on plastics recycling and waste by Ross and Evans [27] which explores a recycling and reuse strategy for plastic packaging to reduce the amount of landfilled waste. To deepen this research, the most cited papers were identified (Table 3). Outstanding among them is Geyer et al. [4] already cited in this same article, with 5,689 citations corresponding to about 813 citations per year. Then comes the article Barnes et al. [28] with 3,042 citations. Since this is an older article, this equals about 203 citations per year. At the last place in the top 10, is the article Hahladakis et al. [5] that has 1,301

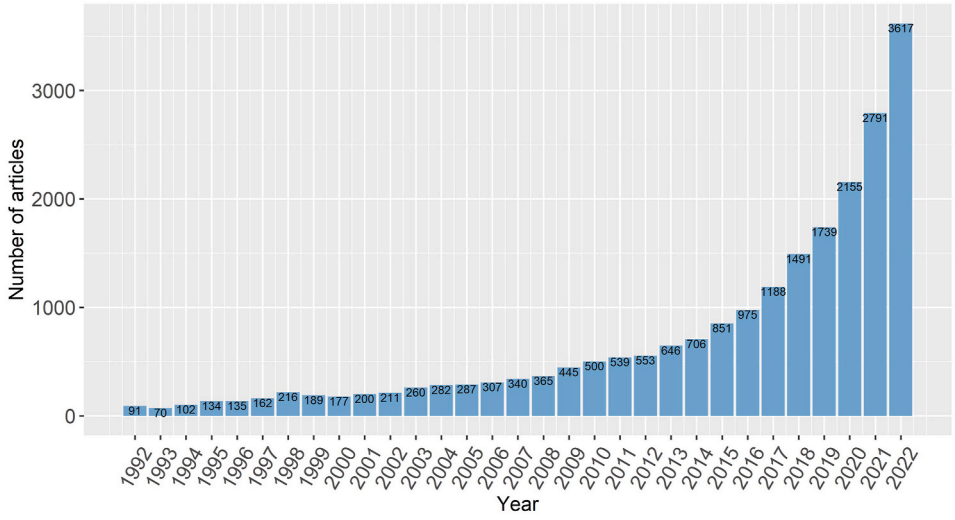

Fig. 1. Evolution of published articles on plastic waste management over 20 years.

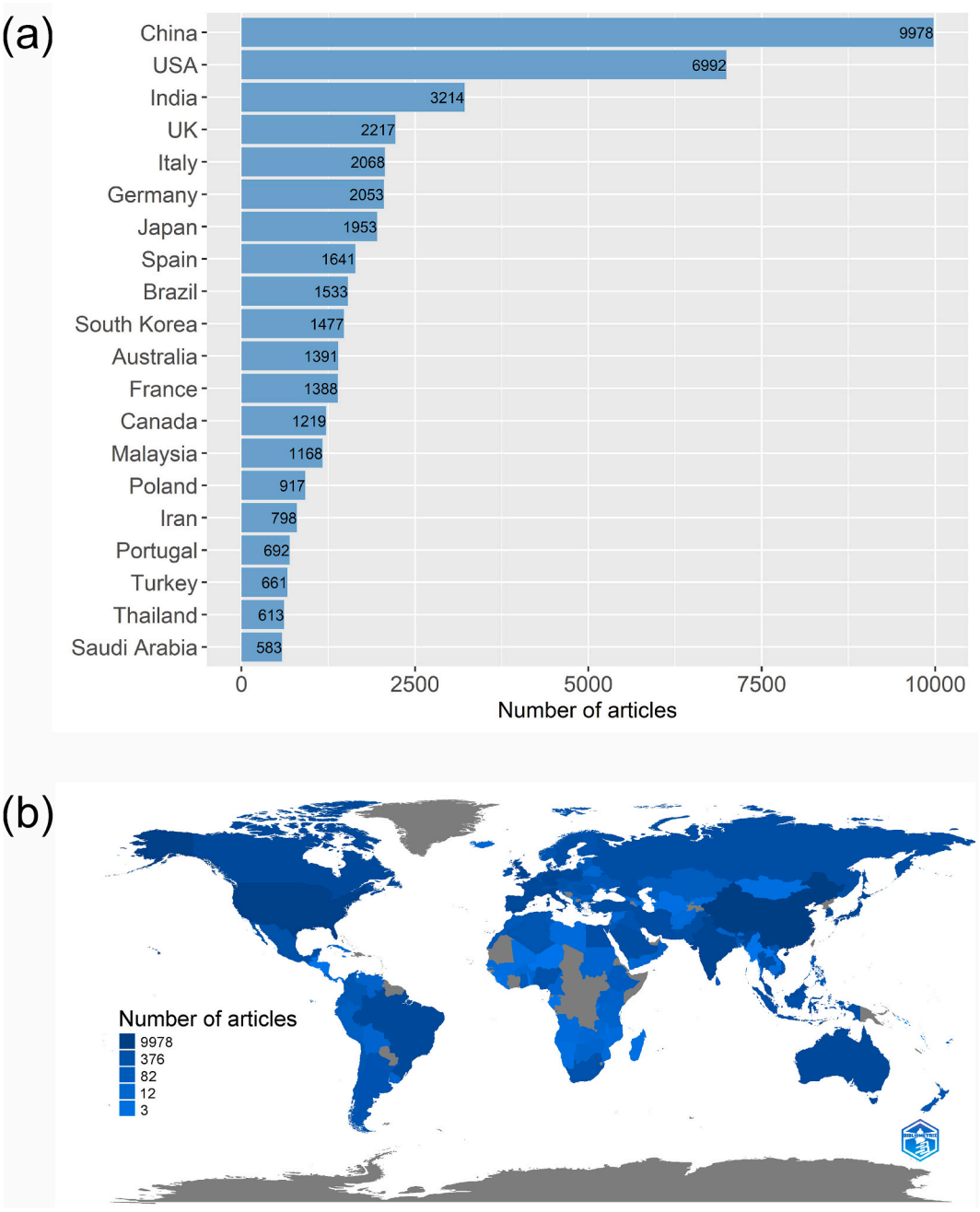

Fig. 2. (a) Top 20 countries with the most scientific productions on plastics. (b) Geographical distribution of the number of publications – dark blue color represents countries with a higher number of publications and grey color represents countries with no publications, with intermediate colors representing intermediate intervals. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

citations which translates to about 217 citations per year.

The most cited papers have great significance, serving as fundamental pillars of knowledge that summarise cutting-edge research and fundamental ideas, shaping intensely the trajectory of that field. These most cited papers also provide a valuable starting point for brand-new research, By fostering collective understanding and driving progress within the subject area, these highly cited papers play a vital role in promoting innovation and academic development, in particular on the production, use, and destination of used plastic, such as the most cited [4], and the consequences of the use of plastic by the pollution caused by plastic fragments [28], and the transport of plastic waste into the environment [32], and the presence of chemical additives in plastics and their consequences for the environment [36], as well as the concern for the biological degradation of plastics [35], and biofilms [30,34]. Table 4 shows the most

Table 1
Most referenced countries in the plastic waste management survey.

Country	Total citations	Average article citations
USA	88,544	31.10
China	73,399	17.40
UK	42,073	44.80
Germany	24,818	29.00
India	24,497	16.20
Italy	22,151	23.90
Japan	18,253	21.50
Spain	18,068	25.80
Canada	14,602	28.30
Australia	14,452	24.60

Fig. 3. Top 50 most used keywords in plastic waste management.

Table 2
Top 10 journals with the most articles published on plastic waste management.

No	Source	Papers	Total citations	H-index	Year of the first published article	JCR quartile
1	Waste Management	617	26.836	79	1994	Q1
2	Journal of Cleaner Production	485	14.198	59	2003	Q1
3	Resources Conservation and Recycling	329	13.986	65	1991	Q1
4	Polymers	320	3.172	26	2014	Q1
5	Construction and Building Materials	318	10.186	52	1996	Q1
6	Science of the Total Environment	307	13.922	57	1995	Q1
7	Sustainability	296	2.650	25	2012	Q2
8	Materials	209	2.120	25	2014	Q2
9	Waste Management & Research	194	3.251	30	1994	Q2
10	Journal of Hazardous Materials	189	8.608	45	1992	Q1

cited authors on the topic under analysis.

The significance of the most cited articles within a particular field cannot be overstated. These articles serve as foundational pillars of knowledge, embodying influential research and critical insights that have indelibly shaped the discipline. They not only lay the groundwork for subsequent studies but also serve as guiding beacons for researchers, offering valuable references and facilitating the exploration of new frontiers. By advancing collective understanding and propelling progress within the subject area, these highly cited articles play a vital role in fostering innovation and scholarly development.

In the educational and intellectual field, the cited authors are of unparalleled importance. Their contributions constitute an enduring legacy that enriches and guides the improvement of expertise in a wide variety of fields. Their theories, discoveries and insights serve as critical references for researchers. They also provide a valuable starting point for brand-new investigations. In addition, by virtue of being widely known, these authors establish a reputation for excellence and authenticity within the discipline and influence the way in which other researchers approach and contribute to the field. Table 4 shows the most cited authors on the subject under review.

In addition, the authors with the highest number of published articles on this topic and their nationality were identified (Table 5).

It should be noted that all these authors are part of the same research group that publishes in EFSA Journal and almost all the papers are published in collaboration, which explains the low value of the fractional papers, i.e., the individual contribution of each author. It can be verified that all authors are countries from the European Union and the overwhelming majority are from Italy and Germany.

In this part of the analysis, the evolution of this topic by analyzing the keywords used by the authors can be outlined. These

Table 3
Most cited articles on plastic waste management.

Paper Title	Year	Source	Reference	Total Citations	TC per Year
Production, use, and fate of all plastics ever made	2017	Science Advances	[4]	5,689	812.71
Accumulation and fragmentation of plastic debris in global environments	2009	The Royal Society B: Biological Series	[28]	3,042	202.80
Nitric oxide synthases: regulation and function	2012	European Heart Journal	[29]	2,435	202.92
Biofibres, biodegradable polymers and biocomposites: An overview	2000	Macromolecular Materials and Engineering	[30]	2,269	94.40
Phosphorus flame retardants: Properties. Production, environmental occurrence, toxicity and analysis	2012	Chemosphere	[31]	1,782	148.50
Transport and release of chemicals from plastics to the environment and to wildlife	2009	The Royal Society B: Biological Series	[32]	1,603	106.87
Our plastic age	2009	Philosophical Transactions of The Royal Society B	[33]	1,532	102.13
Sustainable polymers from renewable resources	2016	Nature	[34]	1,472	184.00
Biological degradation of plastics: A comprehensive review	2008	Biotechnology Advances	[35]	1,340	83.75
An overview of chemical additives present in plastics: Migration, release, fate and environmental impact during their use, disposal and recycling	2018	Journal of Hazardous Materials	[36]	1,301	216.83

Table 4
Top 10 most cited authors on plastic waste management.

Author	Total citations	H-index
Williams P.T.	3143	31
Wang H.	1625	23
Li J.	1412	21
Liu Y.	1267	21
Tang T.	1146	21
Sahajwalla V.	1000	20
Yoshioka T.	1178	20
Zhang H.	1409	20
Wu.C.F.	1363	19
Arena U.	1304	18

Table 5
Top 10 authors with the most published articles on plastic waste management.

Author	Nationality	Articles	Articles (fractionalized)
Milana MR.	Italy	151	7.14
Bolognesi C.	Italy	148	6.69
Grob K.	Switzerland	148	6.69
Tlustos C.	Italy	148	6.69
Zorn H.	Germany	148	6.69
Pocas MDT.	Germany	143	6.46
Lampi E.	Italy	135	6.10
Dudler V.	Switzerland	133	5.91
Papaspyrides C.	Germany	131	5.82
Riviere G	France	123	5.51

keywords can be found in the title, abstract, and keywords of the papers. Research on the significance and characteristics of keywords has focused on different methodologies and algorithms; the use of keywords by authors and publishers; the use of keywords in tagging in behaviors (metatags); and the comparison with titles, abstracts, and texts. Among the 23,299 articles exported from WoS, there were a total of 43,401 keywords used by the authors. Fig. 3 shows the fifty most used keywords, where we can identify the most frequent ones by font size.

As mentioned by Liu et al. [37], on average, each article registers five keywords and, therefore it is possible to conclude that keywords represent an important source of access to scientific articles. Highlighting the importance of keywords in the representation and retrieval of information is a way to promote general study reports and to stimulate the complete filling of the metadata of the deposited documents. This contributes to greater visibility, more probabilities of citation, and a consequent increase in the impact of the scientific production of the depositing authors and the institution itself.

Fig. 4 shows the evolution of the top 10 keywords over the years. Some keywords like behavior, waste, plastics, and pyrolysis have increased dramatically over the last 10 years. The keyword behavior is the keyword with the most occurrences with a total of 1,702 appearances which reveals a great concern about the behavior that people have regarding the use of plastics and its waste

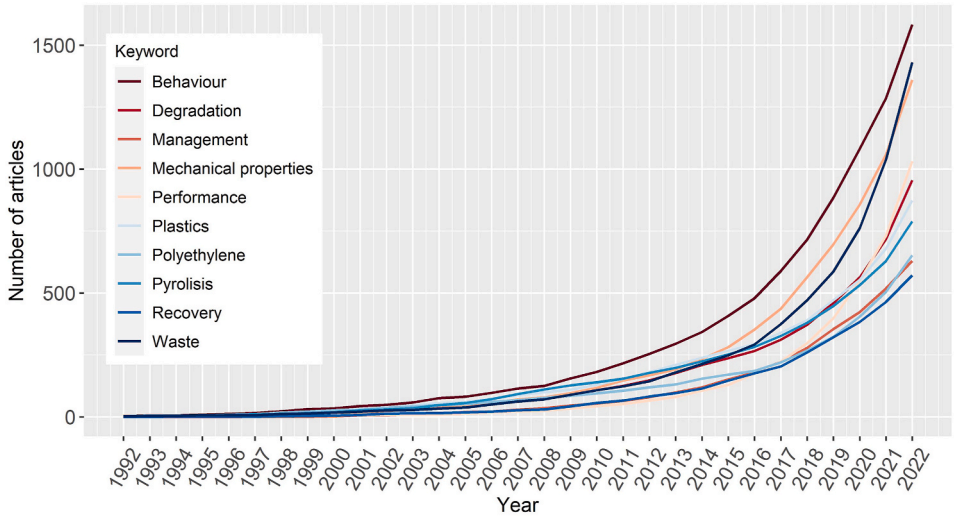

Fig. 4. Evolution of the top 10 keywords over 20 years.

management. The accumulation of plastic waste at an alarming rate highlights the pressing necessity for collaborative actions to tackle this pervasive issue, by fostering awareness, establishing efficient waste management systems, advocating for circular economy principles, and fostering innovation. We can strive towards reducing plastic waste generation and forging a sustainable future. Given this situation, the keyword waste appears as the second most used by the authors, with 1,578 occurrences.

Co-occurrence networks allow visualizing and analyzing the relationships between different terms or concepts in a specific domain of study. This helps researchers identify patterns, trends, and connections between ideas, allowing for a more comprehensive understanding of existing knowledge. By analyzing a co-occurrence network, it is possible to identify terms or concepts that are strongly related to each other but may not be directly linked in the scientific literature. This can lead to the discovery of new associations or knowledge, leading to the generation of new research hypotheses that help review the scientific literature by providing a visual representation of the relationships between the searched terms. This helps researchers identify key terms related to a particular subject, making it easier to select relevant studies and understand the conceptual interconnection. It is also possible to identify groups or communities of terms that represent specific topics or themes in a scientific domain. Which identify emerging topics, growing research areas, or gaps in existing knowledge.

The co-occurrence network concerning the search conducted is presented in Fig. 5 where we can observe not only the most used keywords but also the interconnection between them. We can identify two clusters in this figure, one related to behavior and the other related to residue. The behavior is strongly linked to the mechanical properties associated with plastic recycling, which when incorporated cause the properties of the final material to differ. Here the word behavior has a double meaning – it can be understood as human behavior and the awareness of the population for the problem of the persistence of plastics in the environment and it can be associated with the mechanical behavior that these compounds possess due to the incorporation of plastics. The word performance found in this figure also refers to the function and efficiency of these materials.

The word residue is connected to the word plastic since they are plastic residues, and to the word degradation as this is the big problem of this material, its difficult degradation. We can also see more interconnections such as the word pyrolysis, a technique

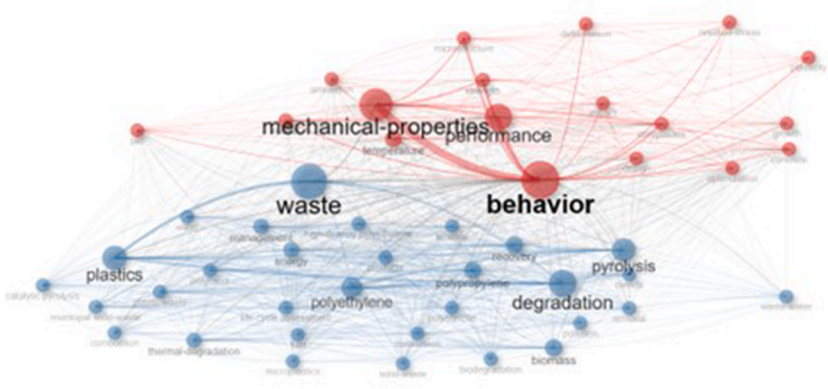

Fig. 5. Co-occurrence network.

widely used to degrade plastic, and the word polyethylene (PE) for being one of the most commercialized polymers and most found either in waste treatment plants or in the seas and oceans, on land and even in certain organisms. It is commonly known as the polymer used to make plastic bags, packaging, films, containers, and other products. Other types of polymers can be identified in this cluster, such as polypropylene (PP), polystyrene (PS), and high-density polyethylene (HDPE), which is a variant of common polyethylene that is widely recyclable, making it a more sustainable option compared to plastics that are difficult to recycle. Recycling HDPE allows us to reduce dependence on virgin raw materials, save energy, and minimize the amount of plastic waste that ends up in landfills or in the environment.

3.2. Bibliometric analysis of the plastic waste literature in the E^3UDRES^2 alliance

In order to focus this research on the E^3UDRES^2 countries, the articles on the topic of plastic recycling and waste were exported, restricting the research to the countries in question. Altogether, 321 articles on this subject were found for the nine member countries. The country with the most published articles is Germany with a total of 135 papers, followed by the Netherlands with 43 articles, and Portugal with 40 papers. Fig. 6 shows the total scientific production of articles on this topic.

The E^3UDRES^2 member country that published the first article on plastics recycling was Belgium in 1991 in the agricultural journal by the Ministry of Agriculture of Brussels. Portugal only published the first paper on recycling and plastic waste management in the paper Carvalho et al. [38] that explores the viability of separating PET from PVC since these two polymers have similar physical and chemical properties when flotation.

Fig. 7 shows the Three-Field Plot for the collected articles. This is a feature in Bibliometrix with a powerful visual representation that effectively combines three essential dimensions: cited references, authors, and keywords. By presenting a holistic view of bibliometric data, this visualization empowers researchers and decision-makers to gauge the academic contribution of authors or institutions, detect potential research collaborations, and make informed strategic decisions to foster innovative research and scientific collaborations.

3.3. Behavioral and technical main themes in the E^3UDRES^2 alliance literature

Within this research, we were able to find two main themes: one related to the behavior of individuals when confronted with this topic and another regarding technological studies conducted to improve the valorization of plastic waste or to characterize plastic components incorporated in equipment. In this section, the word behavior means exclusively this.

Fig. 8 presents the percentages that each theme represents in the research on plastic waste for each country. We can observe that the technical theme is much more explored than the behavioral aspect, with some countries having more than 90% of the technical articles, i.e., concerning recycling processes or studies of the mechanical and chemical performance of these wastes. The topic of the behavior of citizens, companies, and countries has been gaining more interest over the last few years, more specifically since the plastic carrier bag tax was implemented.

By reviewing the articles, we can verify that there are some comparative articles between the European Union countries including the E^3UDRES^2 alliance countries.

In Guiné et al. [39] a questionnaire on food-related waste, namely packaging, was conducted in 13 countries including Hungary, Portugal, Latvia, and Romania. It was concluded that most respondents prefer food that has been produced and packaged more sustainably but do not want to get rid of packaging and seek more sustainable alternatives such as biodegradable films.

Picuno et al. [40] make a comparison of the factors shaping the recycling systems for plastic packaging waste between Austria, Germany, and the Netherlands. In this paper it has shown that the recycling economies of these three countries are very similar,

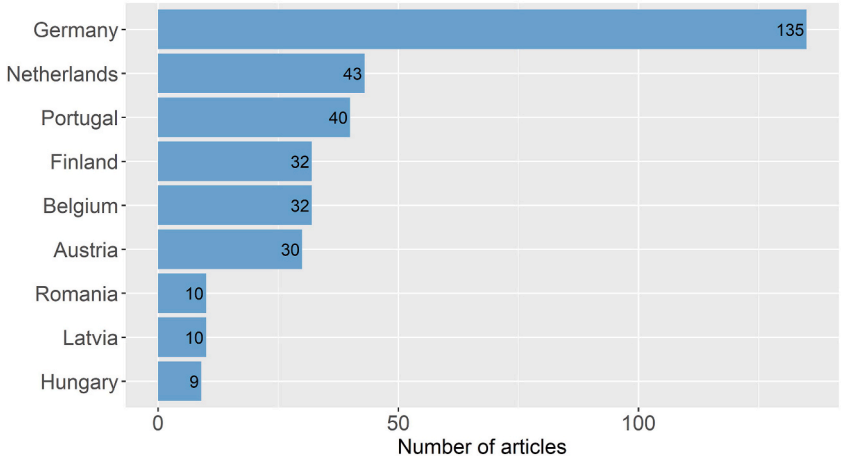

Fig. 6. Number of articles on plastics waste management in each country of the E^3UDRES^2 European University Alliance.

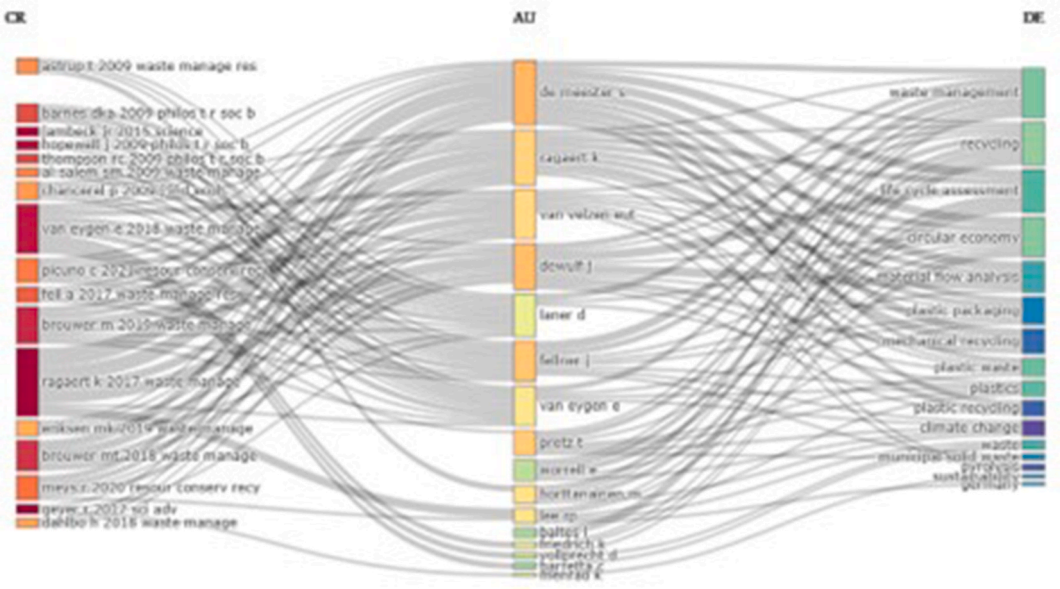

Fig. 7. Three-field plot for the collected articles.

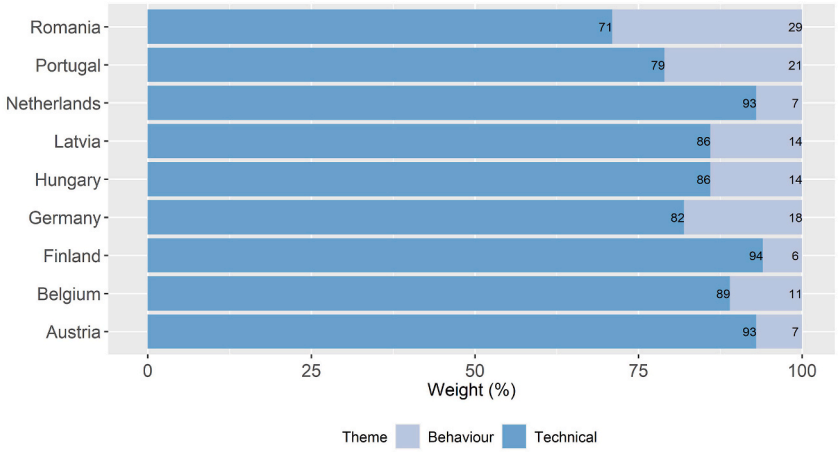

Fig. 8. Weight of each theme in the survey on plastic waste management for each E^3UDRES^2 country.

differing slightly regarding the recycling rates and quality of the recycled plastics obtained. The difference observed results from the waste collection options and the recycling targets of each country. However, none of these economies represents a circular economy as none can impose the necessary policy interventions for recycling that keep stakeholders aligned. It is also noted that to achieve this circularity, it is necessary to improve the scientific understanding of the packaging recycling system and to develop policies capable of supporting packaging that is designed to recycle.

In Jacobsen et al. [41] the key factors that determine municipal differences in the collection and sorting of household plastic waste in Flanders, Belgium, were analyzed. In this paper it is concluded that the separation system performed at the source has a higher acceptance by the citizens, causing more plastics to be separated at the drop-off facilities. This region has the potential to collect more plastics in recycling parks to reduce the amount of household waste but to achieve this, it would be necessary to change the plastic separation regimes of some municipalities, which may be a politically sensitive decision.

Mayanti and Helo [42] explore the potential supply chains for agricultural plastic waste by conducting an economic and environmental analysis of the recycling of baled packaging waste in Finland. The article presents two scenarios, which main difference is the route of the vehicles collecting the baled packaging waste. Results show that the waste collection phase has low environmental impact in both scenarios, being however a very important factor in the economic evaluation, since 32–36% of the total operation cost is related to it.

In Hermanns et al. [43] a completely transparent life-cycle assessment of the treatment of 1 kg of sorted mixed plastic waste using

two processes: (1) pyrolysis with caustic soda or lime, and (2) incineration with energy recovery, was conducted Considering future scenarios, results point out that global warming impacts of pyrolysis will reduce as time goes by, while those of incineration with energy recovery will increase. This publication also contributes to simpler and more informed decision-making for the circular economy transition.

In the specific case of Portugal, the technological theme is the most published on this subject, about 27 of the 34 articles found are on this topic, which translates into a percentage of approximately 79%. From this subtheme, several articles stand out for their quality. Prata et al. [44] explore the plastic waste produced and managed in Portugal over 5 years and compare the Portuguese situation to the European Union. This article also explores the trade market in imports and exports of this type of waste as well as the environmental impact of the treatment of these residues on the environment.

Hermoso-Orzáez [45] demonstrates the technical feasibility and economic profitability of gasification of industrial plastic waste, especially electrical and electronic, mixed with biomass from agriculture for energy production. The best results from an energetic, technical, and economic perspective were obtained for a mixture of 10% plastics with 90% olive biomass.

Larimi et al. [46] report on the latest progress and trends for hydrogen production including pyrolysis of hydrocarbon materials, such as waste plastics. This process has the additional advantages of mitigating environmental pollution caused by these waste streams and the possibility of producing value-added by-products. The conclusions drawn from this study may guide further developments in microwave-reactive catalysts to produce hydrogen from plastics and other hydrocarbons.

Lopes et al. [47] demonstrated that the highest concentrations of marine plastics are in the North of Portugal. Centre, and Lisbon region, mostly from consumer products, fishing gear, and microplastics. Due to these high concentrations, Portuguese citizens can consume up to 1,440 microplastics per year derived from the consumption of mollusks.

In the subtheme of behavior, there are 7 articles related to the recycling of plastics. In general, these papers reflect on consumer behaviors when confronted with fee increases related to plastic use, incentives to recycle, and even the inefficiency of recycling systems.

Almeida et al. [48] explore the consumption behavior of seafood and its packaging in three countries of the European Union: Portugal, Spain, and Ireland. The study showed that the percentage of recycling of these packages is relatively high in the three countries and that consumers were more willing to pay more for seafood products with less packaging.

Martinho et al. [49] evaluated the effect of the plastic carrier bag tax applied in Portugal in 2015 on consumer behavior. This study found that, after 4 months, there was a 74% reduction in the use of plastic carrier bags while a 61% increase in the consumption of reusable plastic bags. These results are obtained not only due to the raising of awareness of the population on this problem but also due to supermarkets and hypermarkets that have offered a more environmentally friendly solution to lightweight plastic bags.

3.4. Analysis of the final destinations of domestic plastic waste in each country of the E^3UDRES^2 alliance

Going beyond the existing scientific literature, the authors embarked on a quest to uncover the final destinations of plastic waste. This exploration is a crucial first step towards carrying out a comprehensive assessment of its environmental consequences and is of fundamental significance in driving forward the principles of a circular economy. The motivation for this research came from a previous study centered on the concept of circular economy, in which the authors wanted to elucidate the waste management strategies implemented in E^3UDRES^2 countries [50].

With this in mind, in-depth research of data from the aforementioned countries was undertaken; using the data of domestic plastic waste generated, recycled, and/or incinerated, it was possible to calculate the remaining values to close the mass balance. As they were taken from different databases, there may be some differences in the actual values, however, we were able to establish a relationship between the values presented and the reality experienced in each country. Table 6 shows the quantities and percentages of plastic waste generated and how each country disposes of this waste for the year 2021. These results were obtained through an extensive analysis of official statistics and relevant literature and were triangulated to ensure the accuracy and reliability of the information presented.

Germany is the country that produces the most plastic waste, however, due to its large population, the amount of plastic generated per capita is not the highest. Latvia, the least populated country in this study (about 1.88 million inhabitants in 2021) is the country that produces the most plastic waste per capita, with a value of about 57.2 kg per capita, three times higher than Germany's value of 18.5 kg per capita.

Romania stands out in this table for being the country that produces the least waste per capita with a value of 16.5 kg per inhabitant, a value below Portugal's, which produces, on average, 52.1 kg per inhabitant, in a relatively small country, resulting in a total of 538,067 tons of domestic plastic waste generated.

Regarding the destination of this waste, we can highlight Latvia as the country that recycles most of this waste, having recycled 85.4% of the waste that entered treatment plants in 2021, followed by Finland with 49.1%, Belgium with 39.0%, and by Germany with 35.0%. In terms of incineration for energy recovery, Germany stands out, where 64.4% of plastic waste is burned to supply energy to the national grid. The data concerning the incineration of plastics in Austria is confidential and, as such, there are no data on this destination.

In Portugal 63.9% of this waste is landfilled without any kind of recovery, followed by Hungary with 49.0% and Austria with 39.0%. Germany, on the other hand, due to its recycling practices and its awareness of waste generation, is the country, in this alliance, that least disposes of this waste in landfills, with only about 9,240 tons being sent to landfills, corresponding to 0.6% of the plastic waste generated in the country.

In the specific case of Portugal, some explanations for the high plastic waste landfill rate may be factors like the appropriateness of

Table 6
Domestic plastic waste by destination in 2021 for the E^{3}UDRES^2 alliance countries.

Country	Domestic plastic waste generated		Recycled Amount			Incinerated Amount		Landfill Amount	
	Total (1000 ton)	kg/per capita[a]	1000 ton	%	kg/per capita[a]	1000 ton	%	1000 ton	%
Austria	432.38 [b]	48.28	109.39	25.3 [c]	12.21	154.36	35.7 [c]	168.63	39.0
Belgium	366.42 [d]	31.61	142.90	39.0 [e]	12.33	216.18	59.0 [e]	7.33	2.0 [e]
Germany	1539.50 [f]	18.50	538.83	35.0	6.48	991.44	64.4 [g]	9.24	0.6 [g]
Hungary	207.14 [h]	21.33	62.72	30.3 [i]	6.46	42.92	20.7	101.50	49.0 [h]
Latvia	107.72 [j]	57.18	92.03 [j]	85.4	48.85	4.57	4.2	11.12 [j]	10.3
Netherlands	301.95 [k]	17.22	90.77 [k]	30.1	5.18	173.85 [k]	57.6	37.33 [k]	12.4
Portugal	538.07 [l]	52.09	84.75	15.8 [l]	8.20	109.13 [l]	20.3	344.19 [l]	64.0
Finland	101.80 [m]	18.37	50.02 [m]	49.1	9.03	51.28 [m]	50.4	0.50 [m]	0.5
Romania	314.61 [b]	16.45	94.54	30.1 [n]	4.94	111.44 [n]	35.4	108.63	34.5

Remaining values were calculated.

[a] Per capita values were calculated considering the population of each country in 2021 as reported by EuroStat [TPS00001].

[b] EuroStat. Global Indicators Database [ENV_WASGEN].Available on: Statistics | Eurostat (europa.eu).

[c] Waste Management World Magazine. Austria is a model country for recycling (2023). Available on: Austria is a model country for recycling | WMW (waste-management-world.com).

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the design of the plastic waste container to receive the separated plastic waste, or the waste treatment domestic fee that is indiscriminately applied to citizens whether they separate waste or not. Moreover, this high plastic waste landfill rate is not in agreement with the rate of scientific articles published in Portugal about the issue. In fact, there seems to be a disconnection between research, society, and administration.

3.5. Recommendations

In general, waste management and circular economy appear as increasingly important strategies for addressing environmental challenges and promoting sustainable development. As we have seen, research and interest in these topics have grown exponentially in the last few years, indicating a shift in the recognition of their importance around the world. However, there is still a disconnection between research, society, and administration, especially in some of the analyzed countries. This way, comprehensive strategies for circular economy and waste management are needed to achieve meaningful development. Specifically, awareness actions and effective action plans should be implemented by public administration bodies, *i.e.*, municipalities and central governments, through the adoption of true environment-centered policies.

Specifically, the following recommendations are proposed to reduce plastic waste disposal.

1) **Promoting separation and recycling** – encouraging and incentivizing recycling practices, along with effective waste separation initiatives, can significantly reduce the environmental impact of waste. Public awareness campaigns can play a central role in fostering a culture of responsible waste disposal.
2) **Technological integration for waste utilization** – incorporating advanced technologies capable of utilizing various fractions of residues can enhance the efficiency of waste management processes. This includes innovative methods for processing different types of waste to extract valuable resources and reduce overall environmental impact.
3) **Enforcing rules and policies** –enforcing stringent rules and policies is crucial for upholding adherence to sustainable waste management practices. This entails establishing clear protocols for utilization of eco-friendly materials in product development, and waste disposal and recycling.

4) **Financial support for sustainable practices** – providing financial support and incentives for the adoption of sustainable practices is instrumental. This can involve subsidies, grants, or tax benefits for businesses and individuals who prioritize eco-friendly materials and sustainable production methods, specially bioplastics.
5) **Reducing consumption** – efforts to decrease overall consumption, particularly of single-use items, contribute significantly to waste reduction. Public awareness campaigns and regulatory measures can encourage a shift towards more sustainable and mindful consumption patterns.
6) **Imposing circular design principles** – integrate circular design principles into the development of plastic products. This involves considering the entire life cycle, from raw material extraction to end-of-life disposal, and designing products that can be easily recycled or reutilized, with special emphasis in bioplastics.

By implementing these (few) recommendations, we can pave the way for a sustainable future with a significant reduction in environmental impact.

4. Conclusions

This paper delves into the current state of plastic waste management, particularly within the nine countries of the European Educational University E^3UDRES^2, employing both academic literature and official statistics to determine the alignment of scientific advancements with practical waste management practices. The paper encompasses a bibliometric analysis of global plastic waste literature and the plastic waste literature about E^3UDRES^2 countries. Moreover, a mass balance was calculated for domestic waste management in each alliance country during 2021. The aim was to evaluate how scientific research in plastic waste management is being translated into practical applications, particularly within the E^3UDRES^2 context.

In the first part of the study, it was possible to identify the 20 countries with the most articles published on the subject (i.e., plastic waste), with China, the USA, and India standing out. As far as citations are concerned, the countries that stand out are the USA, China, and the United Kingdom. The journals that published the highest number of articles on recycling and plastic waste were *Waste Management, the Journal of Cleaner Production, and Recycling*. In the analysis of the top 10 authors with the highest number of publications, we have several members of the same research group, mostly of Italian and German nationality. Co-occurrence networks allowed us to identify two clusters and their interconnections: behavior and residue. The cluster related to behavior is the keyword most often used by the authors and is mostly related to the mechanical properties of plastics when recycled or incorporated into other materials. However, it can also have another meaning related to human behavior and public awareness of the problem of the persistence of these materials in the environment. The other waste-related cluster is strongly connected to the techniques for recycling and the degradation of plastic waste. It is also connected to the different types of polymers that are available, which have different techniques and properties when recycled. From the sustainability point of view, recycling plastic waste into new products is an important contribution to the circular economy as it reduces reliance on virgin raw materials and the associated environmental impacts of plastic disposal.

A total of 32 articles focusing on plastic waste management in the E^3UDRES^2 countries, provided valuable insight into sustainable practices within the alliance. Notably, Germany showcased a prominent presence with a total of 135 articles, followed by the Netherlands boasting 43 articles, and Portugal contributing 40 articles to the collection.

Concerning domestic waste management and final disposal, Latvia emerged as the top performer, with an impressive plastics recycling rate of nearly 85% by 2021. This is followed by Finland with a plastic recycling rate of 49%. In terms of plastic waste generation, Germany stands out, with an estimated 1,539 kt of plastic waste entering waste treatment facilities in 2021. Despite its large population, Germany's per capita waste generation remained comparatively low at 18.5 kg per person, with a significant proportion (64%) of these materials being subject to incineration.

In general, waste management and circular economy appear as increasingly important strategies for addressing environmental challenges and promoting sustainable development. As we have seen, research and interest in these topics have grown exponentially in the last few years, indicating a shift in the recognition of their importance around the world. However, there is still a disconnection between research, society, and administration, especially in some of the studied countries. This way, comprehensive strategies for circular economy and waste management are needed to achieve meaningful development. Specifically, awareness actions and effective action plans should be implemented by public administration organs, *i.e.*, municipalities and central governments, through the adoption of true environment-centered policies.

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Data availability statement

Data will be made available on request.

CRediT authorship contribution statement

Sara Soares: Writing – review & editing, Writing – original draft, Formal analysis. **Fátima Serralha:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Maria Catarina Paz:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Nelson Carriço:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Sergiu-Valentin Galatanu:** Methodology, Investigation, Conceptualization.

Declaration of competing interest

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

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