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A Review and Bibliometric Analysis of Sorting and Recycling of Plastic Wastes

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ABSTRACT

Global plastic pollution is a negative impact on the environment as the production and use of plastic are increasing rapidly. Plastic recycling is a significant step towards a circular economy. Over the decades, much plastic has been in circulation for various applications. Recycling plastic wastes (PW) entails waste sorting using some physical properties including plastic types, colors, and shapes, to produce high-quality recycled plastics. Classification of PWs includes common plastic types: Polyethylene terephthalate (PET), High-density polyethylene (HDPE), Polyvinyl chloride (PVC), Low-density polyethylene (LDPE), Polypropylene (PP), Polystyrene (PS), and others. The traditional method of sorting PW achieves good accuracy but low throughput at an excessive cost. Automated processes in plastic sorting are developed to overcome this. This study analyzes automated sorting techniques and examines bibliometric data on plastic waste research over the past four decades. The Scopus database was used to retrieve statistics on the subject, which were then examined using the bibliometric program in the VOSviewer software. The data visualization was also carried out with VOSviewer. The results of this study can guide future research and provide crucial details to improve plastic waste management.

1. INTRODUCTION

Since 1950, plastic production has continued to increase by million tonnes yearly from an initial volume of 2 million tonnes to 380 million tonnes presently. It is projected to double and almost quadruple by 2035 and 2050, respectively [1].

Plastics are made up of polymers with distinctive properties that make them moldable, making suitable substitutions for traditional materials like metals, wood, glass, etc. They are light, strong, hygienic, and impenetrable for liquids [2, 3]. As a result, almost 30% percent of plastics are used for long-term infrastructures such as pipes, and building materials, with the remaining 70 percent used for medium-life, durable consumer applications such as electronics, furniture, vehicles, and so on [4]. Plastics are broadly classified into seven major types (Plastic 1 – Plastic 7), namely, PET (polyethylene terephthalate), HDPE (high density polyethylene), PVC (polyvinyl chloride), LDPE (low density polyethylene), PP (polypropylene), PS (polystyrene), and others, mostly PC (polycarbonate). The various recycled products of each of the plastic is described as shown in Table 1.

Thermoplastics claim tremendous usage in non-plastic applications such as textile fibers and coatings (Table 1) and in commodity plastic applications such as packaging, which accounts for more than 80% of all PW [5].

Most household or packaging PWs end up in the municipality, the landfill, or sometimes incinerated [6]. Municipal PW can be separated from household waste before recycling. Mechanical separators are available to separate mixed polymers. However, the automated separation of mixed polymers aided with features for separation, including plastic types, colors, shapes, and density, making separation easy to classify separated plastic into different polymers for recycling, as reusable materials, or materials for energy recovery [7]. Studies show that a fundamental challenge of plastic packaging waste (PPW) recycling is that most PWs are not separated from other waste; instead, they are either deposited in landfills for incineration or left as waste to litter the earth [8].

Recycling plastic is still a novel work as part of the objectives of the Sustainable Development Goals (SDGs), and it has not been widely studied enough. As a result, it is imperative to research and improve the separation techniques of PW from mixed Municipal solid waste (MSW) to enhance the efficient recycling of PW. The main objective of this study is to review different PW sorting techniques and investigate the bibliometric analysis on the study.

This study reviews the separation technologies of several types of PW and presents a bibliometric investigation of PW sorting methods and recycling. There are many recent automated sorting methods to classify PWs from these co-mingled wastes. These techniques of PW separation could be collectively explored to ensure these wastes are maximally sorted for recycling. Therefore, this study would provide experts with immediate insight into the study of these technologies.

The application of Artificial intelligence (AI) has transformed all sectors of industries. The circular economy is not left out in this development as it is well influenced. AI models have recently attracted the attention of scientists who have also successfully tackled engineering problems [9]. However, since heuristic search methods are accessible, for critical and challenging issues that require a long calculation time [10], it is, therefore, necessary to employ these automated methods to create efficient techniques to solve problems in real-life applications. Recent advancement in many fields indicates that the application of AI is proffering better solutions to difficult challenges [11, 12].

Table 1. Recycled plastic and applications [13, 14]

Symbols	Plastic-type	Plastic code	Uses
1 PET/PETE	Plastic 1	PET	Packaging and detergent bottles, packaging films
2 HDPE	Plastic 2	HDPE	Pallets, toys, detergent bottles, automobile pasts
3 V/PVC	Plastic 3	PVC	Medical materials, food packaging, bottles
4 LDPE	Plastic 4	LDPE	Food packaging, bottles, tires
5 PP	Plastic 5	PP	Bins, recycling crates
6 PS/EPS	Plastic 6	PS	Disposable cutleries
7 OTHER	Plastic 7	Others	Buckets, containers

2. GENERAL OVERVIEW OF SORTING SYSTEMS

The recycling of PPW is an essential step toward meeting the EU Circular Economy and Green Deal goals of reducing dependence on fossil fuels, greenhouse gas (GHG) emissions, and environmental damage from littering through unregulated disposal routes [15].

Recycling of PPW starts with mechanical recycling by collecting waste from various sources of waste generation. The next crucial step in the recycling process of the waste treatment cascade after the waste arrives at the material recovery facility (MRF) is sorting the various PWs into types of plastics, i.e., PET, HDPE, PVC, LDPE, PP, PS, and others. The efficient use of sorted waste for recycling depends on proper sorting and separation techniques for the PPW. As a result, numerous sorting methods are used today in sorting plastics. Most sorting in this age of technological innovation is computerized, but manual sorting is also occasionally employed to check the accuracy of automated sorting [16-18].

Plastics are not all recycled in the same way. It relies on the additives found in such plastics, as well as the properties of the plastic itself. To make matters worse, limitations in collection and separation processes make it difficult to increase the amount of plastic waste that can be recycled. Different types of plastic waste are traditionally separated by hand. However, automated separation methods have been developed to promote high throughput of high purity polymers due to human error in the separation [19]. This method is based on material identification codes. It is essential to consider the identification codes, and consider the risk of human error [20]. Figure 1 maps out the sorting hierarchy.

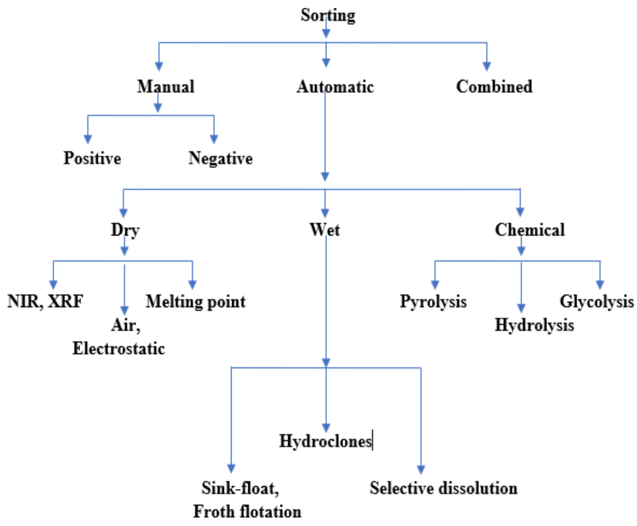

Figure 1. Plastic sorting techniques [21]

2.1 Sorting techniques

Although the automatic sorting technique is preferred to the manual sorting method due to its recovery rate in terms of productivity [22], it still depends on the manual process, and most sorting facilities incorporate the two methods [23].

Automated recycling of post-consumer plastic waste is a complex chain of activities involving three important steps [15, 24, 25]. The first step is the collection of plastic waste from households or the recovery of plastic waste from MSW, this is followed by sorting of the waste, and lastly, mechanical recycling to produce pellets [26]. The primary goal of plastic waste sorting is to produce high-purity polymers by eliminating unwanted pollutants like metals, glass, etc. from plastic waste [17].

Plastics need to be classified into categories for recycling, reuse, or reduction, which is difficult to do with human labor. For this purpose, the classification of plastic waste with automated processes is suggested. In addition to metals, organic waste, plastics, paper and glass, waste must be separated into many types. Because few of the components in each category are now suitable for reuse, advanced techniques should be used to identify the material types for each category. It can sort into the categories PET, PP, PS, PVC, HDPE, LDPE, and others and can be used in a sorting plant or in private households [27].

Plastic waste sorting is a very essential step in various waste management techniques. This includes sizing, either manually or with screens [28]. Manual sorting is appropriate when there are large quantities of plastic components, but it is a labor-intensive process. The manual sorting method can achieve good accuracy but at the cost of throughput.

It is therefore desirable to have a model for identifying plastic waste so that recycling may be done effectively. Because mixing up one form of recycled plastic with another might lead to processing issues, it is imperative to separate various plastics according to type [28, 29].

Consequently nowadays, separating plastic waste involves using varieties of automatic technologies (computer-assisted) which are majorly employed in the sorting processes of plastic waste [16]. With this aid, sorted plastic wastes are classified into recyclable plastics, reusable plastics, or plastic waste for energy recovery using digital image processing technology [17]. Depending on the features of the feed and the quality standards for the output products, e.g., single polymer stream or combined polymer stream, the technique (or combination of technologies) is selected [17].

The following are the common sorting technologies along with their drawbacks [16, 17, 30]:

1. Gravity sorting
2. Electrostatic sorting
3. Magnetic density sorting
4. Sink-float sorting
5. Optical sorting
6. Chemical sorting techniques

2.2 Air classifier

Air sorting of plastic waste is practically achieved by cutting bigger waste into flakes between 0.55-1.25cm. The flakes are injected into the air classifier where they are forced to fall against an ascending column of air. The air stream allows denser materials to be blown up while heavier material like glass powder, paper, and plastic foil drops into a float. The sorting of post-consumer plastic packaging materials is represented in a simplified production flow chart in Figure 2. The air sorting technique takes into consideration variables like material weight and the structure of the materials. Sorting PET bottles with an HDPE cap allows the PET particles to float while the cap material sinks [17]. Plastic is also sorted from heavier materials such as copper, stones, and ferrous metals in the separation process involving gravity, where gravity and vibration are used to move the coarse fraction for further sorting [31].

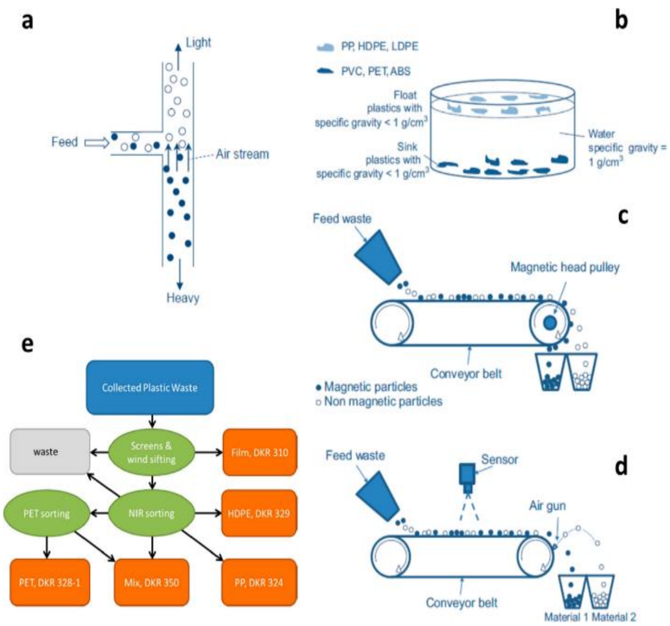

Figure 2. Prototype sorting technologies [28]

Table 2. Densities of various plastic types [32]

Plastic-type	Density (g/cm³)
PET	1.35-1.38
HDPE	0.94-0.96
PVC	1.32-1.42
LDPE	0.91-0.93
PP	0.90-0.92
PS	1.03-1.06

Table 2 presents the specific gravities of different plastic polymers. The separation of plastics using gravity separation techniques depends solely on the density of plastics and other heavier materials [33]. The gravity sorting technique comprises the dry and wet, which include air sorting, sink-float sorting, jigging, and hydro-cloning [34].

2.3 Ballistic sorter

Ballistic sorting allows a stream of material to be split into a stream of three-dimensional (3D) solid objects and a stream of flat, flexible (2D) objects [26]. Plastic waste sizes are usually found in the range of 5-30cm fractions or more. The flat, flexible cardboard, paper, and plastic film are supposed to carry over the paddles to the front of the machine while using the ballistic sorters or air classifier. The machine effectively sorts fine fractions through a range of screen hole sizes. The larger fractions are selected using the manual sorting of large 2D plastic films. High sorting efficiency is made possible by changing the range of the angle of inclination and the length of the sorting paddles [17].

Ballistic sorting allows a stream of material to be split into a stream of three-dimensional (3D) solid objects and a stream of flat, flexible (2D) objects [35].

2.4 Sink-float sorting

This sorting technique is also referred to as float-sink separation; it is a straightforward density-based sorting method [36]. It is the most popular technique for sorting shredded flakes, typically using water as the flotation medium, with several unique properties of the flotation technique being linked to the specific plastic properties such as density and surface energy [37] as described in Figure 2b. One disadvantage of sink-float tanks is low throughput [21].

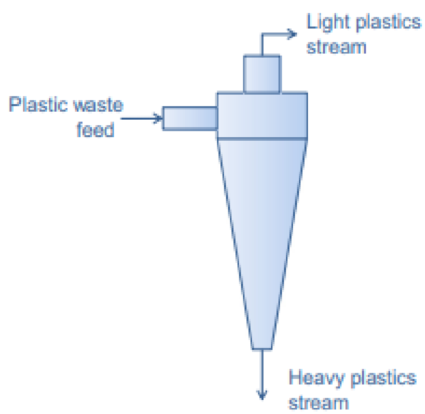

Figure 3. A plastic hydrocyclone sorter [17]

2.5 Hydrocyclone

Hydrocloning is a sorting technology commonly used to increase the efficiency of density separations in terms of throughput and purity. Typically, sludge is fed to the cyclone. A selected solid-to-liquid ratio and operating pressure are used. As a result, the internal fluid motion of the device rotates because of fluid pressure transfer, allowing for the separation of the different materials. Before sorting with a hydro cyclone, the materials must be sufficiently crushed. Thereafter, the feed suspension enters the hydro cyclones through a tangential opening in their conical and connected cylindrical bodies. A hydro cyclone converts the energy of the fluid pressure into a rotational motion of the fluid. The cyclone transports lighter fractions up and heavier fractions down [17, 30]. Hydrocloning sorting is illustrated as shown in Figure 3.

2.6 Jigging

Mechanical sorting of plastic involves a new technique called a hybrid jig. This is a combination of jigging and flotation, introducing air bubbles into the particle bed during jigging to change the apparent specific gravity by sticking the particles, allowing the sorting of particles with different surface properties even when their specific gravities are similar [38, 39].

2.7 Electrostatic sorting technique

Another sorting method is the electrostatic charging of different plastics. With this technique, the plastic parts are separated based on the fluctuations in their electrostatic charge [40]. Materials are sorted and collected according to their triboelectric charge by allowing them to fall freely through an electric field created between two parallel sets of electrodes with opposite charges [30]. When plastic waste particles of different qualities rub against each other, their electrical charges are transferred. As a result, surfaces are subsequently affected by different electric charges, allowing separation within an electric field that also contains charged electrodes. Typically, the triboelectric effect is used to charge plastic particles [17, 36] as illustrated in Figure 4.

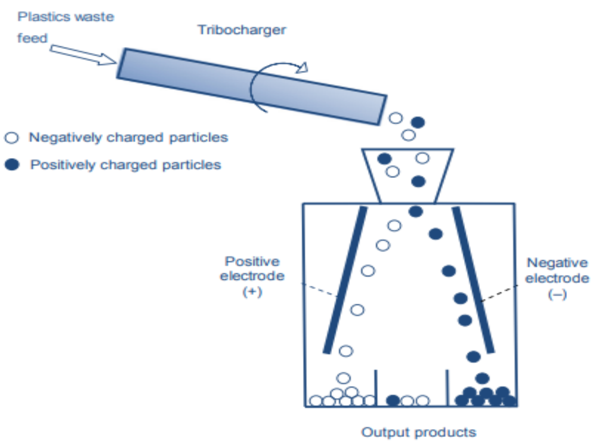

Figure 4. An illustration of a triboelectric sorting process [17]

For various polymers, this separation can be used successfully after the triboelectric charging sequence [17]. A framework for how a binary mixture can be separated electrostatically is established when its components acquire charges of opposite polarity. A triboelectric charging sequence serves as a polarity indicator. In one of the reported triboelectric charging sequences, ABS stands for acrylonitrile butadiene styrene, PP stands for polypropylene, PC stands for polycarbonate and PTFE stands for polytetrafluoroethylene [41]:

(+ end) ABS – PP – PC – PET – PS – PE – PVC – PTFE (– end)

Rubbing two plastics together in this order makes the plastic closer to the positive pole become positively charged and the plastic closer to the negative pole becomes negatively charged. For instance, rubbing PVC against PET makes PET to be positively charged and PVC negatively charged. On the other hand, when PET rubs against PP, PET is charged positively and PP negatively [17].

The problem associated with this technique is that falling particles fall with gravity which is not controllable. Also, particles containing additives and dirt alter particle surface charging [30].

2.8 Magnetic density sorting

A development in density-based technology known as magnetic density sorting (MSD) uses a magnetic liquid as the separation medium in a blend of different polymers. The magnetic fluid used consists of water (i.e., a liquid) and magnetic particles, particularly iron oxide particles between 10 and 20 nm, suspended in the fluid. The unique magnetic field creates artificial gravity, like a magnetic force. Both the density of the liquid and this magnetic force change exponentially in the vertical direction. The discarded plastic particles, therefore, float in the liquid at a level where their effective density is equal to their specific gravity. Separation is possible between plastic particles with small changes in density, such as rubber, PVC, PE, and PP [16]. The schematics of an MDS are given in Figure 5.

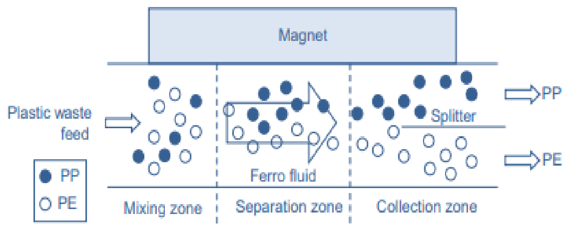

Figure 5. Scheme of a magnetic density sorting technique for PP and PE [17]

Specific care should be taken to ensure that the following basic steps are correctly completed: (1) wetting, (2) feeding, sorting, and collecting to prevent flow turbulence from affecting particle flow within the magnetic fluid before, during, and after separation [16, 17].

2.9 Optical sorting

Sorting plastic into different polymer types is often achieved by using the physical sorting-enabling properties of certain materials/polymers. Spectroscopy and x-ray technology can be used to sort plastics by resin [42, 43]. Separation often takes place in handling architectures that are built and developed to improve the behavior of waste particles concerning the chosen property to perform the separation. Figure 6 illustrates the scheme of a sensor-based technique in sorting. As previously mentioned, this behavior is typically achieved by changes in the particle trajectory at the device exit(s) and/or by concentration in different parts of the sorting device. As a result of the mechanical sorting of these various streams, concentrates, wastes, and occasionally one or more classes of intermediate compositional products known as "middlings" are produced. Therefore, material physical characteristics might be viewed as the "direct" cause of separation [17, 23].

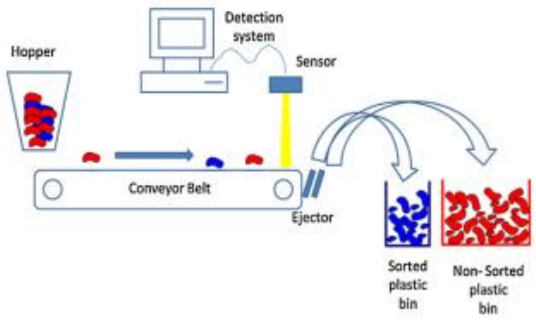

Figure 6. Schematic of an optical sorting technique [44]

Sensor-based sorting methods can be broadly categorized based on sensing and collection of materials illustration is shown in Figure 6. Materials are first subjected to the chosen sensing standard, perform material identification, and then based on that, collection of desired items from the waste stream under investigation is carried out. An effective sensor-based sorter is made up of three important components comprising the conveyor belt to feed in the materials, a computer-aided sensor identifying and examining the material for selection, and an air-pressured system to artificially sort the materials [17].

2.10 Fourier-transform near-infrared (FT-NIR)

Sorting of mixed rigid recyclables is done using an automated sorting technique that is widely used by operators of material recovery plants and by many polymers recycling plants [4]. Probably the most used technology in plastics recycling is near-infrared spectroscopy (NIR). Its basis is a collection of polymer spectra correctly activated by light to reflect their full spectrum [44]. The sorting mechanism primarily consists of a feeding hopper, a conveyor belt, a detection system, an optical sensor, and an ejector (separation section) as shown in Figure 6. The high-definition near-infrared (NIR) technology intends to separate different materials in the wavelength range of 700–2500 nm.

Near-infrared sensors concurrently distinguish many polymers (PET, HDPE, LDPE, PP, PS, PVC, PC, ABS, PVC, etc.) because they each have a characteristic spectral signature in this wavelength range. To capture the spectral response of plastics (i.e., to analyze and identify them concerning previously established reference spectral collections of the different polymers), fiber optic architectures can be used extensively in NIR. This allows very flexible architectures to be defined. Additionally, a major limitation is its inability to detect dark and black polymers because of their low surface reflection [17, 44].

2.11 X-ray fluorescence (XRF)

In X-ray fluorescence, in contrast to infrared spectroscopy, the characteristic properties result from the organic nature of the polymers rather than from a specific ion or element [44]. Infrared spectroscopy methods expose the unknown plastic to waves and study the response of the objects [30].

Although this approach is expected to be widely used to sort plastics in the future, it is currently most used to separate PVC from PET and to sort brominated plastic from a stream of shredded plastic feed [16, 17]. An innovative XRF-based technique called Energy Dispersive X-ray Fluorescence (EDXRF) was developed and actively adds tracers to the polymer matrix [45].

XRF can identify black and/or very dark polymers without the need for sample preparation or collection [46]. The inability of this technique is the ability to distinguish between polymers when sorting plastic. In addition, there are several safety limitations when using X-ray devices [17].

2.12 Hydrolysis, glycolysis, pyrolysis

Plastic can be chemically sorted so that polymer molecules can be converted back into unprocessed monomers [30]. PET is completely depolymerized into its monomers by hydrolysis when reacted with water in an acidic, alkaline, or neutral environment [47]. High temperatures (200–250℃), high pressures (1.4–2 MPa), and a lengthy depolymerization process are disadvantages of the hydrolysis process. Due to the high effort involved, this approach is often not used [7]. The depolymerization reaction for PET conversion at 50% is 35℃ for almost 5 years and complete depolymerization requires 72 years anywhere in the world [47]. Hydrolysis is used to classify post-consumer and industrial plastic waste containing cellulosic residues [30].

In the glycolytic sorting process, the long chains of long polymers are broken down into short chains of oligomers, which are then re-polymerized to form new polymers [48]. This technique does not result in complete depolymerization [49]. For instance, the glycolytic sorting of PET produces bis(hydroxyethyl) terephthalate (BHET), which is a substrate to produce PET and other oligomers, by inserting ethylene glycol into PET chains [7].

Pyrolysis is a traditional technology [28]. The chemical sorting of plastic using a chemical process describes pyrolysis as the process of disintegration of polymeric materials caused by heating without oxygen [7]. Between early and mature technologies, pyrolysis has attracted the most scientific attention among the processes for converting plastics into fuel or other value-added products. Pyrolysis can be a useful management tool that supports mechanical recycling [50]. This process produces HC1 which is neutralized or isolated for commercial use. If the plastic waste is properly pre-treated, the relatively low PVC/chlorine concentration of mixed plastic waste (from packaging) is acceptable for current chemical sorting processes. Not all plastics used in mixed plastic separation are susceptible to foreign materials such as PET or contaminants such as PVC [28, 30].

3. MATERIALS AND METHODS

3.1 Research methodology

Information on bibliometric analysis of research on a specific topic can be found by searching several scholarly databases [51] Bibliometric strategies have been employed by numerous researchers. Bibliometric analyzes typically focus on specific academics, research institutions, nations, and disciplines. As a basis for further quality improvement, it also shows its existing condition and development trend [52]. Depending on the research data used, bibliometrics can take different approaches, including citation analysis, co-citation analysis, bibliographic linking citation [53], and co-word analysis for keywords [54]. The bibliometric analysis provides insight into the temporal extent of literature and information transfer within a specific subject area by examining data collected in the database such as citations, authors, keywords, or the number of articles read [55]. Bibliometric techniques is used to extract the fundamental, cognitive, and social systems of a discipline. In addition, discussions on the various uses to find the most prolific authors, journals, and institutions, assess trends, and locate areas of study that shaped a particular topic [56, 57].

3.2 Data mining and search methodology

As one of the most renowned and comprehensive databases for bibliometric research, VOSviewer contains millions of scientific publications of varying quality and importance [58]. So, the VOSviewer baseline collection was searched for information on bibliometric analysis of research trends in plastics sorting and recycling. A bibliographic data acquisition using Scopus was conducted on 27 October 2022 to obtain the data inputs, by using the keywords ((“Plastic waste sorting techniques”) OR (“Plastic waste recycling”)). Reviews and articles were considered. TITLE-ABS-KEY (("Plastic waste sorting techniques") OR ("Plastic waste recycling")). The result of this query string was 196 documents.

Search results of the core topic were examined, and it was found that the source, author, affiliation, nation/territory, subject area, and type of document with no limit to the years of study. Total articles, CiteScore, total citations, and h-index are some bibliometric indicators used for ranking purposes. Figure 7 provides a clustering of data for analysis.

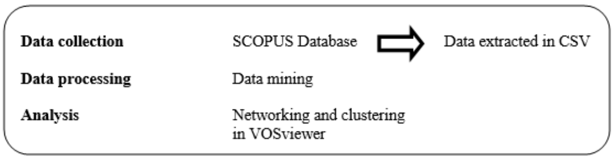

Figure 7. Summary of the research methodology

3.3 The bibliometric maps

VOSviewer (version 1.6.8, Center for Science and Technology Studies, Leiden University, The Netherlands), a bibliometric mapping and visualization tool, was used to import the author's citation, bibliography, and keywords from 208 articles. Objects produced by VOSviewer can be found on maps. The elements in this analysis are the focus objects and the author's country or keywords. Any pair of objects can be connected or associated, or there can be a link. All connections have a positive value for numbers, which serves as strength. A stronger relationship results from a higher value. The number of publications co-authored by two connected countries for co-authorship studies is indicated by the strength of the connection from country to country, while the cumulative degree of connection shows the overall strength of the connections a nation has with other nations for co-authorship. The number of publications in which two keywords appear in the co-occurrence study correlates with the strength of the authors' keyword relationship [59].

3.4 Analysis of co-occurrence and co-authorship

In the minimum keyword occurrences analysis with at least 2 in VOSviewer of the 2,091 keywords, 435 meet the threshold. Analysis of the normalization with associative strength for the chosen network visualization method used to show the yearly average publication, amount, and strength of associations between the keywords. A keyword's color corresponds to the year in which it typically occurs in a document. All 16 countries associated with 58 authors were included in the co-authorship analysis. The strength of the co-authorship links with other countries was calculated for each of the 16 countries under analysis. Also, countries with the maximum links were selected for the analysis. The network consists of five clusters based on citation relationships, and each cluster network is represented by a different color. The clusters were created by grouping related countries, and each cluster contains the significant countries that contributed to each co-authorship work, including the United States, United Kingdom, Belgium, China, Italy, Japan, Hong Kong, Pakistan, South Korea, Saudi Arabia, Spain, Malaysia, Indonesia, India, Germany, Netherlands.

4. RESULTS AND DISCUSSION

4.1 Relevant data information

A total of 208 research papers were released from the Scopus database during the year (Figure 8) [58]. Over some years until 2000, there was a random increase in publications on plastic waste sorting and recycling. After then, annual publications gradually increased, leading to a significant increase in the total number of articles generated. So, the annual release is expected to keep growing. The study of the subject area based on the keywords like recycling, plastic recycling, and plastic waste showed that studies focused mainly on (213 articles), (127 articles) in environmental science, and (54 articles) in engineering. However, plastic waste management is a multi-faceted field, one of which was flagged as falling under the category. According to the results, the publications included in this study were written in four different languages.

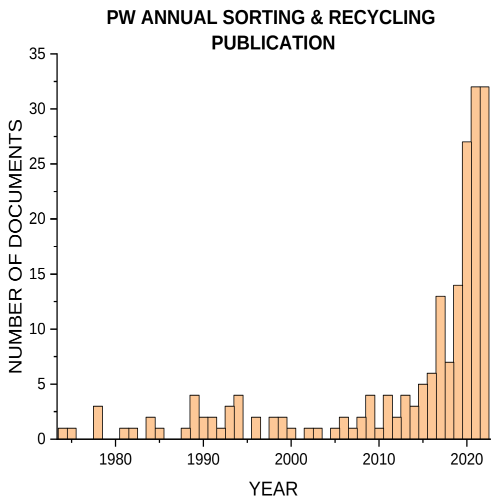

Figure 8. Cumulative research articles by year on plastic waste sorting and recycling in Scopus

4.2 Relevant articles

The study found that the top 10 most successful journals belong to six different publishers (Table 3). With a total of five of the 10 competing journals, Elsevier published the most articles. Elsevier is first in the publication hierarchy, followed by Springer Science and Business Media Deutschland GmbH and MDPI. John Wiley and Sons Inc. published a magazine. The most productive journal was the Iop Conference Series Earth and Environmental Science, which published 29,544 articles. Sustainability Switzerland came second with 14,052 articles, followed by Environmental Science and Pollution Research with 5,408 articles, Journal of Cleaner Production with 5,347 articles, and Construction and Building Materials with 5,347 articles (4,064 articles).

In the 2021 CiteScore report, five journals had CiteScores of 10 or more. Resources Conservation and Recycling (17.9) and Journal of Cleaner Production are the top two papers with the highest CiteScores (15.8). While the least ranked, 10th lowest is the Society of Plastics Engineers with 140,083 articles, the Annual Technical Conference - ANTEC, Conference Proceedings total citation, and CiteScore were remarkably low compared to other journals.

4.3 International institutions, leading countries, and leading organizations

The collaborative efforts of organizations including the Center for environmental remediation, institute of geographic sciences and natural resources research, Moe key laboratory of regional energy and environmental systems optimization, environmental research academy, north China electric power university, National institute for nutrition and health, Chinese center for disease control and prevention, state key laboratory of environmental criteria and risk assessment, Chinese research academy of environmental sciences all in China contributed in producing the strongest link strength with the maximum citations of 138.

In VOSviewer, the closer the two countries are, the stronger and greater their connection. Most countries are China, Pakistan, Malaysia, and Saudi Arabia. The co-authorship results showed that China was the country with the largest association, with 959 co-authorships associated with 16 countries/territories.

Table 3. The 10 prolific PW sorting techniques or recycling research journals are listed as the most cited articles.

No	Journal name	TP	TC	Cite Score 2021	The most cited article (reference)	Times Cited	Publisher
1	Resources Conservation and Recycling	657	34,543	17.9	A critical review of the impacts of COVID-19 on the global economy and ecosystems and opportunities for circular economy strategies	245	Elsevier B.V.
2	Environmental Science and Pollution Research	5,408	97,758	6.6	Renewable and non-renewable energy consumption, economic complexity, CO2 emissions, and ecological footprint in the USA: testing the EKC hypothesis with a structural break	140	Springer Science and Business Media Deutschland GmbH
3	Sustainability Switzerland	14,052	181,699	5.0	Plant growth promoting rhizobacteria (PGPR) as green bioinoculants: Recent developments, constraints, and prospects	137	MDPI
4	Chemsuschem	507	29,707	14.1	Sustainability Assessment of Mechanochemistry by Using the Twelve Principles of Green Chemistry	100	John Wiley and Sons Inc
5	Journal Of Cleaner Production	5,347	284,941	15.8	A review on conventional and novel materials towards heavy metal adsorption in wastewater treatment application	247	Elsevier Ltd
6	Waste Management	618	32,935	13.5	Global E-waste management: Can WEEE make a difference? A review of e-waste trends, legislation, contemporary issues, and future challenges	72	Elsevier Ltd
7	Iop Conference Series Earth and Environmental Science	29,544	45,063	0.6	Review on the correlation between mixing, microstructure, and strength of cementitious products with nanoparticles	89	IOP Publishing Ltd
8	Journal Of Analytical and Applied Pyrolysis	321	9,156	9.1	Biochar as a low-cost adsorbent for aqueous heavy metal removal: A review	108	Elsevier B.V.
9	Annual Technical Conference - ANTEC, Conference Proceedings	138	124	0.1	Comparative study of filled and unfilled polylactic acid produced via injection 10molding and 3d printing	4	Society of Plastics Engineers
10	Construction and Building Materials	4,064 4,064	140,083 140,083	10.6 10.6	Fly ash-based eco-friendly geopolymer concrete: A critical review of the long-term durability properties	110	Elsevier Ltd

TP: Total Publications; TC: Total Citation; PW: Plastic waste.

Table 4. List of top 15 authors in PW sorting techniques or recycling

No	Author	Author's Scopus ID	Year of 1st publication*	TP	h-index	TC	Current affiliation	Country
1	de Meester, Steven D	50461212600	2011*	99	28	2490	Universiteit Gent	Belgium
2	Kusenberg, Marvin	57219560266	2020*	14	6	129	Universiteit Gent	Belgium
3	Ragaert, Kim J	26031615400	2007**	76	22	2437	Universiteit Maastricht	Netherlands
4	Tang, Zhenwu	20436564500	2007*	77	22	2413	Minzu University of China	China
5	Van Geem, Kevin M	8386577200	2004*	356	45	7213	Universiteit Gent	Belgium
6	Chai, Miao	56800201100	2015***	10	6	345	Ltd, Jinan	China
7	Cheng, Jiali	55492692500	2009**	27	12	650	Chinese Center for Disease Control and Prevention	China
8	Djokic, Marko R	55331090400	2012*	49	14	832	Universiteit Gent	Belgium
9	Huang, Qifei	7403634859	2004**	191	30	3590	Chinese Research Academy of Environmental Sciences	China
10	Kresovic, Uros	57217418434	2020***	8	5	103	Indaver NV, Mechelen	Belgium
11	Mbohwa, Charles S	6603262827	2002*	595	24	2235	University of Johannesburg	South Africa
12	Mwanza, Bupe Getrude	56960643300	2015*	39	8	213	University of Zambia	Zambia
13	Nie, Zhiqiang	50162067400	2011*	51	22	1530	Chinese Research Academy of Environmental Sciences	China
14	Wang, Yuwen	56800169100	2015**	9	5	180	Jingmen Technical College	China
15	Wei, Ren	35604665100	2010*	52	26	2562	Universität Greifswald	Germany

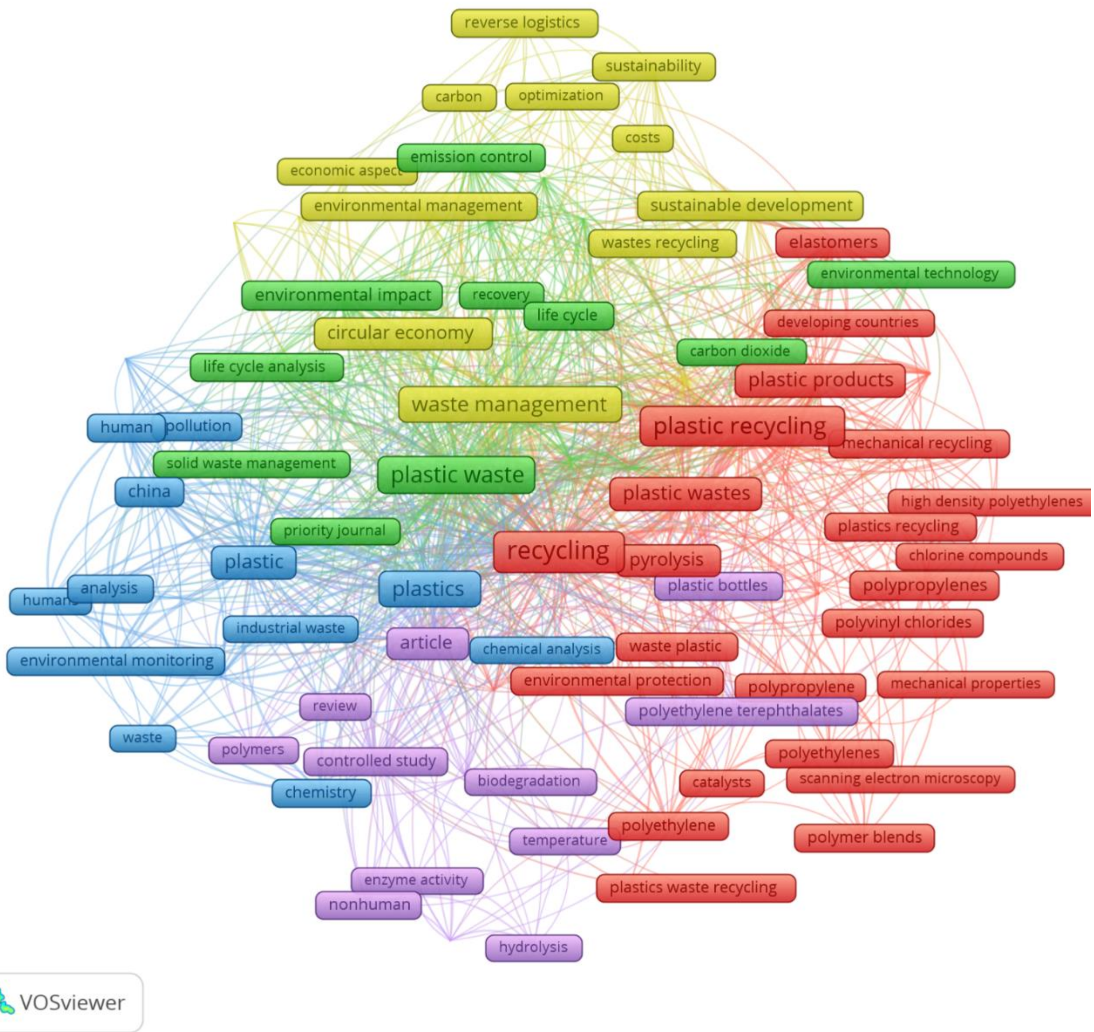

Figure 9. A screenshot of the bibliometric map created based on co-occurrence with network visualization

Pakistan followed the list (11 links), Malaysia, and Saudi Arabia with 10 links each and more. In addition, it was found that two-thirds of the countries listed had joint international publications for fewer than ten countries. However, for the publication of articles on PW sorting techniques and recycling, researchers in Italy, Japan, the Netherlands, and Indonesia were associated with fewer than 3 countries.

4.4 Leading authors

According to Table 4, the top 15 in the field of sorting and recycling plastic waste are as follows: China has the most authors with six, followed by Belgium (five), the Netherlands (one), South Africa (one), Germany (one), and Zambia (one). In the first publications, which appeared between 2000 and 2010, eight authors were involved as first authors, five as co-authors, and two as last authors. The order of authorship is not expressly regulated.

As of 2011, de Meester, Steven D the leading author records a total of 99 articles, a 28-hour index, and 2,490 citations. Kusenberg, Marvin and Ragaert, Kim J, top 2nd and 3rd authors are affiliated with Universiteit Gent and Universiteit Maastricht, respectively. African authors from the University of Johannesburg, South Africa ranked 11th (Mbohwa, Charles S) and 12th (Mwanza, Bupe Getrude) from the University of Zambia, while the 15th author (Wei, Ren) is from the University of Greifswald in Germany. The authors of the articles listed in Table 4 as the most cited articles may or may not be included in the author list of Table 4.

4.4.1 Author's keywords

Examining the patterns in the studies on recycling and developing PW sorting techniques and recycling. All keywords from the review articles were collected for the study, which involved two processes and the analysis of keywords and co-words. To show the connections between the keywords in each visualized co-word network, the first co-word networks were created in each sub-period. Second, the study identified keywords that appeared more than once in seven topics to better understand how research interests change over time.

A total of 532 author keywords were used. Since phrases of related species and similar terms were flagged, 15 keywords for VOSviewer mapping met the minimum threshold of 5 occurrences. The study found that event and 50 links to other terms in Figure 9 were the most frequently recognized keywords at 171, followed by PW sorting and recycling.

4.5 Limitations of the study

By limiting searches to titles and abstracts only, Plastic waste sorting technique and recycling may not have captured all articles on PW sorting and recycling that were available on Scopus. One suggestion to improve the performance of future studies is to compare data from many databases, including IEEE Xplore, Scopus, and Web of Science. The use of bibliometric analysis opens numerous sources of data that are conducive to further investigation. The database was limited to just 15 articles on sorting and recycling plastic waste. Future studies should include more scientific articles over a longer study period for improved universality. Also, the content of publications considered were not evaluated for its scientifically sound quality, instead, it merely visualized the research patterns on the topic.

To reproduce or recreate previous quantitative studies on PW sorting and recycling in an evolving research area, it is crucial to identify new problems and trends related to this research topic. However, the limitations of bibliometric investigation have the potential to shift the notion of clusters as the theoretical underpinning of PW sorting and recycling activities. Future research should create a creative classification system to examine work patterns and technological advances in more detail. Since only one VOSviewer application was used in this study, specialized bibliometric analysis tools could be used in the follow-up research.

5. CONCLUSIONS

This report, based on 196 publications from the Scopus database, provided a summary of advances in PW sorting methods and recycling studies. This field of study has seen significant growth in publishing since 2000 and this trend is expected to continue. We found that Asian nations have a lot of publications and solid international partnerships. (Such as Saudi Arabia, China, Pakistan, and Malaysia). To strengthen their research collaborations, these institutions could offer incentives to scientists from other nations (e.g., the United States). The study of pollution, environmental science, and garbage recycling are just a few of the topics we've covered. We also spoke to PW Management about a few recently researched topics, such as recycling and sorting methods, which could prove to be popular study topics in the future.

Recycling methods are becoming increasingly important for businesses to become circular and engage with waste management. It might be useful to consider the following for future work to support decision-making that takes both efficiency and sustainability into account [60].

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