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APPLICATION OF OPTIMIZATION TECHNIQUES IN THE RECYCLING SECTOR: A BIBLIOMETRIC ANALYSIS

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Abstract:

Optimization techniques are vital for improving the operations of collection and recycling processes, reduction of waste and enhancement of recoverable resources. Recycling plays a significant role and optimization processes are essential for improving recycling efficiency. In this sense, these techniques assist in planning the best collection route, sorting method and resource distribution by applying mathematical models and algorithms. In recycling, optimization can help to choose the methods of processing materials, energy consumption and cost reduction. This study aims to identify the development, trends and research gaps related to the application of optimization techniques in the recycling sector. A bibliometric analysis was performed on 499 Scopus-indexed documents that have been published from 1978 to 2024. The key bibliometric methods used include citation analysis, co-authorship analysis, network analysis and performance analysis. The analysis shows that optimization in the recycling documents was generated from engineering and environmental science research. Journal of Cleaner Production is the source with the highest number of publications and citations. The countries contributing the most to this body of literature are China, followed by the United States. This paper contributes to an understanding of the research landscape, key influential works and collaboration networks in the application of optimization techniques in recycling.

Keywords:

Optimization, Recycling, Environment, Bibliometric Analysis

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Introduction

Recycling industry is a sector that focuses on the collection, processing and conversion of waste materials into reusable products. This process involves several key steps, starting from sorting, cleaning and reprocessing the materials. The materials that are commonly recycled are plastics, metals, glass, paper and electronic waste. The primary goal of recycling is to reduce the amount of waste sent to landfills. This action would conserve natural resources and support a more sustainable, circular economy by reintroducing recycled materials into the production cycle. This ultimately helps in minimizing the environmental impact and saving energy.

Optimization techniques refer to operational research in solving a particular problem to identify the right solution for a given problem while considering different criteria. Particular forms of optimization approaches are linear optimization, integer optimization, nonlinear optimization and dynamic programming. Multi-objective optimization and metaheuristic algorithms like genetic algorithms and simulated annealing are more general methods that offer good solutions. Optimization techniques have been widely used hand-in-hand in optimizing the process related to the recycling industry. Several studies have been conducted in the field of recycling using modeling and optimization techniques. Gent et al. (2011) created a mathematical model to predict the quality of density media separations in plastic recycling based on particle size and density. Meyer et al. (2009) focused on recovering carbon fibers from composite waste, highlighting the potential for material reuse. Santander et al. (2020) developed a mixed integer linear programming model to assess a local closed-loop supply chain, demonstrating significant economic and environmental benefits through a university case study on recycling 3D printing waste. Additionally, Khoei et al. (2002) introduced a robust design method to improve quality and reduce costs in aluminium recycling. Wang et al. (2007a) utilized response surface methodology to optimize the coagulation-flocculation process and evaluating various factors to enhance the efficiency of wastewater treatment.

In recent years, Rosenberg et al., (2023) presents a dynamic reverse supply chain optimization model for end-of-life electric vehicle battery systems. They optimize network growth, reducing costs through economies of scale and improved logistics ultimately enhancing the efficiency of battery recycling processes by incorporating multi-period planning. Lithium-ion batteries are getting more usage and Wu et al., (2024) develop a physical recycling method integrating thermal treatment, mechanical separation and air separation to enhance lithium-ion battery recovery, with and the carbon footprint assessment. Waste management is another increasingly prominent field of research and practice, attracting significant attention due to its critical role in environmental sustainability and resource efficiency. Olawade et al., (2024) examines the role of AI in waste management by focusing on its applications in recycling activities, while highlighting optimization techniques for improving efficiency and sustainability. A two-stage stochastic model was developed by Xie et al. (2024) in optimizing the location and capacity of construction waste recycling centers with consideration of uncertainties in waste generation and recycled material demand in Guangzhou. Microplastics pollution in aquatic ecosystem remains an ongoing challenge. Aviso et al., (2023) introduces plastics recycling networks and develops linear programming and mixed-integer linear programming models to optimize waste plastic allocation to recycling plants with consideration of contamination tolerance and demonstrating their effectiveness in mitigating plastic pollution. These studies showcase the integration of optimization techniques in advancing recycling processes. Optimization helps to choose the methods of processing materials, energy consumption and cost reduction in the recycling sector.

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This study aims to identify the development, trends and research gaps related to the application of optimization techniques in the recycling sector. This bibliometric study is conducted to address the following research questions (RQs). RQ1. What is the current impact of publications on the application of optimization techniques in the recycling sector? RQ2. What publication trends can be identified in the application of optimization techniques in the recycling sector? RQ3. Which countries have significantly contributed to the application of optimization techniques in the recycling sector? RQ4. What is the nature of inter-country collaboration in the publications of the application of optimization techniques in the recycling sector?

Datasets and Methods

In this study, the dataset was downloaded from Scopus database on 1 September 2024. The search keyword is TITLE ("optimi*ation" AND "recycling"). All languages, source type and document type are considered. The search found 504 publications from 1978 to 2024. There are five Erratum documents that were later excluded, making 499 publications used for this purpose.

In this study, publishing trends were initially illustrated to provide an overview of the landscape. A method called citation analysis is used to identify the most influential publications based on total citations (TC). Further analysis was conducted on the total number of publications (TP), TC and TC/TP ratios for journals, as well as for countries and territories. Citation metrics, document types, languages and subject areas were examined using BiblioMagika (Ahmi, 2024). Data cleaning was performed with OpenRefine (Ahmi, 2023), which involved addressing missing data and ensuring consistency in author affiliations. Performance analysis is then performed to evaluate publication trends over time.

The authors and research hotspots associated with the field of optimization techniques applied to the recycling sector were examined through another method called co-authorship analysis. In this case, social networks were compiled by using VOSviewer, a software developed by Van Eck & Waltman. According to the methodology provided by Van Eck & Waltman (2010), the connection networks depicted in VOSviewer are based on distance and each network has numbers of nodes that are positioned in the two dimensions based on the visualization of similarities principle. Network analysis is a method used to visualize social networks and research hotspots, mapping relationships between countries. The circles symbolize the publication of a country where the size of that circle is proportional to co-occurrence or occurrence value. The distance between two nodes reflects the dissimilarity of the nodes, where a smaller distance suggests a high level of similarity between the nodes (Van Eck & Waltman, 2014). In addition to this, VOSviewer also enables the formation of clusters based on the proximity of the network nodes and nodes within these clusters. They are coloured differently for each cluster (Van Eck & Waltman, 2010). The findings of the study are elaborated in the next section of the paper.

Results and Discussion

Current State

A citation analysis was performed on 499 publications related to the application of optimization techniques in the recycling sector, sourced from the Scopus database, as shown in Table 1. The findings revealed that 77% of the total publications had been cited. Over a span of 46 years, these

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publications received a total of 7,583 citations globally. The h-index, which reflects the cumulative impact of an author's contributions (Hirsch, 2005) was found to be 45. Meanwhile, the g-index, which weighs highly cited articles (Egghe, 2006), was 70 which is defined as the largest number of g-index such that the top g-index articles cumulatively received at least g^2 citations. The m-index is defined as the h-index divided by the number of years since its first publication (Choudhri et al., 2015).

Table 1: Citation Metrics

Main Information	Total Publications (TP)
Publications Years	1978 - 2024
Total Publications	499
Number of Cited Papers	384
Total Citations	7,583
Citation per Paper	15.20
Citation per Cited Paper	19.75
Citation per Year	164.85
Citation per Author	3.82
h-index	45
g-index	70

Article is the most dominant document type accounting for 71.74%, followed by conference papers at 24.45%, as shown in Table 2. Other document types made up less than 5% of the total. Regarding language, Table 3 indicates that 89.18% of publications on the application of optimization techniques in the recycling sector were published in English, with Chinese and German accounting for 6.61% and 2.20%, respectively. Publications in other languages contributed less than 1% to the field.

Table 2: Document Type

Document Type	TP	%
Article	358	71.74%
Conference Paper	122	24.45%
Review	8	1.60%
Book Chapter	7	1.40%
Short Survey	2	0.40%
Letter	1	0.20%
Note	1	0.20%

Table 3: Languages

Language	TP	%
English	445	89.18%
Chinese	33	6.61%
German	11	2.20%
Japanese	3	0.60%
Russian	3	0.60%
Spanish	2	0.40%
French	1	0.20%
Portuguese	1	0.20%

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Table 4 presents that almost half of the subject area of the publications on the application of optimization techniques in the recycling sector is in Engineering field with 46.09% of the total publication. This implies that engineering research forms a large part of the effort towards improvement of recycling using optimization techniques. Next in ranking is Environmental Science with 29.26% of the total publications. This shows that research in the area of the environment is crucial in the development of recycling optimization methodologies. Other significant areas of contribution include Computer Science together with Material Science, Chemical Engineering, Energy and Chemistry which account for between 14% and 18% of the published records. These fields probably supply crucial area knowledge for optimization of recycling. Each of the rest of the subject areas included the publication of fewer than 10% of the total represented in the list of articles. Other technical domains also contribute, though not as much as quantitatively oriented ones do.

Table 4: Subject Area

Subject Area	TP	%
Engineering	230	46.09%
Environmental Science	146	29.26%
Computer Science	89	17.84%
Materials Science	89	17.84%
Chemical Engineering	83	16.63%
Energy	83	16.63%
Chemistry	73	14.63%
Business, Management and Accounting	41	8.22%
Physics and Astronomy	37	7.41%
Mathematics	34	6.81%
Social Sciences	28	5.61%
Agricultural and Biological Sciences	23	4.61%
Decision Sciences	20	4.01%
Economics, Econometrics and Finance	16	3.21%
Earth and Planetary Sciences	14	2.81%
Medicine	13	2.61%
Biochemistry, Genetics and Molecular Biology	12	2.40%
Multidisciplinary	5	1.00%
Immunology and Microbiology	3	0.60%
Pharmacology, Toxicology and Pharmaceutics	2	0.40%
Arts and Humanities	1	0.20%

Publication Trends

Table 5 illustrates the annual publication trends for the application of optimization techniques in the recycling sector. Since the first publication in 1978, the annual number of publications remained relatively constant for a decade and gradually increased, reaching 10 publications by 2004. However, the publication rate declined until 2009, after which it stabilized in the double digits through 2024. Similarly, the number of cited papers and the h-, g- and m-indexes grew slowly over the first 10 years, indicating a gradual increase in the field's impact on the research community. The average citations per publication and average citations per cited publication followed a similar pattern to the total citations, with low citation values during the first two decades. A rapid increase in total citations was observed in the new millennium, followed by declines to double digits in 2005, 2008 and 2012, with average citations per publication and

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average citations per cited publication reflecting this trend. Since then, both the total publications and cited publications have steadily increased, with the h-, g- and m-indexes showing a slow upward trend after 2013.

Table 5: Publication by Year

Year	TP	NCA	NCP	TC	C/P	C/CP	h	g	m
1978	1	1	0	0	0.00	0.00	0	0	0.000
1981	1	3	0	0	0.00	0.00	0	0	0.000
1982	2	2	1	1	0.50	1.00	1	1	0.023
1984	1	2	1	1	1.00	1.00	1	1	0.024
1993	1	2	1	2	2.00	2.00	1	1	0.031
1994	1	2	1	11	11.00	11.00	1	1	0.032
1995	3	8	2	12	4.00	6.00	2	3	0.067
1996	2	5	0	0	0.00	0.00	0	0	0.000
1997	2	5	2	14	7.00	7.00	2	2	0.071
1998	1	1	1	8	8.00	8.00	1	1	0.037
1999	2	5	2	6	3.00	3.00	1	2	0.038
2000	2	8	2	136	68.00	68.00	2	2	0.080
2001	6	20	5	104	17.33	20.80	4	6	0.167
2002	3	10	2	213	71.00	106.50	2	3	0.087
2003	5	9	4	166	33.20	41.50	4	5	0.182
2004	10	35	9	215	21.50	23.89	6	10	0.286
2005	6	16	5	69	11.50	13.80	4	6	0.200
2006	5	23	5	222	44.40	44.40	4	5	0.211
2007	8	27	6	458	57.25	76.33	5	8	0.278
2008	7	23	7	76	10.86	10.86	5	7	0.294
2009	13	51	10	624	48.00	62.40	8	13	0.500
2010	20	64	15	420	21.00	28.00	11	20	0.733
2011	15	54	15	319	21.27	21.27	5	15	0.357
2012	13	40	11	91	7.00	8.27	5	9	0.385
2013	19	66	14	264	13.89	18.86	7	16	0.583
2014	17	56	13	225	13.24	17.31	8	15	0.727
2015	19	73	15	393	20.68	26.20	7	19	0.700
2016	29	98	23	711	24.52	30.91	13	26	1.444
2017	21	79	16	316	15.05	19.75	9	17	1.125
2018	29	138	25	423	14.59	16.92	13	20	1.857
2019	19	91	16	202	10.63	12.63	8	14	1.333
2020	40	165	34	652	16.30	19.18	14	25	2.800
2021	31	140	23	459	14.81	19.96	11	21	2.750
2022	46	200	40	521	11.33	13.03	13	21	4.333
2023	63	291	46	222	3.52	4.83	8	11	4.000
2024	36	171	12	27	0.75	2.25	4	4	4.000
Total	**499**	**1984**	**384**	**7583**	**15.20**	**19.75**	**45**	**70**	**0.957**

Notes: TP = total number of publications; NCA = Number of Citing Authors; NCP = number of cited publications; TC = total citations; C/P = average citations per publication; C/CP = average citations per cited publication; h = h-index; g = g-index; and m = m-index.

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Highly Cited Documents

The most active source title that published five or more documents on the application of optimization techniques in the recycling sector is presented in Table 6. The Journal of Cleaner Production leads with 20 publications and holds the highest publications with the highest h-, g- and m-indexes indicating its influence in this field. Resources, Conservation and Recycling ranks second, with 11 publications but with a high total citation count which exceeds those of the Journal of Cleaner Production by nearly 10%, reflecting its significant impact. Sustainability (Switzerland) ranks third with 9 publications and 156 citations. ACS Sustainable Chemistry and Engineering has a high citation-per-publication ratio (38.60), suggesting strong influence despite fewer publications. Other journals like Waste Management and Industrial and Engineering Chemistry Research contribute with moderate publications and citations, highlighting their relevance in the field.

Total citations are an indicator of research quality and impact. Table 7 highlights the most highly cited documents on the application of optimization techniques in the recycling sector. Notably, the articles by Meyer et al. (2009) and Wang et al. (2007a) have each received over 200 citations. While the first document related to this subject was published in 1978, the research in this field did not start receiving much attention until almost three decades later, as evidenced by the total citation counts. Meyer et al. (2009) focused on CFRP recycling via pyrolysis and stands out as a key publication. Wang et al. (2007a) made significant contributions to paper recycling wastewater treatment and topology optimization. Santander et al. (2020) offers a notable recent study on 3D printing plastic recycling with the highest average citations per year at 22.4, followed by Zhang et al. (2015) and Meyer et al. (2009), with 19.6 and 17.25 average citations per year, respectively. These works highlight key process optimizations across various recycling sectors. Although Meyer et al. (2009) is not the highest ranking in average citations per year, it has made a substantial impact in the field, maintaining citations for over 15 years.

Table 6: Most Active Source Titles that Published Five or More Documents

Source Title	TP	NCA	NCP	TC	C/P	C/CP	h	g	m
Journal of Cleaner Production	20	77	20	470	23.50	23.50	10	20	0.500
Resources, Conservation and Recycling	11	48	11	514	46.73	46.73	10	11	0.400
Sustainability (Switzerland)	9	36	9	156	17.33	17.33	5	9	0.556
Industrial and Engineering Chemistry Research	6	22	6	75	12.50	12.50	4	6	0.200
AIP Conference Proceedings	6	25	4	20	3.33	5.00	2	4	0.118
Waste Management	5	20	4	136	27.20	34.00	4	5	0.250
ACS Sustainable Chemistry and Engineering	5	30	5	193	38.60	38.60	5	5	0.625
Computer Aided Chemical Engineering	5	14	4	12	2.40	3.00	2	3	0.154
JOM	5	21	5	72	14.40	14.40	4	5	0.190

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Table 7: Top 10 Most Cited Documents Ranked According to Total Contribution

No.	Author(s)	Title	Source Title	TC	C/Y
1	Meyer et al. (2009)	CFRP-recycling following a pyrolysis route: Process optimization and potentials	Journal of Composite Materials	276	17.25
2	Wang et al. (2007a)	Optimization of coagulation-flocculation process for a paper-recycling wastewater treatment using response surface methodology	Colloids and Surfaces A: Physicochemical and Engineering Aspects	242	13.44
3	Zhang et al. (2015)	A closed-loop process for recycling LiNi1/3Co1/3Mn1/3O2 from the cathode scraps of lithium-ion batteries: Process optimization and kinetics analysis	Separation and Purification Technology	196	19.6
4	Hagelüken (2006)	Improving metal returns and eco-efficiency in electronics recycling - A holistic approach for interface optimisation between pre-processing and integrated metals smelting and refining	IEEE International Symposium on Electronics and the Environment	192	10.11
5	Wang et al. (2007b)	Large-scale topology optimization using preconditioned Krylov subspace methods with recycling	International Journal for Numerical Methods in Engineering	165	9.17
6	Wang et al. (2016)	Heavy metal removal by GLDA washing: Optimization, redistribution, recycling and changes in soil fertility	Science of the Total Environment	152	16.89
7	Gent et al. (2011)	Optimization of the recovery of plastics for recycling by density media separation cyclones	Resources, Conservation and Recycling	121	8.64
8	Santander et al. (2020)	Closed loop supply chain network for local and distributed plastic recycling for 3D printing: a MILP-based optimization approach	Resources, Conservation and Recycling	112	22.4
9	Makkonen et al. (2002)	Optimisation of steel plant recycling in Finland: Dusts, scales and sludge	Resources, Conservation and Recycling	107	4.65
10	Khoei et al. (2002)	Design optimisation of aluminium recycling processes using Taguchi technique	Journal of Materials Processing Technology	106	4.61

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Notes: TC = total citations; C/Y = citation per year.

Publication by Countries

Table 8 presents the recycling sector's documents employing optimization techniques, with a total publication count exceeding 14, published by 11 countries. Overall, China tops the list with 170 publications, while the second has less than quarter of this number. China is also at the top with respect to the other indicators. The United States follows with 37 publications, Germany, India, South Korea and Iran each having more than 20 publications. Although China leads in total citations, but in terms of average citations per paper and average citations per cited publication, China has less impact as compared to others. This is probably due to the large number of publications used as division to get this average value as compared to other countries. Their h- (24), g- (45) and m-indexes (1.333) reflected impactful research over time.

Table 8: Top Countries that Contributed More than 14 Publications

Country	TP	NCA	NCP	TC	C/P	C/CP	h	g	m
China	170	716	120	2092	12.31	17.43	24	45	1.333
United States	37	100	34	1023	27.65	30.09	17	31	0.773
Germany	28	76	21	653	23.32	31.10	10	25	0.333
India	27	92	21	444	16.44	21.14	11	21	0.500
South Korea	25	104	22	365	14.60	16.59	11	19	0.458
Iran	24	79	21	487	20.29	23.19	11	22	0.478
United Kingdom	19	55	17	373	19.63	21.94	10	19	0.385
Japan	17	72	13	277	16.29	21.31	8	16	0.267
France	17	56	13	269	15.82	20.69	7	16	0.233
Spain	15	44	13	472	31.47	36.31	7	15	0.241
Italy	15	65	12	308	20.53	25.67	8	15	0.308

Notes: TP = total number of publications; NCA = Number of Citing Authors; NCP = number of cited publications; TC = total citations; C/P = average citations per publication; C/CP = average citations per cited publication; h = h-index; g = g-index; and m = m-index.

Co-Authorship Analysis by Countries

A network analysis visualized inter-country collaboration for the research in the application of optimization techniques in the recycling sector as in Figure 1. There are five sets of the colour for the 61 countries representing the research collaboration relationships. The size of the circle reflects the total number of publications, thickness and position of the lines illustrate the intensity and depth of collaboration.

The largest purple cluster is internal collaboration within China, Hong Kong, Russia as well as Japan, Netherlands, South Korea. China is the central cluster, linked to the other clusters extensively including the United States which represented by the biggest yellow circle located next to China's circle. Notably, the blue (Asian and Australia) shows the collaborations between the cluster and green clusters (Asian and Europe) suggested the collaboration beyond the continents. The cluster in red (South Korea, Netherlands and South Africa) is isolated from other clusters suggesting a preference for geographically proximate collaborations, with the links with China, Canada and Singapore. China is involved with all the clusters, which underlines its position in the context of the optimization research network. In general, China plays a central role of the clusters with internal linkages as well as external connectivity of the global collaboration with diversified internal and external inclination compared to other clusters which may have inclination towards regional or international linkage. The

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visualization and clusters describe the patterns and composition of global research co-authorship.

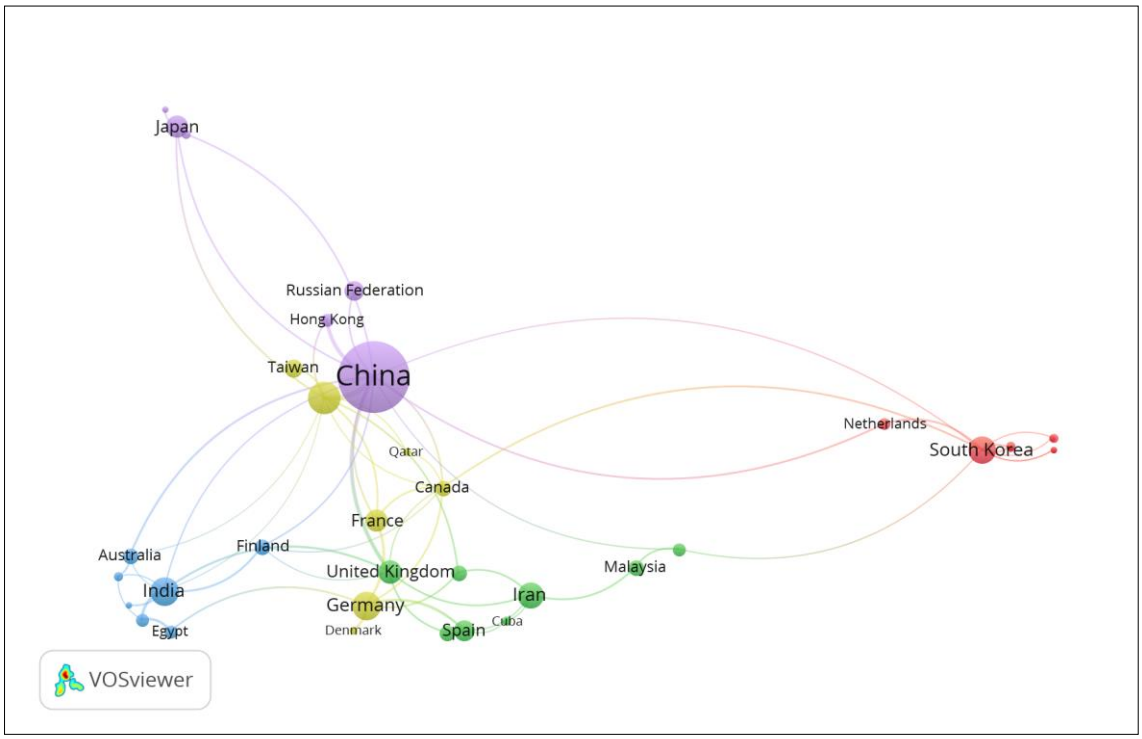

Figure 1: Network Visualization of Map of Co-Authorship by Countries

The practical application of optimization techniques in the recycling sector has significantly contributed to improving resource efficiency, reducing waste and enhancing the economic viability of recycling operations. Over the past 46 years, extensive research has been conducted, with the publications on this field receiving a total of 7,583 citations, demonstrating the field's impact. The h-index of 45 and g-index of 70 indicate a strong scholarly influence, reinforcing the importance of optimization in recycling. Engineering and environmental science dominate this research area, reflecting the crucial role of technical advancements in optimizing recycling methodologies. Optimization techniques, such as mathematical modeling, machine learning and simulation have been widely used to enhance process efficiency, lower costs and reduce environmental impact. Moreover, the interdisciplinary contributions from computer science, material science, chemical engineering and energy studies highlight the integration of diverse expertise in refining recycling systems. The high citation rate and broad scope of research indicate that optimization techniques are essential in driving innovation, ensuring sustainability and addressing challenges such as material recovery, waste reduction and closed-loop supply chains in the recycling sector.

Conclusion

In this paper, a total of 499 publications in the application of optimization techniques in the recycling sector was analyzed after eliminating the Erratum papers. The publishing trend of publications, influential publications, countries, documents and the authors were analyzed based on bibliometric analysis. Moreover, the dynamics of collaboration among authors and research hotspots in the application of optimization techniques in the recycling sector were analyzed by creating social networks for more than four decades from 1978 and 2024. The

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number of publications in the application of optimization techniques in the recycling sector field started to increase since 2009 and the publications published after the year 2000 obtained more citations.

Journal of Cleaner Production and Resources, Conservation and Recycling lead in publications and citations for optimization techniques in recycling research. Sustainability (Switzerland) and ACS Sustainable Chemistry and Engineering also show significant influence, despite fewer publications, highlighting their impact in this field. Meyer et al. (2009) lead in citations for optimizing CFRP recycling, while Zhang et al. (2015) has the highest citation-per-year for lithium-ion battery recycling. Wang et al. (2007b) contributed to paper recycling and topology optimization and Santander et al. (2020) studied 3D printing plastic recycling. These works showcase key recycling process optimizations in various recycling sectors.

Since 2020, publications from Canada, the Netherlands, Finland and Turkey have seen an increasing pattern, although China initially led in applying optimization techniques within recycling sector research. Chinese researchers, who have made significant contributions to this field, tend to collaborate with numerous researchers worldwide, establishing themselves as a central link among various countries. Furthermore, the application of optimization techniques in recycling sector research has gained increasing attention over the past two decades. These techniques have also attracted considerable interest across many countries in addressing energy and environmental challenges within the recycling sector.

The paper presents a bibliometric analysis of optimization techniques in recycling that explores trends in research publications together with collaborative networks and essential publications. The research examines publications total numbers and citations together with journal impact through BiblioMagika citation measurement and VOSviewer co-authorship examination. The study reveals interdisciplinary contributions from engineering, environmental science and computer science which could offer a research roadmap for future advancements in recycling optimization.

There is limitation of this research, particularly the fact that the dataset is confined to documents indexed in the Scopus database. However, the fact that most higher ranking journals are indexed by Scopus establishes it as a reputable source of data. This study is expected to serve as a valuable reference for future research on the application of optimization techniques in the recycling sector and other relevant fields.

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