

Mapping Three Decades of Municipal Solid Waste Management Research: A Bibliometric Analysis of Trends, Hotspots, and Future Directions

Nida Rabab ^a, Muhammad Safar Korai ^{b,c,*}, Zeeshan Khan ^{c,d}, Anees Ahmed Vighio ^e, Rasool Bux Mahar ^f, Muhammad Yousaf Raza Taseer ^g, Nishan-E-Hyder Soomro ^h, Haniya Batool Ansari ⁱ

^aSchool of Environmental Science and Engineering, Shanghai Jiao Tong University, Shanghai 200240, China

^bInstitute of Environmental Engineering and Management (IEEM), Mehran University of Engineering & Technology (MUET), Jamshoro, Sindh, Pakistan

^cAdvanced Membrane Technology Research Centre (AMTEC), Faculty of Chemical & Energy Engineering (FCEE), University Technology Malaysia Johor Bahru (UTMJB), Block N29a, 81310 Skudai, Johor, Malaysia

^dDepartment of Petroleum & Gas Engineering, Balochistan University of Information Technology, Engineering and Management Sciences (BUITEMS), 87100 Quetta, Pakistan

^eCivil Engineering Department, Mehran University of Engineering & Technology (MUET), Jamshoro, Sindh, Pakistan

^fUS-Pakistan Center for Advanced Studies in Water (USPCAS-W), Mehran University of Engineering and Technology (MUET), Jamshoro, Sindh, Pakistan

^gDepartment of Structure and Materials, Faculty of Civil Engineering, Universiti Teknologi Malaysia (UTM), 81310, Johor Bahru, Johor, Malaysia

^hSchool of Management and Economics, North China University of Water Resources and Electric Power, Zhengzhou 450046, China

ⁱSchool of Business, Zhengzhou University, China

*Corresponding author: Muhammad Safar Korai, Email: safar.korai@faculty.muet.edu.pk

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ABSTRACT

Municipal solid waste has emerged as a critical global challenge, with annual generation of 2.2 billion tonnes/year and is expected to increase to 3.4 billion metric tonnes by 2050. This study presents a comprehensive bibliometric analysis of municipal solid waste research over three decades (1995–2025) using 20,438 articles from the Web of Science Core Collection. Employing CiteSpace and Bibliometrix for science mapping, the analysis examines research gaps, institutional collaborations, and methodological developments. The findings reveal three evolutionary phases such as foundation (1995–2005), development (2006–2015), and transition & innovation (2016–2025), with exponential publication growth after 2015. Environmental Science & Technology and Waste Management emerged as the most influential journals. Geographically, India and China dominate research productivity, reflecting waste management challenges in rapidly urbanizing economies. The Hong Kong Polytechnic University, Universiti Teknologi Malaysia, and Korea University lead institutional contributions. Keyword analysis identifies food waste, heavy metals, sewage sludge, and life cycle assessment as persistent hotspots, with emerging frontiers in circular economy, waste-to-energy, pyrolysis, and artificial intelligence. Methodological comparison reveals a paradigm shift toward hybrid approaches that overcome the limitations of individual methods. Co-citation cluster analysis delineates five thematic domains such as waste characterization, vegetation contamination, transportation optimization, and thermal treatment. Critical research gaps include scalable valorization technologies, integrating circular economy and mathematical modeling, and digitalization through artificial intelligence. The study provides researchers, policymakers, and practitioners with a comprehensive roadmap of the evolution of municipal solid waste research, current frontiers, and future trajectories essential for transitioning toward sustainable waste management and circular economy paradigms.

1. Introduction

Municipal solid waste (MSW) has become a persistent problem due to fast urbanisation, industrialisation, and economic growth [1, 2]. The worldwide generation of MSW has been increasing annually by approximately 2.2 billion tonnes/year and is expected to increase to

3.4 billion metric tonnes by 2050 [3]. According to a report [4], total Greenhouse Gas (GHG) emissions (CH₄, CO₂, and N₂O) from waste management contribute approximately 5% of overall GHG emissions into the atmosphere. The results of the study [5] show that the average global GHG emissions from 1 tonne of MSW in 2023, based on the existing MSW management

practices, were approximately 89.7 kg CO₂e. The major contributor was the open dumping of MSW, contributing almost 70% of GHG emissions. The global MSW management sector emitted a total of 173.2 Mt CO₂e GHG emissions in 2023. If no improvements are made to existing systems, GHG emissions from the waste sector are projected to increase to 203.4 Mt CO₂e by 2030, and to 289.5 Mt CO₂e by 2050, as stated by [5]. If solid waste is mishandled, this may cause degradation of environmental quality, thus causing public health issues and contributing to climate change. Therefore, it is essential to manage MSW for resource conservation and to avoid public health issues. The process of MSW management consists of different processes, including waste segregation, collection, transportation, and final disposal. Waste generation is a significant part of human activity, and therefore, its management can be a colossal problem. Thus, waste management is necessary to protect the environment, preserve natural resources, and improve public health. The MSW is often a complex process involving several actors and processes that need to be optimised for efficiency [6]. To manage solid waste properly, proper integration between each phase is necessary. To assess the integration of these phases, there are several tools and techniques available to evaluate the quality of solid waste management systems [7]. According to different research studies [8,9], improper waste bin collection methods, poor roads, insufficient infrastructure, absence of information about the collection plan, insufficient numbers of vehicles, and poor route planning hinder the collection and transportation of MSW. In developing regions, these issues are intensified by funding and governance constraints [10,11]. Several studies have been carried out to cover the area of MSW research, highlighting its different processes and methods, such as landfilling, composting, and incineration. To minimise GHG emissions, a study revealed that composting is a low-cost and environmentally friendly method in comparison to other approaches, such as landfilling [12]. Whereas researchers from South Africa, like [13], testified that if 71,793 tons of garden waste were sent through a turned windrow composting facility, 13,282 tons of CO₂ equivalent would be emitted. However, if it were left untreated, then the amount would be higher and could reach up to 93,187 tons of CO₂ equivalent. Another method of MSW treatment is incineration. This method usually requires maintenance after 20–30 years, but if less waste is sent to the facility, the cost can be reduced for many years and make incineration economically more feasible [14]. Different methods are used, such as life cycle assessment methods [15,16], multi-criteria decision analysis [17], and material flow analyses [18] to evaluate MSW. Recent research increasingly combines these methods with energy accounting, artificial intelligence, machine learning, and optimisation models for predictive waste-management planning [19–21]. The focus of this review paper is to evaluate the scientific analysis of MSW through bibliometric analysis, which is a main

element of environmental management. To measure scientific progress, bibliometric methods have been used in many disciplines of science and engineering and are a common research instrument for systematic analysis [22]. Earlier bibliometric studies on MSW covered 1993–2008 [23], 1991–2010 [24], bibliometric analysis of MSW using the visualisation tool, and the VOSviewer up to 2021 by [25], 1996–2022 by [26] focused on bibliometric analysis of MSW from South African Perspective using VOSviewer, 2010–2021 [11] by using visual mapping method, and 1994–2024 using performance evaluation techniques [27], but recent research integrates text-mining and visualization tools to capture evolving patterns.

The traditional literature review offers qualitative data; bibliometric analysis gives a quantitative and systematic assessment of the evolution of scientific knowledge [11,26,27]. It allows researchers to detect trends in publication volume and identify key journals, authors, highly cited papers, main international and institutional collaboration networks, and new trends of research within a research field [27]. Furthermore, the bibliometric analysis with visualization tools helps to spot research hotspots, gaps in the knowledge, and emerging trends in research that can guide researchers, policy makers and funding institutions in prioritising research [26,27]. The MSW Management has received several bibliometric studies, but most of them have focused on specific time periods, geographical regions, and/or analytical approaches [25] and fail to adequately reflect the rapid growth of the research landscape in recent years, stimulated by the development of various circular economy strategies [17,18], digital technologies, artificial intelligence, life-cycle assessment, and climate change mitigation programmes [5,13,16]. Thus, a new and thorough bibliometric evaluation from 1995 to 2025 is necessary to show the long-term trend in research, to reveal the emerging trends and collaborations, and to present an adequate knowledge base for the progress of sustainable municipal solid waste management research and practice. Therefore, this study was conducted over the last three decades (1995–2025) to focus on (1) Analysis of the authors' production with citation over time, (2) Analysis of the cited journals, the affiliations of Institutions, and Countries, (3) Keywords and research hotspots analysis, (4) Life-Cycle Assessment of annual scientific publications, (5) Co-citation cluster analysis.

2. Materials and Methods

In this study, a bibliometric analysis of MSW management was performed. A bibliometric analysis is a systematic method used to classify research features and to analyze academic literature as introduced by [23]. It helps to investigate scientific publications through a sequence of procedures, such as publication outputs of journals, institutions, countries, and authors, citation analysis classifies pathways focused on research growth; and content analysis [28]. It was primarily used in the

field of information and library science, and later on has been used extensively to measure scientific progress across different scientific fields. It is a tool widely used for systematic analysis in the field of science and engineering to evaluate the research trends and status of a given topic, along with ascertaining future research direction to assist new researchers. In bibliometric analysis, two indicators are commonly used i.e., journal impact factor (IF) and the h-index. The IF was created by the Institute of Scientific Information and is used to assess the quality of a journal, and a high IF typically indicates a higher quality of a journal [29, 30]. These factors provide transparent, replicable evidence of global research performance and emerging themes [31]. Similarly, the h-index means that h of the overall articles are cited at least h times, and the higher the value of the h-index, the greater the scientific achievement. These bibliometric indicators have been chosen due to their ability to comprehensively analyze the productivity of research, its scientific impact, and the quality of publications. Furthermore, citation analysis, co-authorship analysis, keyword co-occurrence analysis, and collaboration analysis were used to explore the organizational structure, research hotspots, and collaboration among co-authors in the municipal solid waste management research area.

2.1 Data Sources and Treatment

To conduct the bibliometric analysis, the literature dataset was collected from Thomson Reuters Web of Science (WoS) Core Collection database to compile the literature study and to collect comprehensive, authoritative, and reliable data for MSW analysis [27]. The WoS is one of the largest and most reliable scientific databases in the world. The Web of Science Core Collection was chosen due to its extensive citation indexing, high-quality, peer-reviewed, and standardised bibliographic records, and because it is one of the most widely used and reliable databases for bibliometric research. In terms of the metadata of the citations, WoS provides more consistency than other databases and fewer duplicate records, which enhances the precision and repeatability of bibliometric analysis. It aggregates research articles from high-quality journals from a range of disciplines. It provides robust author information and more consistent knowledge of journals.

In this paper, an advanced search has been conducted to access the right publications. The literature search was carried out with the help of well-defined keywords for MSW management and Boolean operators (AND/OR) in the Web of Science Core Collection. Only English-language publications from 1995–2025 were included in the search. To keep the quality and consistency of the dataset, only peer-reviewed research articles as well as reviews were included. The excluded publications were those that did not have an adequate bibliographic reference, followed by duplicate records, conference papers, editorials, book chapters, notes, and documents. All other publications were screened on a manual basis

by the titles, abstracts, and keywords to make sure that they are relevant.

The data extraction research is divided into two tiers. Level 1 filters data containing MSW management. At Level 2, to get the most relevant articles, manual screening and CiteSpace software were applied for further analysis of the research study. In this study, we limited our search to the WoS database to get a total of 32,484 articles. The final screening comprised 20,438 articles based on the WoS core collection. Compared with previous bibliometric studies, this extended dataset captures three additional decades, allowing for longitudinal trend analysis [32]. Fig. 1 shows a review flowchart for this review. The search method was developed using well-chosen keywords to ensure that relevant publications were retrieved, but with minimal irrelevant records. Selection of the literature was done according to the PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to ensure selection was transparent, reproducible, and both identified and screened. The whole selection process is shown in Fig. 1.

The search was complemented by manual screening to maximise the retrieval of relevant publications while minimising irrelevant records (Table 1). This systematic approach contributes to the quality and completeness of the dataset. The search was limited to articles and review papers published in English in the last 30 years (from 1995 to 2025). Boolean operators (AND, OR) and wildcards (asterisk) were employed to maximize retrieval of relevant publications while at the same time providing solid coverage of the research field.

Table 1
Search Strategy

Item	Description
Database	Web of Science Core Collection
Search period	1995–2025
Search fields	Title, Abstract, Author Keywords
Search keywords	Municipal Solid Waste, Solid Waste Management, Waste Management, etc.
Boolean operators	AND, OR
Language	English
Document type	Articles and Reviews
Initial records	32,484
Final records	20,438
Analytical Tools	Bibliometrix, Biblioshiny, CiteSpace, Microsoft Excel

The Web of Science Core Collection is chosen as it offers high-quality and peer-reviewed publications with standardized bibliographic records and comprehensive citation indexing, which makes it one of the most reliable bibliometric databases. Its metadata consistency allows for precise performance analysis, citation mapping, and visualization of collaboration networks, while minimizing inconsistencies that come from integrating data from a variety of sources. While Scopus has more

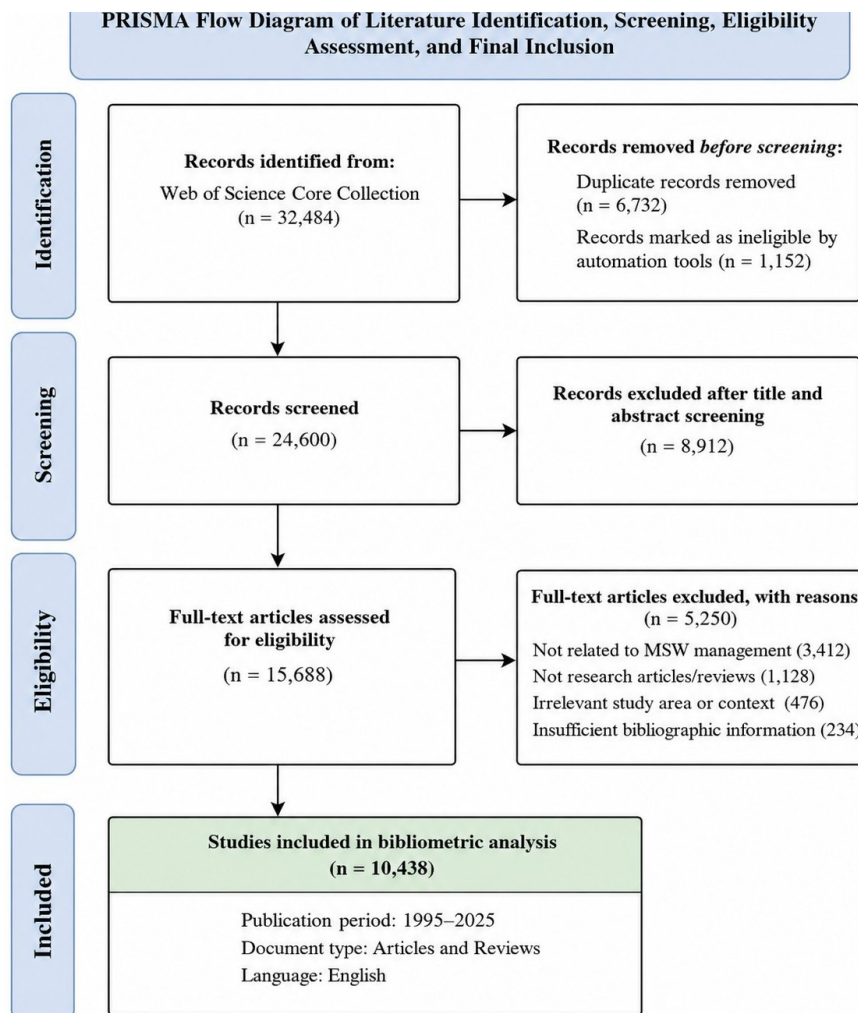


Fig. 1. PRISMA-Based Flow Diagram of Literature Selection

journals, a single curated set of databases increases the consistency of data and reproducibility. Future studies could combine other databases like Web of Science, Scopus, and Dimensions to give a more comprehensive picture of the global research landscape.

2.2 Analysis Tools

The presentation of scientific data provided by network analysis and graph theory is an evolving trend in bibliometric methods. Several bibliometric tools that have been created for science mapping and analysis of scientific domains [33]. CiteSpace is one of them, developed by Dr. Chen Chaomei from Drexel University, USA, for visualization and analysis of scientific literature [34]. VOSviewer is well known for its visualisation network functions; however, for this study, CiteSpace was chosen because of its advanced functions. It offers co-citation clustering, timeline analysis, burst detection, and identification of emerging research trends, which closely match the aim and objectives of this bibliometric analysis. Moreover, CiteSpace is a specialized scientific literature software that has been broadly used to visualize the patterns, research trends, and dynamics of scientific domains and intellectual bases due to its advanced applications and dominant functions [35, 36]. Therefore, in this study, CiteSpace is used because it provides in-depth visualization, pattern analysis, and trend analysis in scientific literature. To extract overall

statistical information of related publications and to visualize the network analysis, the analysis has been done on authors, keywords, citations, categories, countries, and institutions using network analysis, which provides useful insights. Further, these tools are currently considered a staple of environmental bibliometric studies because they provide strong clustering and time-evolution capabilities [37]. Pre-processing of data was done by normalizing the names of authors, institutions, and keywords in order to minimize repetition. Besides, the qualitative interpretation of the content was also included to connect the bibliometric trends with the engineering practices, including waste-to-energy conversion, design of the circular-economy policies, and the digitalization of smart-waste [11]. The application of Bibliometrix to analyze quantitative performance and evaluate collaborations, and CiteSpace to visualize the knowledge structure, knowledge mapping, and temporal trends. These tools complement each other and offer a comprehensive, repeatable, and dependable bibliometric analysis.

2.3 Bibliometric Method and Techniques

The methodology for this study is based on bibliometric analysis, incorporating science mapping, network analysis, and performance analysis. This study adheres to the bibliometric guidelines proposed by [38], which include four key stages: establishing the research ob-

jectives, collecting relevant data, performing analysis and visualisation, and interpreting the findings. Several bibliometric analysis tools are available, such as VOSviewer, BibExcel, Histcite, Bibliometrix, SciMat, Pajek, Gephi, and UCINET [39]. Bibliometrix was chosen for this study due to its comprehensive support for various bibliometric indicators, enabling an effective assessment of publication output, citation patterns, and collaboration networks [40, 41]. Its web-based interface, Biblioshiny, offers a user-friendly platform that simplifies complex analyses, making it accessible even for researchers with limited programming skills. Additionally, the tool adheres to PRISMA guidelines, ensuring systematic and transparent reporting of bibliometric studies [42]. Microsoft Excel is also utilised to enhance the visualization of graphs and charts generated from the Bibliometrix results. To perform the co-occurrence analysis, Authors' Keywords were chosen, as they directly reflect the main themes and research issues identified by the authors, which is particularly appropriate for determining emerging hotspots of research and recent advancements in the field of MSW. While Keywords Plus will yield more information from the cited references, which were computed algorithmically, they will also contain fewer term counts that are relevant to the topic. Thus, Authors' Keywords were deemed more suitable for mapping the existing concept structure of the field. However, future bibliometric studies could include both Authors' Keywords and Keywords Plus in order to get a clearer picture of the research landscape.

3. Results and Discussion

3.1 Mainstream Methods

The MSW is a significant yet diverse issue. The implementation of MSW frameworks is obstructed by the amount of waste generated and inadequate infrastructure to manage, process, and dispose of waste properly [43]. In addition to this, no single method can address the issue due to different social, economic, and technological scenarios. Therefore, it is perilous to incorporate diverse methods so that an innovative future perspective can be obtained. Table 2 lists 5 mainstream methods in the field of MSW, comprising quantitative methods, which include Energy Analysis, Life Cycle Assessment (LCA), Carbon Footprint (CF), Geographic Information System (GIS), and Qualitative Methods such as System Dynamics. Building on the work of [44], the idea of emergy brought established researchers another worldview targeting the evaluation of assets from a nature-centered perspective.

The fundamental benefit of employing emergy research is its capacity to integrate environmental and socioeconomic flows, for example, monetary value and labor on a typical scale [55]. Another study by [56] used emergy accounting techniques to achieve a contributor or nature-based environmental footprint perspective. The significance of emergy analysis is prominent in the field of waste management. Several other studies have

also been carried out on emergy analysis. Such as studies conducted by [57] and [58] based on environmental evaluation of solid waste management encompass developed countries, which mainly include Brazil, China, and other Western countries, and developing countries like Indonesia. LCA has been utilized as a viable environmental tool in numerous MSW studies. It has a great deal to offer regarding the application, selection, and use of appropriate MSW strategies, technologies, and projects to accomplish explicit waste management goals and objectives. Hence, various studies present in the literature used LCA as an instrument of waste management [59–62]. The accuracy of the results of LCA depends primarily on the large volume of high-quality data [63]. The GIS approach is an innovative tool to study how to optimize the collection of solid waste and also tends to improve the efficiency of MSW with the help of its systematic use [64]. The study conducted by [65] investigates the amount of waste produced in the Coimbatore urban area and provides practical and authoritatively clear answers to the garbage disposal problem.

The GIS-based multi-measure selection tool and its use in solving environmental problems are provided by [66]. The SD is a rigorous procedure used to study complex frameworks assisted through computer simulation. It can accommodate time suspensions, internal response circles, which are required when predicting the amount of MSW generation [67]. Another study by [68], presented a state-of-the-art methodology of system dynamics to estimate solid waste generation in a fast-growing city area based on limited samples. In this study, with the help of five different models of solid waste, they have presented several trends of solid waste generation. In their study, they have used Stella, a simulation tool, to identify different patterns of waste production.

The CF measurement is a critical method for calculating the environmental impact of goods and practices of GHG emissions [69]. Another study [70] stated that CF analysis is an important environmental indicator. Several other studies have also been done on CF, such as a study conducted by [71], which focused on a comparison between biogas recovered from landfill and energy recovered from MSW incineration waste, and which option is appropriate with respect to CF. Similar to these, all methods have their strengths and weaknesses as presented in Table 2. Therefore, a single method cannot be applied to address the key issues of MSW. It is suggested that the combination of different methods would be more feasible for future studies on MSW. For instance, in 2017, a hybrid method of emergy and LCA was applied to assess the environmental impact of MSW. The study combined LCA and emergy on MSW in order to get the hybrid advantage of both methods. The integration offered a way to analyze the quantitative and qualitative assessment of MSW. Studies on Emergy Accounting Analysis (EMA) have experienced significant progress with the development of the

Table 2

Comparison of Major Research Methods of MSW

Method	Initiator (year)	Definition	Advantage	Disadvantage
Life Cycle Assessment	The Coca-Cola Company (1960s)	A systematic set of procedures for collecting and examining the inputs and outputs of materials and energy and the related environmental impacts directly attributable to the operation of a product or service system throughout its life cycle.	Life cycle assessment reveals the “cradle-to-grave” environmental impacts of MSW, and it is especially aimed at comparing different treatment techniques [45].	Results of LCA are widely varying, and its applicability appears to be geographically bounded [46].
System Dynamics	Jay W. Forrester (1956)	A technique for qualitative description, investigation, and analysis of intricate systems based on their procedures, information, boundaries, and strategies, which enables quantitative simulation modelling and analysis for the design of system structure and control [47].	It can be implemented to any complex system and is feasible to incorporate various MSW management processes from a centralized viewpoint [48].	Not all the parameters happened in the real MSW treatment and management can be applied and modified in the system dynamics, which increases the uncertainties [48].
Carbon Footprint	William E. Rees (1990s)	It is a concept that explains each action of an individual that generates greenhouse gases. The output of these gases differs widely from one person to another based on the activities performed by them [49].	The methodology considers both the direct, the indirect, and the avoided carbon emissions during all the MSW stages [50].	Carbon Footprint is a poor representative of the environmental burdens of products, and apart from these, other impacts, such as resource depletion and water pollution, were ignored [51].
Emergy Analysis	Howard T. Odum (1980s)	A method to measure all forms of energy, resources, and human services based on solar energy equivalent, which allows the direct comparison of input and output flows and stocks through the MSW system.	It offers a detailed evaluation of all aspects, including material, energy, labor/capital and environmental impacts. Emergy research enables a study of different economic and ecological costs and resources in local units [52].	The absence of uncertainty analysis in its calculations is a major flaw, particularly because average values are used for transformities.
Geographic Information System	Roger Tomlinson (1967)	A geographic information system (GIS) is a framework for gathering, managing, and analyzing spatial data, and organizes layers of information into visualizations using maps and 3D scenes [53].	GIS gives the precise and real-time information of MSW generation, transportation and treatment so as to make a good decision for policy makers [54].	Spatial data needs field verification. The GIS or RS techniques are not suitable for site investigation or small areas [54].

Unit Emergy Values (UEVs) database [57]. Emergy synthesis has been used to calculate the environmental performance of solid waste management [67]. In general, the combination of such methods is required in order to address this arduous issue of waste management. It is suggested that one potential method is the combination of LCA and GIS in this particular area of waste management. Also, one potential method could be mathematical modeling. Although few studies have been done using mathematical modeling, it is suggested that there is still a gap that can be filled by applying this method in future studies on the area of MSW.

Mathematical Programming (MP) models were commonly used in the design of efficient SWM systems in the past [72]. Numerous case studies in the literature

exhibit the usefulness of the results produced by using mathematical tools. For example a study performed by [73] established mathematical models to identify the generation of suburban solid waste per capita to variables such as household income, number of people, and education. The literature review found that most of the experiments mainly represent the issue from an economic perspective and are meant to minimize the total expense of the project. There continues to be minimal research on the application of mathematical optimization to the design of solid waste management systems with a view to reducing GHG emissions [74]. Circular Economy (CE) is viewed as a key solution to social and environmental issues related to the conventional “take-make-consume-dispose” system [75].

The idea of a circular economy is an effective interface concept that promotes fundamental interactions between resource utilization, waste, and environmental pollution and leads to the convergence of environmental (output-related) and economic (input-related) policies [76]. However, integration of circular economy theory and mathematical modeling could be a potential method for the future trend of waste management. For instance, in order to solve this arduous issue for future considerations, there is a need to survey the general waste administration framework in an all-encompassing manner, which changes from nation to nation, contingent upon their topographical, social, innovative, and financial conditions. This approach will prompt effective vitality frameworks, a decrease in the volume of waste resulting in improved waste treatments, and, furthermore, the use of robotic technology to segregate waste. Newer research has expanded these models to encompass hybrid or data-driven models which include (1) Machine-learning-based LCA can predict environmental burdens, which are at hand [77], (2) GIS-based and multi-criteria waste facility location models [78,79], (3) Several interactions of emergy-LCA to define the ecological and economic efficiency [80]; and (4) Incorporation of system dynamics and artificial intelligence to forecast urban waste flows with different policy connotations [81,82]. The main advantage of the emergy analysis will always be its ability to balance environmental and socio-economic flows (e.g., monetary value and labor) on a similar scale [55]. However, the amount of uncertainty it quantifies is ambiguous, and future studies recommend Monte-Carlo or Bayesian calibration to make it more robust [83]. LCA has continued to be the most-used method of MSW research [59–62]. The latest studies have improved the LCA boundaries with spatial and temporal dynamics, most prominently in the carbon neutrality and circular resource flows [84]. The GIS-based analysis has evolved to the real-time optimization of waste collection using IoT sensors [85]. System Dynamics remains critical to the simulation of policies, and CF analysis is increasingly used alongside the recovery of renewable energy research [86]. These developments are a witness to the failure to address all the complexities of MSW using a single approach; it is becoming the major trend to combine methods such as LCA + GIS or Emergy + LCA [87]. Overall results show that a single analytical technique is not enough to handle the complexity of the MSW management system. On the contrary, recent research shows that there is a clear movement towards integrated and hybrid approaches that integrate environmental, economic, spatial, and technological approaches [50,54,55,57]. The development of this evolution is further evidence of the growing significance of multidisciplinary decision-support tools to create sustainable and resilient waste management systems. Moreover, to ensure a clear correspondence between the research objectives and the findings, the Results and Discussion are organized into five thematic sections. Theme 1 presents the analysis of author pro-

ductivity and citation trends (Objective 1). Theme 2 examines the most influential journals, institutional affiliations, and contributing countries (Objective 2). Theme 3 investigates keyword evolution and emerging research hotspots (Objective 3). Theme 4 evaluates the life-cycle and cumulative growth patterns of annual scientific publications (Objective 4). Finally, Theme 5 presents the co-citation cluster analysis to reveal the intellectual structure and future research directions in MSW management (Objective 5).

3.2 Theme 1. Author Productivity and Citation Analysis (Objective 1)

3.2.1 Analysis of the Author's Production with Citation Over Time

Fig. 2 shows the most productive authors in the research on MSW in terms of publications. Of the mentioned scholars, it seems that Tsang DCW is the most active author, who publishes 77 works, followed Zhang Y. [9] and Wang S. [37]. Other notable contributors are Ok Y.S., Kumar S., Kumar A., Sun Y. & Phillips P.S., Li J., and Wang L., with 32, 30, 28, 27, 24, and 23 respectively [11,25–27].

The concentration of research output by a small number of authors suggests that there is a large concentration of research output around the major scholars and research groups, which is in keeping with the law of Lotka in bibliometric research. According to this law, a large percentage of publications in any scientific field is normally made by a small percentage of scientists. The same conclusions have been drawn in recent bibliometric reviews on solid waste management, as a small number of researchers have contributed significantly to building the sector [88]. Very prolific writers often organize big global partnerships and interdisciplinary working teams, especially on the new fronts of waste valorization, circular economy, and resource recovery technologies. These research topics are gradually taking over MSW studies because they are related to the objectives of sustainable development and environmental sustainability [89,90]. The other interesting observation made in Fig. 2 is that there is a high number of Asian researchers, especially the Chinese and the South Koreans. This indicates the fast development of waste management studies in Asia because of the rise in the urban population, the increase in waste production, and government spending on sustainable waste management technologies [91]. In general, Fig. 2 indicates that a small, yet very productive group of researchers dominates municipal solid waste research; their work produces a significant impact on the development of science and technological advancement in waste management. Fig. 3 shows how the productivity and impact of the authors change over time, but it shows a concentration on the frequency of publication and the total number of citations per year (TC/year).

The number shows that the majority of authors started to publish in this area after 2010, and the productivity rate rises significantly from 2018 to 2024. This tendency is

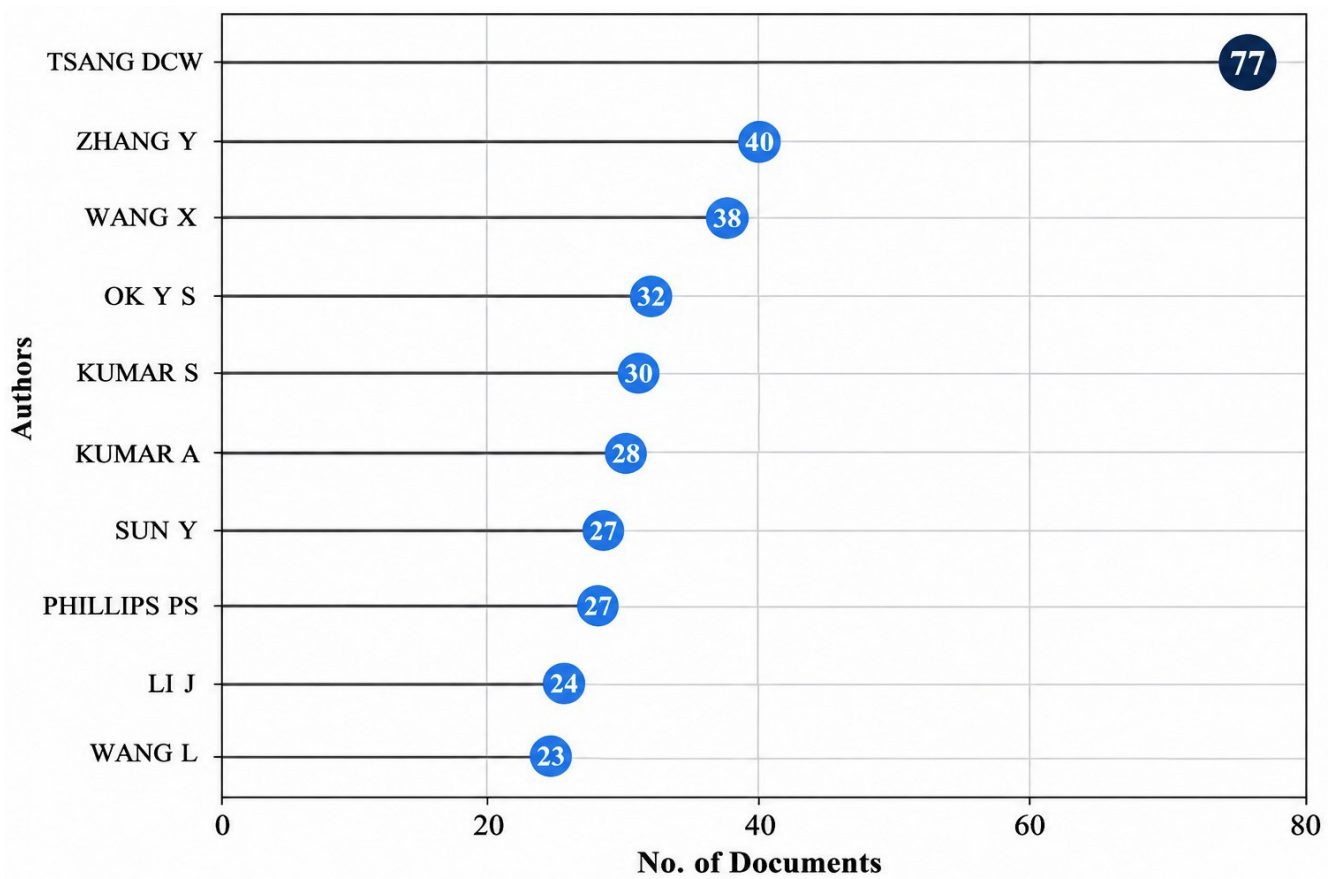


Fig. 2. Author's Number of Documents

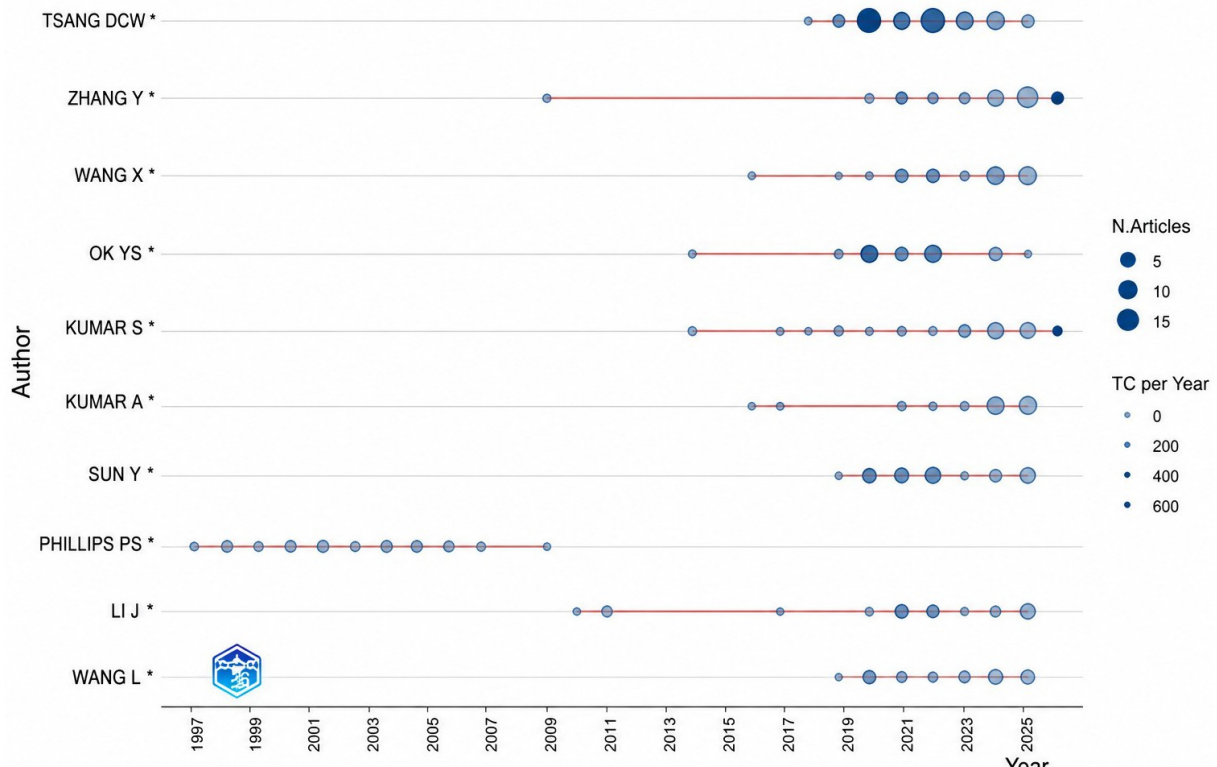


Fig. 3. Author's Production with Citation Over Time Period

the consequence of the increasing concern of the world about waste production, environmental pollution, and sustainable city building. Recent research indicates that MSW research has been growing at an alarming rate over the past decade, which can be attributed to sustainability policies and the global shift to circular economy models [90]. The fact that the number of publications has been on the rise is also associated with the growing attempts to enhance the waste collection

systems, waste-to-energy technologies, and recycling procedures. Such issues have been central to the contemporary research on waste management as urban areas aim at reducing landfills' reliance on them and improving resource utilization [89]. Fig. 3 displays the number of publications, with the bubble size and the intensity of the color symbolizing the citations per year, or in other words, the scientific impact of the particular author. Tsang DCW and Zhang Y. are both productive

and have a high citation impact, which proves that they are the leaders in the development of MSW research. The rate of high citations is also associated with the studies that cover emerging and high-impact issues, such as the circular economy, waste valorisation, and advanced waste treatment technologies. These issues have received more and more attention because scientists want to transform waste into useful products and minimize the negative effect on the environment [92].

As Fig. 3 also demonstrates, there are authors, e.g., Phillips P.S., who worked in the field earlier and published their works in the late 1990s and early 2000s. The initial research centered on conventional methods like waste management, including landfills and waste collection systems. Nevertheless, the latest publications show a definite shift toward an integrated and sustainable waste management model, which can include smart waste management, the circular economy, and resource recovery technologies. It is a change in the priorities of environmental research and policy [93]. The joint analysis of Figs. 2 and 3 reveals several significant trends in the field of MSW research, such as (1) the level of publication output has grown notably after 2015 in line with the rising significance of sustainable waste management and circular economy policies, (2) highly cited authors serve as contributors to the emerging areas of research, specifically, waste valorisation, recycling technologies, and waste-to-energy systems, and (3) the research field is becoming more and more multidisciplinary, incorporating environmental engineering, materials science, and studies of sustainability. These tendencies prove that developing trends in MSW research are toward innovative technologies in resource recovery and circular economy frameworks that are required to overcome global waste challenges and to meet sustainable development objectives. The most recent high-citation articles indicate that MSW is a central element of the carbon-neutral agendas and the circular economy [94]. The focus of these studies is on the recovery of renewable energy, resource circularity, and digital monitoring technologies. The increase in the number of relevant AI- and IoT-based waste-management articles is an indication of a paradigm shift to smart waste systems [95, 96]. In its entirety, the analysis provides evidence that the development of MSW research has been increasingly guided by internationally renowned scholars who have contributed to the shift from traditional waste management systems to the circular economy and waste valorization, towards smart waste management technologies.

3.3 Theme 2. Analysis of Research Sources, Institutions, and Countries (Objective 2)

3.3.1 Major Categories of Disciplines

The comprehensive database of articles assists in revealing a reliable and detailed picture of the academic MSW work available [97].

A preliminary study was conducted to classify which

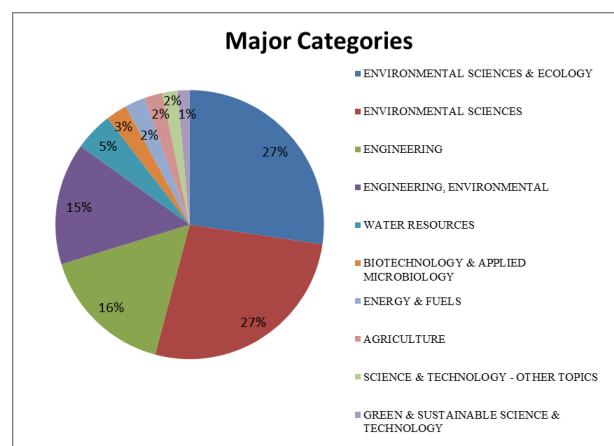


Fig. 4. Major Categories and Their Shares

journals concentrate more on the area of MSW, with titles containing keywords related to environmental management and waste. The extracted publications from WoS can be categorized into ten major disciplines. As shown in Fig. 4, the majority of papers belong to the category of environmental science and ecology, accounting for 27%, and predominantly, environmental science is 27%. However, engineering is (16%), and then engineering and environment is (15%). The other papers belong to the discipline of water resources (5%), biotechnology and applied microbiology (3%), energy and fuels (2%), agriculture (2%), science and technology (2%), and green & sustainable science & technology (1%), as mentioned in Fig. 4. Similarly, the selected 14,438 articles were published in 394 different journals. To sum up, the disciplinary distribution supports the idea that MSW research is becoming a very interdisciplinary endeavor. Environmental science, engineering, biotechnology, sustainability, and energy research have become more and more interwoven. It is becoming increasingly clear that integrated solutions are required to tackle complex waste management problems to create sustainable urban development.

3.3.2 Analysis of Cited Journals

Table 3 presents the most influential journals contributing to MSW research, including their publication counts, h-index, impact factor (IF), and network centrality. The dataset identified 394 journals, which shows that MSW research is multidisciplinary and covers environmental science, environmental engineering, waste management, biotechnology, and sustainability studies. Out of the journals reviewed, Environmental Science and Technology can be considered one of the most effective sources of MSW research. As of the revised data, the journal includes about 6485 articles connected to the topic of MSW, which exhibit a steady increase in the output of environmental research. It has a high h-index of over 520 and an impact factor of about 11.4, which shows that it has a strong citation impact and scientific influence. The journal is dedicated to the issues of environmental chemistry, pollution prevention, and environmental engineering, as well as the use of advanced waste treatment technologies, which is why it occupies the dominant position in the distribution of

Table 3

Top 20 Cited Journals in the Field of MSW upto 2025

S. No.	Journal	Publication Count	h-index	Impact Factor	Centrality
1	Environmental Science & Technology	6485	520	11.4	0.08
2	Water Research	5980	410	13.5	0.09
3	Waste Management	5720	262	8.4	0.07
4	Chemosphere	5310	340	8.3	0.07
5	Science of the Total Environment	5205	365	9.8	0.08
6	Bioresource Technology	4580	345	11.4	0.11
7	Journal of Hazardous Materials	4310	395	13.6	0.04
8	Water Science and Technology	3920	140	2.8	0.05
9	Waste Management & Research	3560	110	5.7	0.05
10	Journal of Environmental Management	3150	240	8.7	0.04
11	Environmental Pollution	2940	320	9.9	0.03
12	Resources, Conservation, and Recycling	2760	215	13.7	0.04
13	Environment International	2280	290	15.1	0.03
14	Applied and Environmental Microbiology	2050	390	5.1	0.07
15	Journal of Cleaner Production	1980	325	11.1	0.03
16	Sustainable Production and Consumption	1340	110	10.2	0.02
17	Environmental Science and Ecotechnology	1180	130	18.2	0.02
18	Waste and Biomass Valorization	1020	95	3.5	0.03
19	Environmental Technology & Innovation	980	85	7.3	0.02
20	Renewable and Sustainable Energy Reviews	760	430	16.8	0.02

MSW-related research. The most productive journal is Water Research, which has about 5980 publications in the dataset and an h-index of more than 410.

The journal has an impact factor of about 13.5, and it is one of the most popular journals in research works associated with wastewater treatment, landfill leachate treatment, and environmental contamination caused by municipal waste disposal. Its centrality value (0.09) is relatively high, meaning that it is in the bridging position between water pollution research and solid waste management research. The other journal, which is one of the strongest, is Waste Management, which is third in productivity. The journal has also published about 5720 articles regarding MSW research, and its h-index is more than 260 and has an impact factor of about 8.4. Considering its specialized focus, the journal has been considered a leading publishing outlet in waste management studies, such as research on waste generation, waste characterization, recycling technologies, landfill engineering, and waste-to-energy systems. Various environmental journals of a multidisciplinary nature also contribute to MSW research. Articles in journals like Chemosphere, Science of the Total Environment, and Journal of Hazardous Materials deal with the pollutant emissions of waste streams, the pollution of landfills, microplastic pollution, and environmental risk assessment. These journals possess significant impact in terms of citations since they are specialized in environmental pollution and toxicology, which have close

relations with the problems of municipal waste management. The journal Bioresource Technology is especially significant in the study of organic waste valorisation, anaerobic digestion, composting, and the production of bioenergy. The journal has a centrality value in the network analysis, which makes it a knowledge hub between waste management, renewable energy, and biotechnology research. Equally, sustainability-related journals, including Resources, Conservation and Recycling and Journal of Cleaner Production, have become more popular in MSW studies because of the increased focus on the concept of a circular economy, sustainable resource management, and life-cycle analysis of waste systems. Another important source is Environment International, which produces high-impact literature on environmental pollution in the world, the impact of waste on human health, and environmental policies. The fact that its impact factor is more than 15 points to the growing consideration of the environmental risks related to the field of municipal waste management. The general conclusion of the analysis is that MSW research is oriented toward the high-impact Q1 journals in the environmental field, which suggests increased scientific relevance to sustainable waste management, pollution control, and the use of a circular economy. This is evidenced by the availability of journals related to various fields of science, which prove the interdisciplinary character of MSW research and combine environmental engineering, biotechnology, environmental chemistry, and sustainability science. The majority of the MSW

publications are published in the top-quartile (Q1) journals in the field of environmental science, which reflects the high interest of researchers all over the world in the topic of sustainable waste management. It is observed that journals dedicated to resource efficiency and the resource economy are gaining momentum in MSW. The availability of journals in environmental science, biotechnology, sustainability science, and engineering means that MSW studies are a combination of several sciences. Unrestricted publications in recent times focus on waste-to-energy technologies, waste recycling, handling plastic waste, and the conservation of carbon. The study also suggests that the trend of publishing research articles in high-impact interdisciplinary journals is likely to persist as a future trend in MSW, aligning with the growing global focus on circular economy approaches, resource recovery, and climate-resilient waste management.

3.3.3 Analysis the Affiliation of Institutions and Countries

Fig. 5 shows the most effective institutional affiliations that produce research on MSW. The findings indicate that the scientific community is becoming interested in sustainable waste management and circular economy approaches and that the results are limited to a few top schools, especially in Asia. The Hong Kong Polytechnic University has the highest number of publications at about 95, which is the highest among all institutions, meaning that it has a high degree of research on environmental engineering, waste valorization, and sustainable urban waste management. This leadership shows Hong Kong's priority on modern recycling systems and sustainable waste treatment technologies [98].

The Malaysian institutions also show a great contribution. In the second and third positions, Universiti Teknologi Malaysia (59 publications) and Universiti Teknologi MARA (55 publications) follow, respectively, and indicate the increased investment of Malaysian researchers in waste management and environmental sustainability [99]. On the same note, Universiti Kebangsaan Malaysia also makes significant contributions to research production, which further underlines the involvement of Malaysia in the same. Korea University (52 publications), Chulalongkorn University (48 publications), and Tsinghua University (37 publications) are other leading institutions and also have great research activity in East and Southeast Asia. The developed waste management policy in these countries has triggered scholarship activities in research regarding recycling technologies and waste-to-energy [100,101]. Moreover, colleges like the University of Northampton and the University of Johannesburg report an increase in research output in Europe and Africa, which suggests the global community of MSW issues. Broadly, the institutional allocation has indicated that Asian universities are the major players in MSW research output due to rising urbanization, the production of waste materials, and sustainability efforts. The trend also draws much

attention to the significance of global cooperation in the development of new and long-term solutions in waste management. Fig. 6 shows the time series development of research productivity of the top scholarly organizations, such as The Hong Kong Polytechnic University, Chulalongkorn University, Universiti Teknologi Malaysia, Universiti Teknologi MARA, and Korea University.

The findings show that institutional input to municipal solid waste (MSW) studies was rather scarce until around 2013–2015, when there was a vast increase in publication volumes. This rate of expansion is aligned with the increased global interest in issues of waste production, urbanization, and environmental sustainability. The Hong Kong Polytechnic University is one of the institutions that are analyzed, which demonstrates the most significant rise in research productivity, especially after 2019. This tendency indicates that East Asia pays a lot of attention to the development of advanced waste treatment methods, circular economy approaches, and waste valorization approaches in its studies. Bibliometric research indicates that MSW research has gained a significant contribution from Asian research institutions owing to the growing government investments in environmental sustainability and urban waste management systems [90]. On the other hand, Universiti Teknologi Malaysia and Universiti Teknologi MARA also show steady growth since 2016, which points to the growing involvement of Southeast Asian universities in the solution of waste management issues in the region. Improved urbanization and population growth in Southeast Asia have greatly enhanced the production of municipal waste, increasing the academic research on the topic of sustainable waste management technologies and resource recovery systems [102]. Moreover, the constant growth in the number of publications from Chulalongkorn University and Korea University is a sign of the development of regional networks of research and interdisciplinary cooperation in waste management research.

The cooperation of institutions has gained more significance in the development of new technologies that include smart waste control, waste-to-energy, and improved recycling plans. Overall, the number indicates the increased involvement of Asian academic institutions in defining global MSW research as a regional trend in research leadership in favor of emerging economies with dire waste management challenges. Fig. 7 shows how the scientific publications on MSW are distributed in the world. The findings have shown that India and China lead in terms of research productivity in the world and are followed by some of the emerging economies such as Malaysia, Indonesia, and Thailand. The hegemony in the production of publications in India is associated with the strong desire of the country to establish efficient waste management frameworks because of the high population increase and subsequent rise in urban waste. China is another major contributor to MSW research, and it shows massive

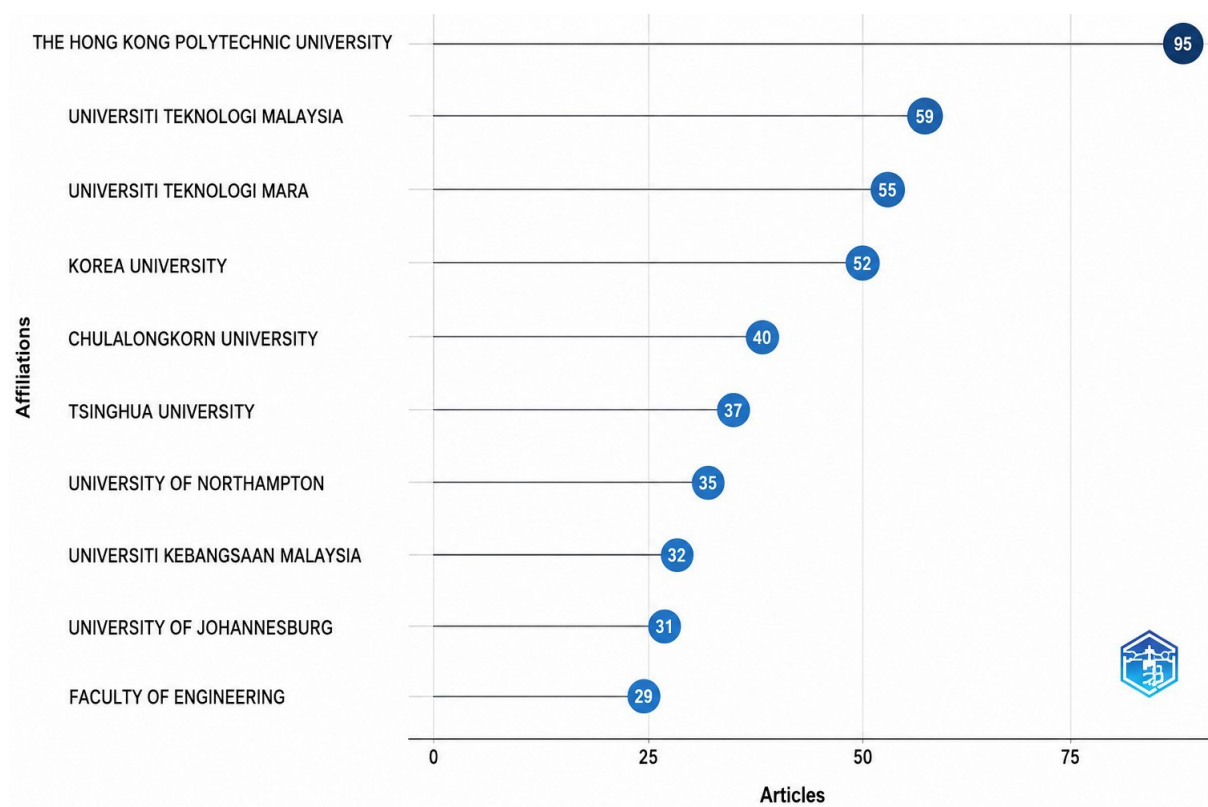


Fig. 5. Affiliation of Institution with Production

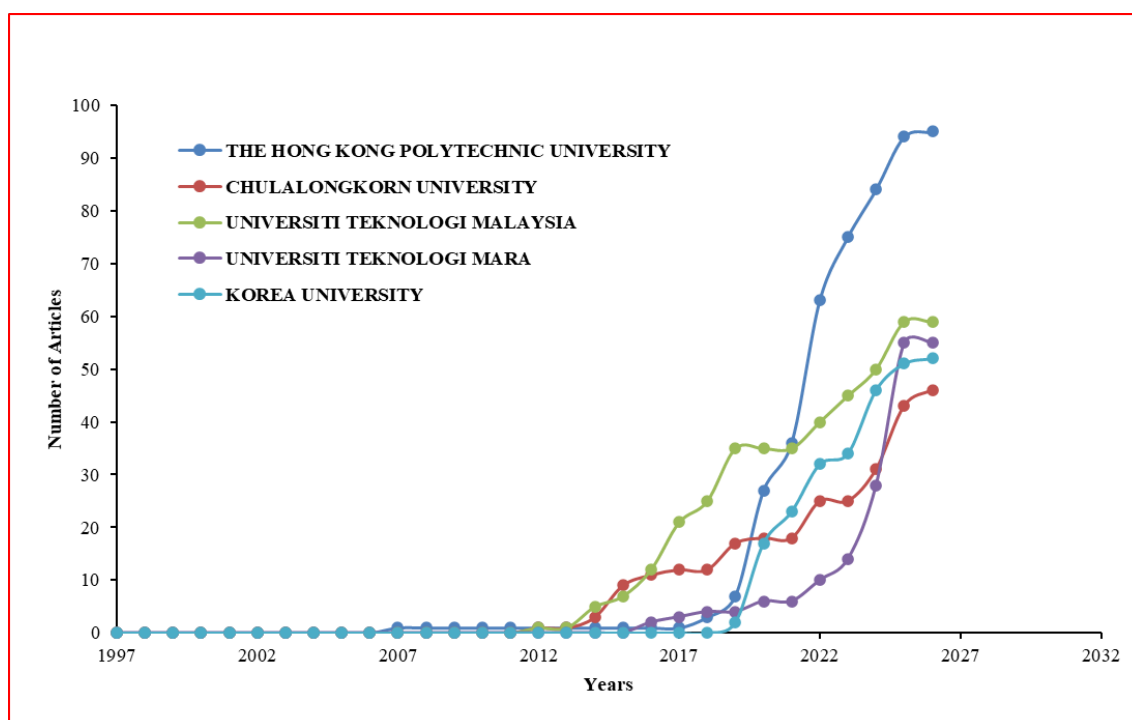


Fig. 6. Affiliation of Institution Overtime Period

national investment in environmental research, waste treatment technology, and the circular economy. The recent bibliometric reviews attest that China and India have become the most significant contributors to the research in waste management worldwide because of the magnitude of the waste production issues and the growing adoption of policies on sustainability [90]. Fig. 7 also shows that there are high research contributions from various developing nations. This tendency means that MSW research is increasingly concentrated in areas where the accumulation of waste creates strong environmental stress. Past bibliometric analyses have revealed that over 130 countries are researching MSW

around the world, while the reality has been that research productivity is highly concentrated among a few countries with well-established research infrastructure [103]. Moreover, developed countries like the United Kingdom and European countries remain dominant in the development of waste management technologies, especially in areas like waste recycling systems, circular economy models, and policy-oriented waste minimization models. Nevertheless, the growing number of research papers published in the developing world indicates that MSW research in the world is slowly moving to areas where waste management issues are of utmost concern.

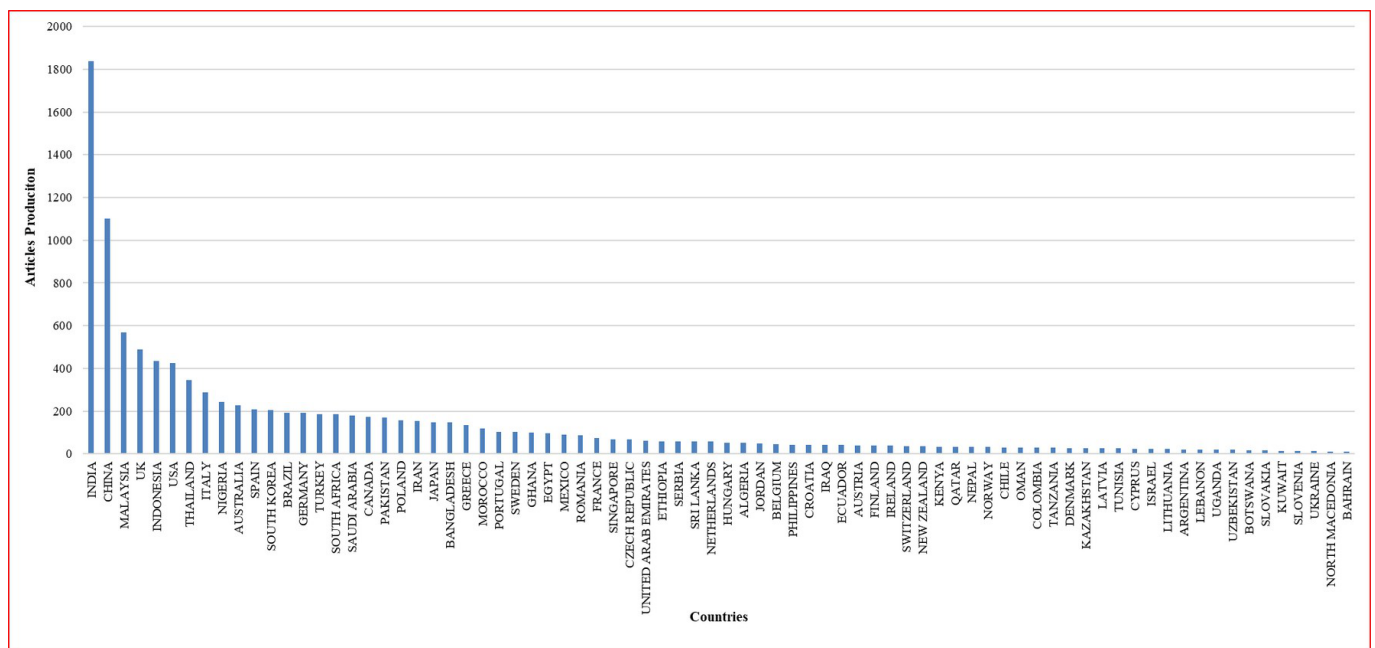


Fig. 7. Total Productions of Different Countries

Fig. 8 presents the time development of MSW research productivity in the leading countries of contribution. The findings indicate a slow growth in publication output between the mid-1990s and around 2015, then after 2018 a steep rise, which points to the fact that the world is becoming more and more interested in waste management. The fastest-growing country with respect to research production is India, especially since 2020. This has been boosted by the rising governmental efforts in dealing with the problem of waste management, such as the national programs on sustainable waste management and environmental protection. In recent works, it is noted that the fast rate of population growth in urban areas and waste production in developing economies have greatly contributed to the enhancement of the research conducted on waste management technologies and policies [90].

There is also a significant rise in research productivity after 2018 in China, which indicates the high investment made by the country in environmental science and technological innovation. The existing research in China has gradually focused on waste-to-energy systems, waste recycling methods, and digital solutions in waste management, as these tools are necessary to decrease reliance on landfills and enhance the efficiency of resource recovery. The United Kingdom exhibits a relatively stable pattern of growth throughout the entire analysis period, which can be explained by the fact that this country has been a pioneer in terms of research related to environmental policy and technologies of sustainable waste management. In the meantime, Malaysia and Indonesia demonstrate remarkable growth in the quantity of research publications post-2019, which may be attributed to the activity of the region in the sphere of the development of the infrastructure of waste management and sustainable waste treatment technology. Recent works highlight the fact that MSW research is now based not on traditional management of landfills but on integrated waste management systems, circu-

lar economies, or on new methods of sorting waste, including artificial intelligence and digital monitoring devices [102]. Taken together, the three figures (Figs. 6, 7, and 8) demonstrate some significant trends in the research on MSW in the world. To begin with, the level of research has grown significantly in the last ten years, as environmental concern has grown and the amount of waste produced across the world has risen. Second, the influence of Asian countries and institutions in MSW studies is on the rise because of rapid urbanization and government investment in environmental sustainability. Third, the thematic focus of MSW research is slowly turning to the principles of a circular economy, waste valorization technologies, and digital waste management systems, which are key to the achievement of sustainable urban development. Overall, the insights gained from these studies highlight the need for continued innovation, global cooperation, and policy investments in sustainable waste management to shape the future of MSW research.

3.4 Theme 3. Keywords and Research Hotspots (Objective 3)

3.4.1 Keywords and Research Hotspots Analysis

The authors' keywords are the words used to specify the main structure of the authors' reasoning, as shown in Fig. 9. They provide the core information of the article. and research trends can be analyzed using these keywords. A knowledge map of keyword occurrence could reflect hot spots and burst keywords (frequently cited keywords) in the articles [104]. Consequently, Fig. 9 illustrates the top keywords in terms of count and centrality. During the data analysis, 493 keywords in total were extracted from the selected papers. The most frequently used keyword was found to be "municipal solid waste." Whereas different authors tried to use keywords closely related to the treatment and process of MSW. The keyword search helps to identify the

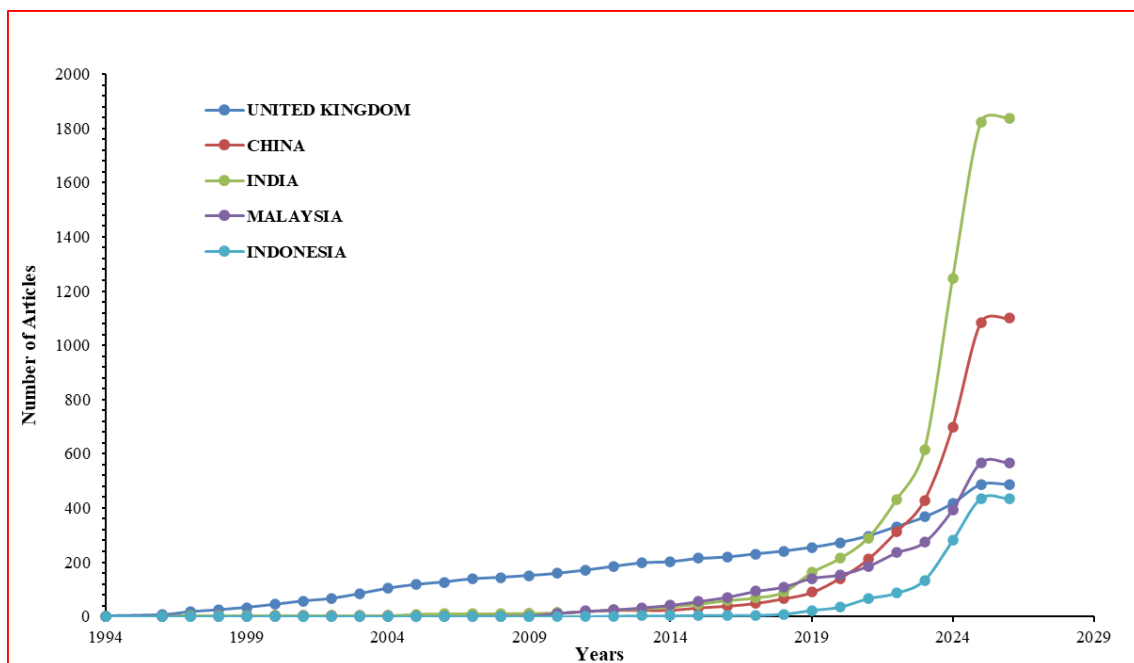


Fig. 8. Production of Countries Over Time

prominent research subject areas of the study. The author keyword analysis shows that “municipal solid waste” is the keyword used most, with a count of 2550 and a centrality of 0.06. “Management” ranks at number two with a publication count of 1193. Following, “heavy metals” ranks at number three with a total of 1168 publications. Similarly, “sewage sludge” and “removal”, with a centrality of 0.05, rank at number four and five, respectively, where (sewage sludge) has a total of 1035 publications and (removal) has 910 publications. These findings indicate that heavy metal treatment and sewage sludge removal are the top technical problems in MSW management.

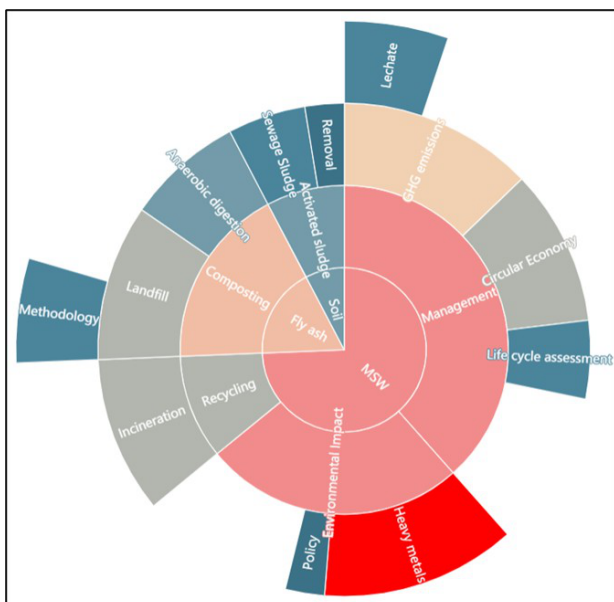


Fig. 9. Taxonomy of Frequently Used Major Keywords

However, in-depth analysis of keyword citation bursts revealed the most used and researched keywords. The analysis revealed that “food waste” was the most noticeable hotspot with a citation burst of 55.3575, showing that household food waste management is becoming the hottest trend in MSW. Whereas other hotspots include generation, emissions, technology, combustion,

pyrolysis, and the most used method is LCA.

The analysis of citation burst revealed that a lot of research has been done on the topic of waste generation. The quantitative amount of waste generation was one of the key research hotspots in the area of MSW. Whereas large numbers of papers were found highlighting the technological advancement needed for the reduction of MSW. A lot of research papers have been found on combustion processes, with a strong citation burst of 47.8585, which illustrates the attention towards the process of incineration. An enormous amount of research was done on the proper collection of MSW. The citation burst of the collection was found to be 25.51 with a centrality of 0.02, which shows its impact is extremely highlighted by the researchers. During analysis, it was found that researchers from both developing and developed countries have shown keen interest in MSW in different cities. It was observed that they mostly prioritize their target area on the basis of the cities or countries they belong. Nevertheless, large numbers of papers were found in the area of the transportation sector, highlighting the emissions caused during the bulk transportation of waste from the collection point to the final disposal facilities of MSW. A large number of papers also highlighted the problem of carbon emissions during this process. Furthermore, analysis revealed that among developing countries, China has the 30.3701 strongest citation burst among all the countries, which has made it one of the hot research spots.

Additionally, the three-field plot that connects the mentioned references, authors, and keywords was created (Fig. 10), which allows for a complete view of the intellectual framework and thematic evolution of waste management research. The mentioned reference field brings to the fore some of the pioneering studies that have been instrumental in the advancement of research in waste management. These are also influential journals that normally discuss the trends in waste production

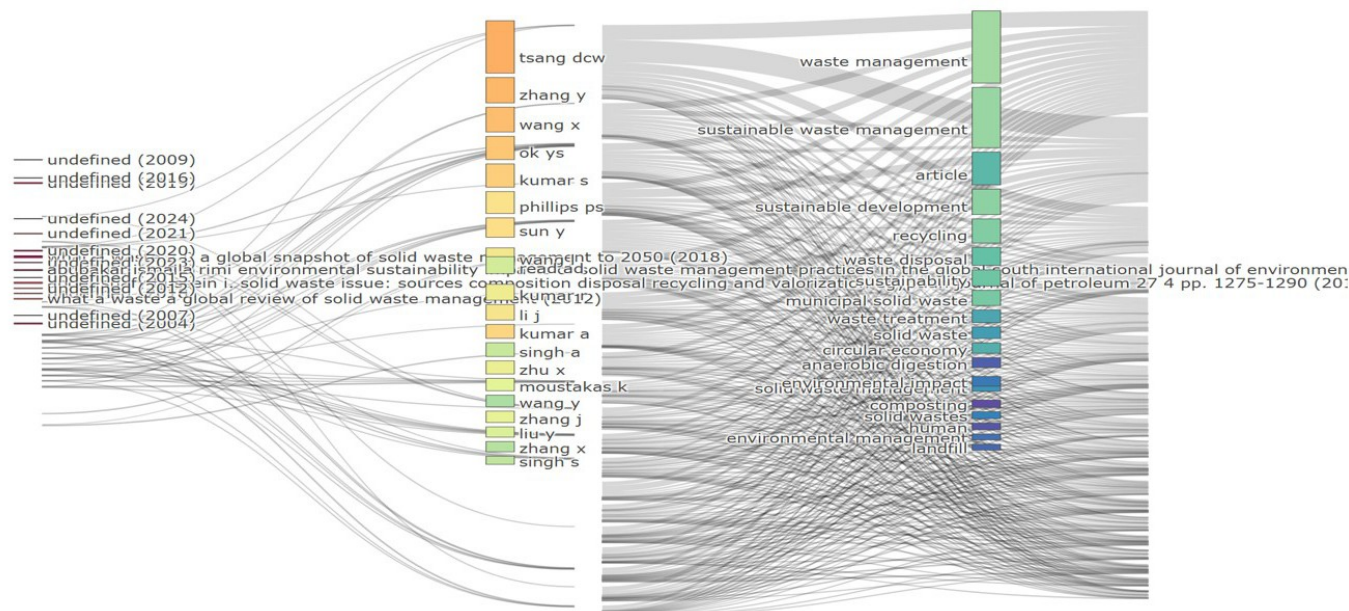


Fig. 10. Three-field plot linking cited references, authors, and keywords

all over the world, the environmental effects of waste disposal, and policy frameworks governing sustainable waste management. The idea of these studies became the conceptual base of modern research on the strategies of the circular economy and integrated waste management systems [105]. The field of authors presents a number of well-known researchers who have contributed quite a lot in the field. Both authors represent a close association with the foundations in the literature as well as with the emergent research topics, which implies their significant contribution to the scientific knowledge in the area of waste management and sustainability research. The keyword field shows the prevalent themes in the literature. Waste management, sustainable waste management, municipal solid waste, recycling, waste treatment, circular economy, composting, landfill, and environmental management are major areas of research. The popularity of these keywords suggests a clear change in emphasis in research from traditional waste disposal solutions to sustainable resource management and the concepts of the circular economy [106]. Recent literature emphasizes the fact that the concept of the circular economy is gaining prominence in the mainstream of contemporary waste management strategies due to its ability to foster waste minimization, recovery of resources, and sustainable consumption habits [107]. Nevertheless, several issues still exist despite the significant progress. To give an example, institutional obstacles, monetary constraints, and technological difficulties tend to restrict the adoption of circular economy models in waste management systems, specifically in developing nations [108]. Thematic and keyword analyses show a clear overall trend from the focus on conventional waste disposal to that of resource recovery, circular economy, digital technologies, and sustainable waste management. These new research hotspots can offer guidance for future research on municipal solid waste management, as well as for policy.

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3.5 Theme 4. Life-Cycle Assessment of Scientific Publications (Objective 4)

3.5.1 Life-Cycle Assessment of Annual Scientific Publications

The life-cycle analysis of annual publications (Fig. 11) reveals the temporal evolution and maturity trajectory of municipal solid waste (MSW) research over the past three decades.

The fact that the annual publications are distributed in a classical technology or knowledge life-cycle pattern is a common occurrence in a fast-growing research span. Based on the curve-fitting results, the growth of the publications has a clearly faster growth phase, and then the model predicts a leveling off, after which the model estimates the maximum level to occur around 2024.3. The goodness of fit ($R^2 = 0.737$) shows that the life-cycle model is acceptable in explaining the dynamics of the development of MSW research. In the early period (1995–2005), the number of publications was not very large, and it is one of the signs of the infancy of MSW research. Research at the time was mainly dedicated to basic waste management, such as landfill operation, waste characterization, and municipal waste collection systems. The scientific community had not realized the larger environmental consequences of the rising urban waste production by that time [109]. There was a slow rise in the volume of publications between 2006 and 2015 due to the increase in environmental consciousness about the ecological effects of solid waste disposal. Research started to grow in this stage in terms of recycling technologies, composting, and waste reduction measures. Also, the concept of sustainable development and a circular economy triggered the development of research in the field of resource recovery based on the municipal waste streams [110]. The introduction of international environmental policies and waste management regulations has also led to the

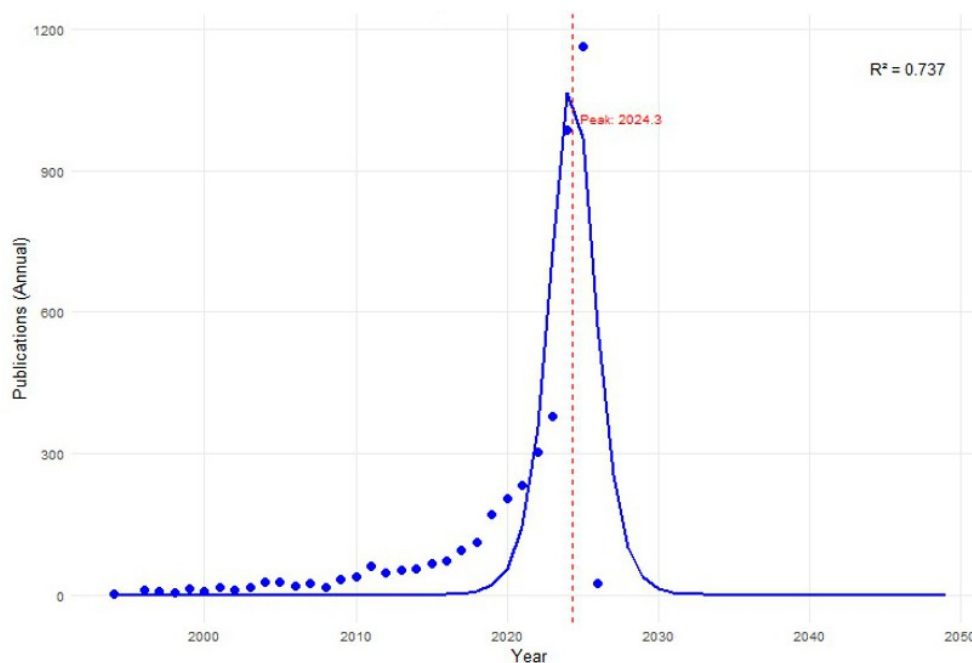


Fig. 11. Life Cycle Assessment of Annual Publications

growth of research in this field of study. It has a sharp increase in the number of publications in 2016 and reaches its peak of 157 publications in 2024. This flood is an indication of the increased need to solve global waste issues, given urbanization, population explosion, and rising consumption trends. As per recent reports, the generation of municipal solid waste materials all over the world is projected to rise beyond 3.8 billion tonnes per year by 2050, worsening the situation for sustainable waste management research. This has led to the development of MSW research which is now a multidisciplinary field that includes environmental science, renewable energy, material recovery, and circular economic strategies. This tendency of intensive research is justified in recent bibliometric studies. As an example, Santos Neto et al. [89] have demonstrated that there has been a significant rise in the literature that addresses the optimization of the waste collection system and sustainable waste logistics, which is due to the necessity to increase the efficiency of operations in the field of waste management in urban areas. Also, Muis et al. [111] emphasized that there is a growing scientific interest in waste-to-energy technologies, especially among developing nations where energy generation from waste is viewed as a significant alternative to a traditional landfill. The estimated fall in the life-cycle curve past 2025 is not always to be taken as lessening scientific knowledge or research interest, but instead as a shift to a stage of maturity in the scientific knowledge life cycle. Growth in publications in established areas of research usually levels out as the knowledge structures become stable and the research shifts to technological optimization and practice [90]. This means that future studies in MSW management will emphasize high waste valorization technologies, an integrated waste management system, and implementation of the circular economy. Comprehensively, the life-cycle analysis suggests that MSW research is now in the mature stage, requiring more technological optimization, interdisciplinary in-

tegration, and evidence-based policy implementation than fundamental conceptual development.

3.5.2 Cumulative publication growth analysis

The cumulative growth curve shown in Fig. 12 follows a logistic or S-shaped pattern, which is widely used to describe the diffusion of scientific knowledge and innovation within a research domain.

The curve shows the cumulative publication growth over time and marks various phases of scientific development. The initial development of MSW research is defined by the slow growth in the number of cumulative publications at the beginning of the period (1995–2005). The major occupations at this level were mainly engineering-related sciences that were concerned with methods of waste dumping and environmental pollution prevention. The cumulative growth curve starts to grow steadily between 2006 and 2015 as increasing interest in the research subject has been noted, and more scientific output is being produced. This development follows the development of combined waste management policies and rising global policies to curb landfill addiction. In the same way, the European Union waste policies and other regions supported the study of recycling, composting, and waste valorization [112]. The accelerated growth period is between 2016 and 2025, and the cumulative publication curve was steep at this time. This is the most fruitful phase of MSW research development, when the field enjoyed considerable scientific growth. Several reasons led to this acceleration, and they included the rising significance of the framework of a circular economy, the rise in environmental regulations, and technological innovations in waste treatment procedures. Recent works note that digital technologies and artificial intelligence are becoming more important components of waste management systems, which will allow for better waste sorting, predictive modeling of waste generation, and smarter collection systems [110].

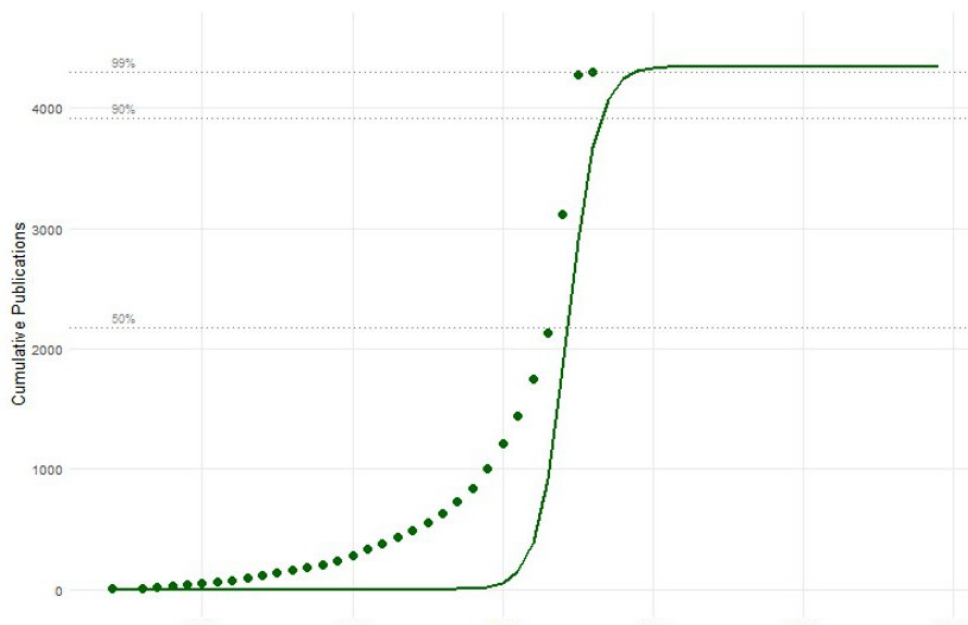


Fig. 12. Cumulative Growth Curve of Publications

Moreover, the combination of life-cycle assessment and sustainability evaluation practices resulted in the advancement of the scientific concept concerning the environmental effects linked to various waste management plans [89]. The cumulative curve is expected to hit a plateau by around 2028–2030, which indicates that the research area might eventually reach a maturity stage where most of the groundwork has already been published. Within bibliometrics theory, this form of saturation is sign that the scientific community has already developed a relatively stable knowledge base, and that future research will focus on technological innovation, policy implementation, and interdisciplinary integration as opposed to fundamental exploration [90]. The reference thresholds indicated in the cumulative curve (50%, 90%, and 99%) are various phases of diffusion of knowledge. The 50 percent mark is the halfway point of the knowledge growth, as half of all available contributions to science have already been made. The 90% and 99% marks are high levels of maturity, and these are where the research output starts to stabilize and the field is nearly saturated. The overall trend of cumulative publications reflects an ongoing growth and saturation of MSW research over the last 30 years. The forecast of publications stability is a sign of the consolidation of a mature knowledge base, as well as the persistence of the field's innovation potential in digital technologies, circular economy, artificial intelligence, and strategies for waste management in the face of climate change.

3.5.3 Implications for future research

The bibliometric trends of the life cycle and cumulative growth curves give a number of hints about the way MSW research can evolve. To begin with, future research topics are likely to be dominated by the circular economy and waste valorization. There is a growing interest in turning waste into useful resources, including fuels and chemicals, as well as construction materials [110]. Second, waste-to-energy technologies will remain a subject of research because governments

are embarking on sustainable ways of waste disposal, whilst at the same time solving energy needs. Pyrolysis, gasification, and anaerobic digestion are the technologies that can be expected to be significant in future waste management systems [111]. Third, smart waste management and digitalization are becoming a relevant field of study. The waste collection efficiency and rate of recycling can be greatly increased through the integration of artificial intelligence, Internet of Things (IoT), and big data analytics. Lastly, it will be necessary to integrate the disciplines of environmental science, energy engineering, urban planning, and policy studies to come up with sustainable waste management frameworks that will be able to address the complex issues of waste production in the world.

3.6 Theme 5. Co-citation Cluster Analysis and Intellectual Structure (Objective 5)

3.6.1 Co-Citation Cluster Analysis

Co-Citation Cluster Analysis is a tool used to identify relationships between articles based on their citations. It can be done in binary ways: co-citation and bibliographic linking [113]. Co-citation analysis indicates that two articles are jointly cited in other papers; in addition, a bibliographic link indicates that the same article appears in the references of two or more articles, making the citing papers connected [114]. In this study, by running CiteSpace, cluster labels were designed to demonstrate the cluster trend shown in Fig. 13, where each cluster illustrates one keyword, and its size indicates its co-occurrence frequency. The edge between the two nodes reflects the co-citation relationship of the two nodes, and the thickness of the lines expresses the frequency of co-citation [115]. In a broad spectrum, nodes in the same cluster show analogous roles in the network [116]. Fig. 13 shows the co-citation cluster analysis of keywords. To show and explore the references of papers on municipal solid waste, the top 10% of references with the highest annual citations were

selected for co-citation cluster analysis. It further shows that the co-citation network is made up of 200 nodes and 2160 edges, with a density of 0.1085, and is divided into 5 clusters.

According to a study [23], a cluster refers to a collection of co-citation references with constricted connections seen in a certain area. To reveal the underlying structure of complex networks, it is essential to recognize the structure of a cluster [117]. The quality of a cluster configuration is measured by the silhouette value of a cluster. Our analyses further reveal that the mean silhouette was 0.6452 for the total networks. Cluster no. 0 and cluster no. 1 are the largest clusters and show the domination of “municipal solid waste” as the central keyword in MSW research. A large number of papers were found with municipal solid waste as one of the frequently used keywords. Cluster no. 2 reveals the attention placed on MSW generation from pharmaceutical industries and the disposal methods of this category of waste. This includes landfilling, incineration, and other thermal processes like pyrolysis and gasification. The waste generation from pharmaceutical industries has been discussed in various papers. A large number of papers also discussed the incineration facilities for waste disposal and garnered attention towards the pollution of heavy metals. Whereas cluster no. 3 indicates vegetation, which draws attention to the untreated wastewater generated from industrial and municipal solid waste, which goes directly into the water streams and is then used for vegetation, highlighting the substantial impact of open MSW dumping on soil and vegetation. This leads to the presence of a large number of heavy metals in vegetables and other irrigated crops. The extracted papers also revealed that a lot of research has been done on the heavy metal contents present in waste, mainly generated from industrial sectors. Several studies were also found on compost planting and organic farming to reduce the waste content. Cluster no. 4 highlights the transportation of MSW, which is one of the crucial areas of waste management. A large number of papers were found on the environmental impact of the transportation of waste. Several studies suggested the use of unique vehicles, which include the use of smaller and greener transportation methods, particularly in the city centers of urban areas. This cluster illustrates the attention towards one of the crucial areas of waste management linked with the need for an efficient transportation system.

Additionally, the trend of average citations per year provides important insights into the scientific influence and knowledge diffusion within the field of waste management research (Fig. 14). In the initial years of 1994 to 2005, the rate of citation was not very high as there were few publications and the scope of waste management studies was also not very wide. The studies of this era were mainly concerned with tracking the pollution of the surroundings and the elementary waste disposal methods. The rate of citation started to grow slowly between 2006 and 2016, as the field of research matured,

and interdisciplinary directions in which environmental engineering, sustainability science, and urban planning are combined. The emergence of LCA and systems of waste management integration throughout this time is what contributed to the significant improvement of the scientific contribution of waste management studies [118]. There is the greatest citation impact in the years 2017–2021, with the average rate of citation the highest. This tendency aligns with the release of powerful research dedicated to the issue of circular economy strategies, managing plastic waste, and technologies of sustainable recovery of resources.

Recent findings also highlight that a circular economy can substantially enhance waste management efficiency by encouraging recycling, reuse, and energy recovery systems that can minimize environmental pollution and resource depletion [106, 119]. The second reason supporting the high citation impact is that the research on waste management is being progressively brought in line with global sustainability agendas, that is, the United Nations Sustainable Development Goals (SDGs). It has been shown that better waste management systems may be of great importance in terms of the mitigation of climate change, conservation of resources, and sustainable urban development [120]. The reduced average of citations after 2022 is not always a positive sign of the decreasing impact of research. Rather, it is a manifestation of the citation lag effect, in which recent articles have not received enough citations. As the body of bibliometric data shows, citation accumulation is a common event that takes several years to manifest itself, particularly in fast-evolving research areas [121].

4. Limitations and Future Research Directions

Previous MSW-related research studies identified numerous research directions. For Example, research conducted by [122] focused on the recycling of sustainable waste management and identified 12 major factors that stimulate sustainable recycling in developing countries. Their study highlighted the shared nature of sustainable MSW management. Another study by [14] mainly focuses on innovative solid waste management with the help of urban symbiosis. The result of the study revealed that by utilizing the recycled materials in different industrial processes, the CO₂ emissions can be reduced. The paper also proposed that by avoiding the production of waste at the source and by turning waste into a resource, and with the application of urban symbiosis, we can reduce resource consumption, which will lead to a reduced amount of waste disposal and generation. Whereas another paper was found similar in terms of methodology, written by [89]. However, the paper only focuses on identifying the global trends of MSW research during the years 1997 to 2014. Whereas our study focuses on the extensive time period of the last thirty years, recent and updated information can be presented. Likewise, in this study, we combined bibliometric analysis and network analysis so that new vigorous research trends, hotspots, and academic collab-

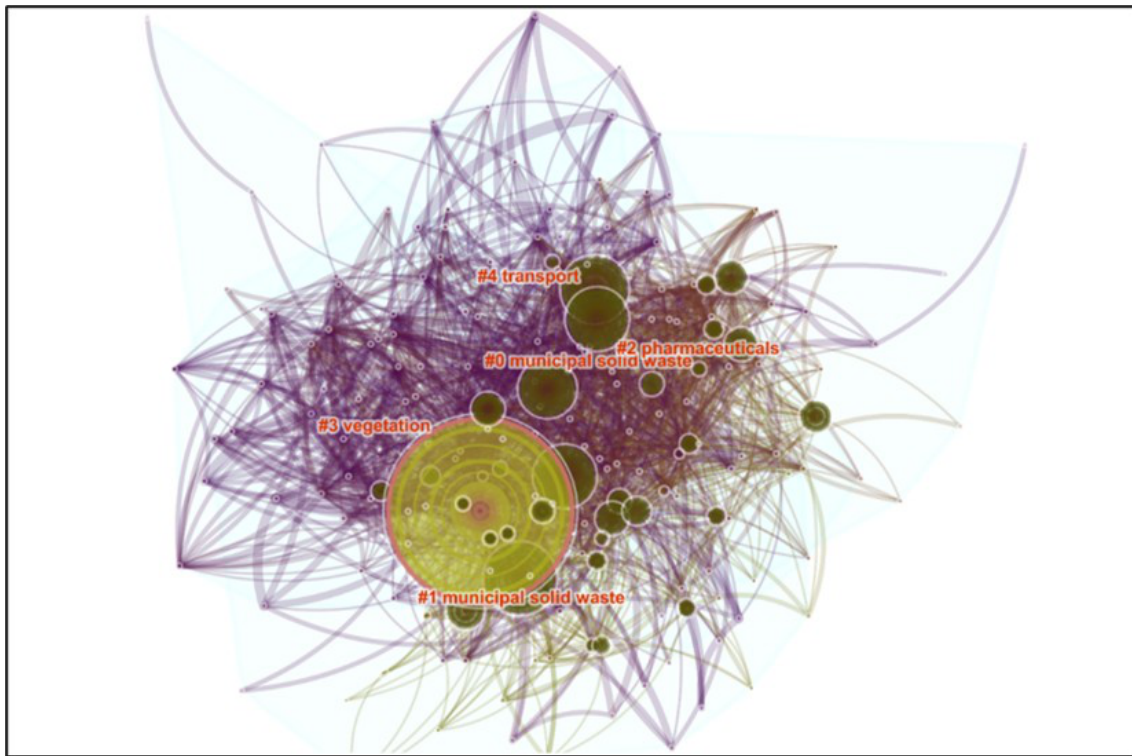


Fig. 13. Co-Citation Cluster analysis of Keywords

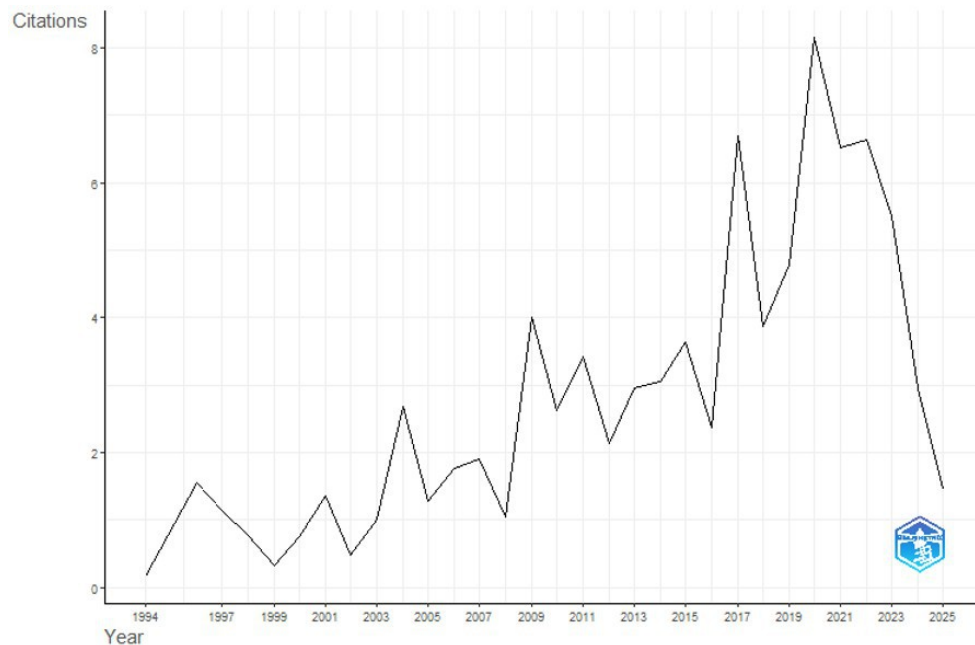


Fig. 14. Average Citation Per Year

orations can be discovered. Moreover, the four-decade evolution of MSW research reveals three distinct phases, including (1) Foundation (1995–2005): Focused on collection, disposal, and public-health concerns; (2) Development (2006–2015): Introduction of LCA and GIS methods; and (3) Transition & Innovation (2016–2025): Emphasis on circular economy and policy analysis & integration of digital tools, artificial intelligence, & smart-city systems [94,96]. The bibliometric results of this study show that researchers from both developed and developing countries have contributed to the area of MSW. It has been observed that researchers from developing countries are focused more on the proper disposal of solid waste. Whereas researchers from developed countries are actively working towards its treatment and further utilization of the waste. Such as Waste-to-energy

and the circular economy concept. It is expected that future studies would be more focused on the concepts of circular economy for sustainable MSW management and its possible integration. Moreover, Future research should therefore focus on developing scalable waste valorization technologies, strengthening waste management policies, and enhancing international collaboration in sustainability research. Addressing these challenges will be essential for achieving efficient and sustainable waste management systems globally. The future direction lies in integrating technological innovation with community participation and data-driven decision-making frameworks.

Changes in research priorities over the past three decades illustrate the global shift in viewpoints on MSW management. Waste collection, disposal, and environmental

protection have been the main focus of early research while more recent studies have also started to address the concept of resource recovery, circular economy approaches, digital technologies and artificial intelligence, life cycle assessment, and carbon-neutral waste management systems [50, 51, 54, 55]. These are current areas that have been shaped by the current rapid urbanization, increasing waste production, tougher environmental standards, technological progress, climate change concerns, and the global march towards sustainable development. However, there are still a number of underexplored areas, such as the role of AI in circular economy frameworks, digital twin technologies for smart waste management, climate resilience of waste systems, socioeconomic aspects of waste valorization and waste management strategies for low- and middle-income countries. Further work should therefore focus on interdisciplinary approaches that combine innovations in engineering, policy development, stakeholder engagement, and data-driven decision-making to ensure resource efficiency, reduce greenhouse emissions, and realize the Sustainable Development Goals (SDGs), particularly SDGs 11, 12, and 13. This means there will be a shift in thinking by considering waste as a valuable resource. Despite its comprehensive dataset, this bibliometric study has several limitations. Only WoS-indexed articles were analyzed, excluding conference papers and regional repositories that might contain practical case studies. Although VOSviewer and CiteSpace ensure robust visualization, manual interpretation can introduce subjectivity. Future research should integrate Scopus and Dimensions databases and employ natural-language processing (NLP) for automated thematic clustering [123].

4.1 Policy Implications

Lastly, the literature review indicates that it is crucial to suggest policies for future research. In the past, numerous research studies have been conducted worldwide on the area of MSW, discussing different policy implications by considering the local realities of the study regions. The policies may differ from country to country due to different infrastructure, economic level, industrial facilities, technology, land, and culture. The bibliometric indicators highlight the increasing role of circular-economy legislation, extended producer responsibility (EPR), and climate-neutral strategies [124]. Developed economies prioritize waste valorization and material circularity, whereas developing countries still struggle with collection and segregation systems [125]. It is suggested that countries must outline their specific policies by taking into consideration the local realities of each and every city. The integrated solid waste management system should be applied in order to prevent its harmful impact on the environment. The strategies related to recycling, source reduction, and resource recovery should be developed by considering available resources and the technological and economic feasibility of each country, which means the key to success is

to ensure the development of realistic plans. To manage the problem of solid waste, international cooperation among countries can play a dynamic role. Developing countries can seek technological assistance from developed countries to solve the issue of MSW. Whereas, in developing countries, the lack of knowledge, skills, and experience in handling MSW can be solved by promoting capacity building. The involvement of public officials, stakeholders, and the general public is needed to handle the issue. In addition, strategies for public education, such as the use of different popular modes of communication like the Internet, TV, billboards, and pamphlets, can be used for promoting awareness.

The output of this bibliometric analysis will help to inform policymakers, funding bodies, researchers, and environmental professionals in prioritizing future investments and strategies for the sustainable management of MSW. The research hotspots and the networks identified in this study can inform funding bodies about high-impact, interdisciplinary research and help governments to develop evidence-based policies to encourage resource efficiency, waste valorization and circular economy solutions. In addition, improving the cooperation and transfer of technology on an international level will enable the spread of innovative solutions for waste management, especially in developing countries. The shift towards smart waste management systems, low-carbon technologies, and sustainable resource recovery also directly supports the goals of global environmental protection such as climate change mitigation, pollution reduction, sustainable urban development, and achieving the United Nations Sustainable Development Goals (SDGs), such as SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action).

5. Conclusion

This bibliometric analysis of 20,438 publications over thirty years (1995–2025) reveals that municipal solid waste research has matured through four evolutionary phases, with exponential growth after 2015 signaling heightened global concern. Asia, particularly India and China, now dominates research productivity, reflecting the urgency of waste challenges in rapidly urbanizing regions. Five major findings emerge: (1) Life Cycle Assessment remains the predominant methodology, though hybrid approaches combining LCA, GIS, Emergy Analysis, and machine learning represent the future trajectory; (2) Research hotspots have shifted from conventional disposal concerns toward circular economy principles, waste-to-energy technologies, and digitalization; (3) Critical gaps persist in scalable valorization technologies, mathematical modeling integration, and AI-enabled smart waste systems; (4) International collaboration and context-specific policies are essential, particularly for developing countries facing infrastructure constraints; and (5) The field is transitioning from foundational exploration to applied optimization, with waste increasingly viewed as a valuable resource

rather than a disposal problem. These findings provide researchers and policymakers with a comprehensive roadmap for advancing sustainable waste management in alignment with global climate and sustainability goals. The novelty of this study is that it offers a detailed three-decade (1995–2025) bibliometric evaluation of the publication landscape, citation performance, network of collaborators, research areas and emerging themes, all of which provide a comprehensive overview of the development of research on municipal solid waste management. This study is restricted to publications that are covered in the Web of Science Core Collection and in English language publications, but it does provide a sound knowledge base for future studies. Future research should combine a number of bibliographic databases, apply advanced techniques of text mining and artificial intelligence for thematic analysis, and explore new research fields, such as digital waste management, climate-resilient waste systems, circular bioeconomy, and smart-city applications. The results as a whole can be used as guidance for research, funds, and policy makers who are working to promote sustainable resource management, support the circular economy, and contribute to global climate and sustainable development goals by developing evidence-based strategies.

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6. References

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