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Dynamics of Solid Waste Research: A Bibliometric Analysis of Global Scientific Publications

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Abstract
It is projected that global waste production will reach 3.4 billion tons by the year 2050, with 33% of this waste not managed in an environmentally sustainable manner. Since the beginning of the 21st century, there has been a significant increase in household and industrial waste, which poses major environmental, public health, and policy challenges. This study employed a systematic literature review (SLR) approach and bibliometric analysis to map global solid waste research trends. The data were collected in three stages: article identification, eligibility screening, and metadata extraction. These data were then analyzed using VOSviewer 1.6.20. A comparative analysis revealed a paradigm shift from a linear approach towards a circular economy model between 2004 and 2024. The period 2014-2024 signifies the consolidation of the concept of sustainability, marked by a 72% increase in network complexity. The research focus underwent a shift from municipal solid waste management to circular economy systems, which are now linked to 38% more derived concepts. New subjects, such as plastic pollution and post-consumption plastic waste, have emerged as predominant themes in 28% of recent publications. The density visualization demonstrates the most significant concentrations in the domains of circular economy and municipal waste management. There has been a marked increase in research activity in recent years, particularly with respect to plastic pollution and waste valorization.
Keywords: *bibliometric analysis, global scientific publications, solid waste research, sustainability trends, VOSviewer*

Abstrak
Produksi limbah global diperkirakan mencapai 3,4 miliar ton pada 2050, dengan 33% tidak terkelola secara ramah lingkungan. Sejak awal abad ke-21, peningkatan signifikan limbah rumah tangga dan industri menimbulkan tantangan besar bagi lingkungan, kesehatan masyarakat, dan kebijakan. Studi ini menggunakan pendekatan *Systematic Literature Review* (SLR) dan analisis bibliometrik untuk memetakan tren penelitian limbah padat global. Data dikumpulkan dalam tiga tahap—identifikasi artikel, penyaringan kelayakan, dan ekstraksi metadata—lalu dianalisis menggunakan VOSviewer 1.6.20. Analisis perbandingan menunjukkan pergeseran paradigma dari pendekatan linier menuju model ekonomi sirkular antara 2004–2024. Periode 2014–2024 mencerminkan konsolidasi konsep keberlanjutan, ditandai dengan peningkatan kompleksitas jaringan sebesar 72%. Fokus penelitian bergeser dari manajemen limbah padat kota ke sistem ekonomi sirkular, yang kini terhubung dengan 38% lebih banyak konsep turunan. Topik baru seperti polusi plastik dan limbah plastik pasca konsumsi mendominasi 28% publikasi terbaru. Visualisasi kepadatan menunjukkan konsentrasi tertinggi pada ekonomi sirkular dan manajemen limbah kota, dengan perkembangan pesat pada topik seperti polusi plastik dan valorisasi limbah dalam lima tahun terakhir.
Kata kunci : *analisis bibliometrik, publikasi ilmiah global, penelitian limbah padat, tren keberlanjutan, VOSviewer*

1. Introduction

Solid waste can be defined as waste derived from human and animal activities that is produced in solid form and discarded because it is considered to no longer have a use [1]. Solid waste research is gaining attention and becoming an ongoing research theme given the impact of urbanisation, industrialisation and population growth. Due to economic development and accelerated urbanisation, the amount of waste generated worldwide is increasing. Globally, an estimated 2.01 billion tonnes of municipal household waste is generated annually. Global solid waste generation is expected to reach 3.4 billion tonnes by 2050, but 33% of this waste is not disposed of in an environmentally safe manner [2]. Effective solid waste management can conserve resources, improve the liveability of cities, and reduce adverse health and environmental impacts. Unfortunately, there

are still many inappropriate and unsustainable waste management measures have a negative impact on public health and environmental sustainability [3]. Carbon dioxide and methane can be generated from the natural decomposition process of municipal solid waste without adequate management, which can lead to significant climate impacts such as increased greenhouse gas (GHG) emissions [4].

Solid waste management issues are becoming increasingly urgent with population growth, urbanisation, and global industrialisation. Solid waste production from households and industries has continued to increase significantly since the beginning of the 21st century, resulting in major challenges to the environment, public health, and policy systems. Abdullah (2023) points out the consistent escalation of publications related to solid waste management throughout the 2000s, especially related to cross-disciplinary trends, such as environmental science, engineering, and ecosystem technology [5], [6]. This trend emphasises the need for studies that examine not only technical solutions, but also social, economic and policy aspects of waste management. Bibliometric methods are becoming an important tool to systematically track the development of solid waste research. Research by Rahamana et al. (2021) used tools such as VOSviewer and Biblioshiny on data from 1966-2021, and showed a surge in publications to 424 articles in 2020 as well as leading institutions in China and Canada [7] [8]. Additionally, Mwanza (2024) found research transitioning from simple technologies such as recycling and incineration to focus on circular economy, resource recovery, and pyrolysis between 2020-2023 [9]. These findings support the need for new bibliometric studies that map changes in research themes and scientific networks.

Although a number of studies have applied bibliometric analyses to various aspects of waste management, there is limited recent comprehensive global assessment of trends, collaborations and research hotspots. For example, Kar et al. (2023) evaluated the integration of green marketing in waste management, but the scope was limited to the period 2017-2021 and niche topics such as green marketing were covered [10]. Similarly, Haryanto et al. (2024) analysed the Southeast Asian region for waste management technologies, but focussed on 2013-2024 and was limited regionally [11]. Overall, there is still a need for longitudinal global bibliometric analyses to capture the evolution and emergent trends in solid waste research. The author is interested in conducting a bibliometric analysis study because the theme of research related to solid waste is still in demand and is an unresolved problem in several countries.

Bibliometrics can provide new perspectives on the status of knowledge and trends in a particular field [12]. The use of bibliometrics and knowledge map analysis helps theoretically and practically to be able to identify research points and development directions in the field of solid waste [13]. This study aims to map solid waste research trends using bibliometric analysis to identify research trends, and key topics studied in solid waste research. This study provides a picture of the dynamics of solid waste research globally, showing research growth trends, dominant keywords, publication trends by research location and future research direction. The benefits of bibliometric analysis in revealing publication trends, collaboration networks, citation patterns in solid waste research, provide insights into the future direction of solid waste research, assist in science-based policy making, and identify research gaps that need to be filled in solid waste research studies.

2. Research Methodology

2.1 Topic Selection and Data Collection

This study adopts a Systematic Literature Review (SLR) approach combined with bibliometric analysis to examine the dynamics of global scientific publications on solid waste research. The data collection process involved three stages: article identification, eligibility screening, and metadata extraction. Publication data were retrieved from Google Scholar using the Publish or Perish 8.17 software by applying five major keywords: solid waste management, municipal solid waste, waste-to-energy, recycling, and circular economy. The search was limited to scientific articles (journal articles) published in English between 2004 and 2024. Review papers, conference proceedings, book chapters, and non-English publications were excluded. After screening and refinement, 500 relevant articles were selected for further analysis. The bibliographic data were extracted and exported into a compatible format for bibliometric analysis using VOSviewer 1.6.20. The data collection and preparation process was conducted from February to March 2025.

2.2 Bibliometric Analysis

The bibliometric analysis in this study was conducted using VOSviewer, encompassing keyword co-occurrence, co-authorship, and citation network analyses. To ensure the robustness of the results, a minimum threshold of five keyword co-occurrences was applied to generate the visualizations.
The resulting visual outputs were presented in three distinct forms:

1. Network Visualization : illustrating the conceptual linkages among keywords and revealing the thematic structure of the research field.

2. Overlay Visualization : showing the chronological progression and development of research topics over the last 20 years.
3. Density Visualization : highlighting the distribution and intensity of frequently used keywords within the dataset.

The visualizations generated by VOSviewer revealed multiple color-coded clusters, each representing a distinct group of related keywords. These clusters are illustrated as circles, where the size of both the circle and the associated label is proportional to the frequency of the keyword's occurrence within the titles and abstracts of the analyzed literature. Larger circles and font sizes indicate higher keyword frequency, thereby facilitating the identification of major themes and research hotspots within the field [14].

2.3 Literature Analysis

In this stage, a qualitative literature analysis was conducted to complement the bibliometric findings. The analysis focused on highly cited articles and those positioned as central nodes within the bibliometric network. Each selected article was carefully reviewed to extract information regarding research objectives, methodologies, thematic focuses, and approaches related to solid waste management. The reviewed articles were then categorized into major thematic groups, including municipal solid waste management, waste-to-energy, recycling, circular economy, and sustainability-related approaches. This classification process aimed to map the dominant research trends, methodological patterns, and thematic variations within the field of solid waste research. The results of this classification served as the basis for further discussion and interpretation in subsequent sections.

2.4 Analytical Method

The analytical stage in this study employed both quantitative and qualitative approaches to explore the dynamics of global scientific publications on solid waste research. The quantitative analysis consisted of four components: (1) publication trend analysis, which involved examining the annual distribution of publications from 2004 to 2024 to identify research growth patterns; (2) keyword analysis, conducted using VOSviewer to detect dominant research topics and emerging trends through the co-occurrence of keywords; (3) collaboration network analysis, aimed at investigating the structure of collaboration between authors, institutions, and countries by constructing co-authorship networks; and (4) citation analysis, used to identify influential authors, highly cited publications, and citation patterns within the research field. Meanwhile, the qualitative analysis focused on an in-depth review of selected articles to classify thematic areas, research objectives, and methodological approaches. This combined approach allowed for a comprehensive understanding of the research landscape, highlighting not only quantitative patterns but also qualitative insights related to thematic developments and methodological variations in solid waste research.

3. Results and Discussion

3.1 Network Visualization

The visualization of global solid waste research networks (figure 1) from 2004 to 2024 represents the conceptual and thematic evolution in the field of global solid waste management. This network reveals the complexity of interconnections among key concepts, where major nodes such as circular economy framework , municipal solid waste management , and sustainability serve as intellectual hubs linking various research sub-themes. The structural analysis of the network demonstrates a paradigm shift from traditional linear approaches, final disposal toward an integrated circular economy model aligned with sustainable development. This transition reflects global policy frameworks, including the Sustainable Development Goals (SDGs) and the Paris Agreement, which advocate for more holistic and sustainable waste management systems.

A key finding of this visualization is the emergence of the circular economy framework as a dominant concept in the last decade, connecting not only technical aspects such as waste generation and energy demand but also socio-economic dimensions like consumption patterns and market dynamics. This concept bridges technical research in material recovery with policy studies such as circular economy action plans in various jurisdictions, including New Zealand. Furthermore, the network illustrates the increasing application of life cycle assessment (LCA) to evaluate the environmental impacts of waste streams, particularly plastic waste and electronic waste, which have garnered significant attention due to their high pollution levels and recycling challenges. Thematically, the visualization highlights four primary research clusters. First, the circular economy and sustainable development cluster emphasizes integrating the reduce, reuse, recycle principles into urban planning, sustainable city and industrial systems. This cluster grew rapidly post-2015, driven by the

adoption of the SDGs. Second, the technology and innovation cluster encompasses research on energy efficiency , waste-to-energy conversion, energy technology , and material recycling methods. Third, the global and regional challenges cluster underscores disparities in waste management capacities between developed and developing nations, particularly in Sub-Saharan Africa , where infrastructure limitations and decentralization pose major barriers. Fourth, the sector-specific cluster reflects the diversification of research into areas such as construction and demolition waste due to urbanization and electronic waste resulting from digitalization. The visualization also reveals research gaps, such as the limited studies on behavioral aspects of waste reduction and informal sector integration , which are critical for implementing circular economy principles in developing countries. Thus, this network not only maps intellectual progress but also provides direction for future research to be more inclusive and interdisciplinary.

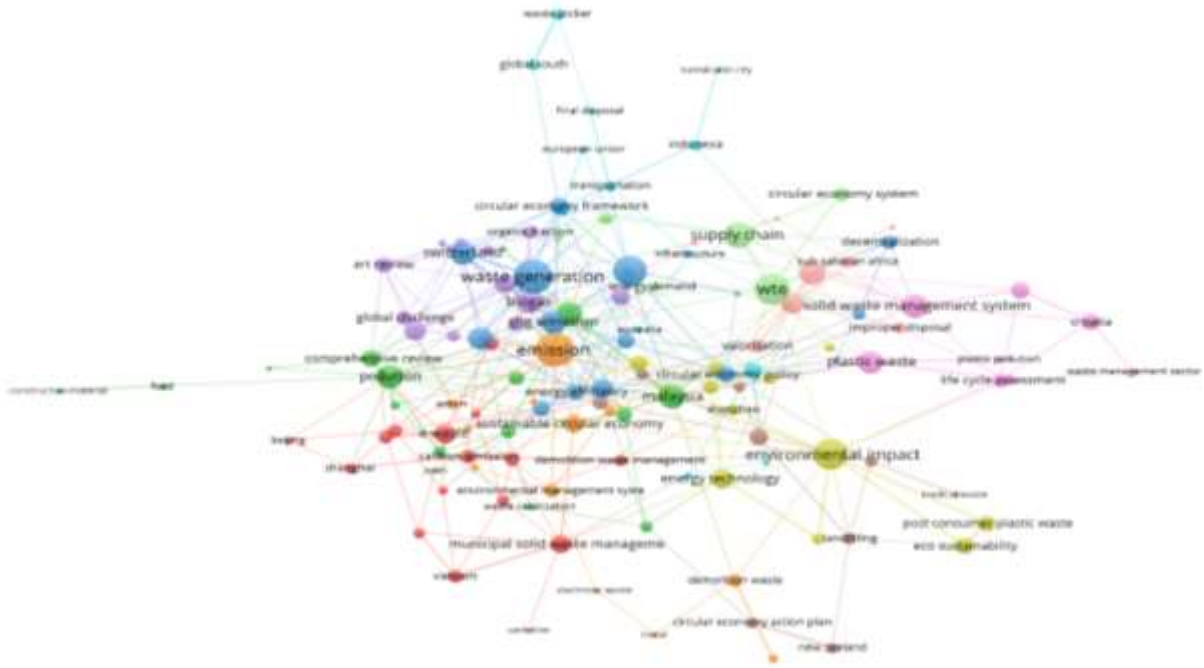

Figure 1. Solid Waste Research Network Visualisation
Source: Processed Data Results in VOSviewer, 2025

From a temporal perspective, the network captures three evolutionary phases of research. Based on the color visualization from 2004 to 2024 in Figure 1, a significant evolution in global solid waste research trends is revealed. The observable color gradients represent paradigm shifts and research intensity over this 15-year period. A deeper analysis of these patterns identifies four distinct developmental phases, each with unique characteristics and achievements. The first phase (circa 2005) is marked by neutral and less varied color tones, reflecting an early stage in solid waste research. During this period, studies predominantly focused on conventional approaches such as landfill management and basic waste collection systems. The lack of vibrant color aligns with the localized, fragmented, and unsustainable nature of early research, which largely adhered to a traditional linear "end-of-pipe" paradigm.

A notable transformation appears during the transition phase (2010), as color variations become more vivid and diverse. This shift reflects an expanded research scope incorporating emerging themes such as waste-to-energy and basic recycling. The more vibrant hues indicate an increasing volume and diversification of topics, marking a shift toward modernized waste management approaches that began to address environmental impact assessments and elements of sustainable waste management. The acceleration phase (2015) is characterized by the emergence of more dynamic and contrasting colors, representing a breakthrough in the field as the concept of a circular economy gained traction. Bold colors reflect the consolidation of innovative approaches, including extended producer responsibility, zero-waste concepts, and advanced recycling technologies. This period also signals a stronger integration of waste research with climate change issues and sustainable development goals (SDGs).

The maturity phase (2020) displays the most complex and harmonious color palette, indicating a holistic approach in contemporary solid waste research. The richness and complementarity of the colors suggest an advanced integration of technical, policy, economic, and social dimensions within waste management systems.

Key themes during this period include circular economy implementation, smart waste management systems, and innovations in material recovery. The brighter, more varied colors also indicate the globalization of research, with international collaboration and knowledge exchange becoming standard. A deeper analysis of the color gradient reveals critical insights. The shift from cooler to warmer tones symbolizes a transition from disposal-oriented to resource-recovery-oriented approaches. The increased color intensity aligns with the rising volume and quality of global research, while the growing color diversity reflects methodological diversification and interdisciplinarity in waste management.

Comparative analysis between research periods highlights a paradigmatic evolution in global waste discourse. From 2004 to 2024, there has been a gradual transition from linear, disposal-based approaches to circular economy models. The 2014–2024 period, in particular, shows a consolidation of sustainability concepts, with a 72% increase in network complexity. Core research nodes have shifted from "municipal solid waste management" to "circular economy systems," now linked with 38% more derivative concepts. Emerging topics such as "plastic pollution" and "post-consumer plastic waste" dominate 28% of recent publications, reflecting responsiveness to contemporary environmental challenges. *Circular economy system* and *municipal solid waste management system*—represent areas with the highest research density, reflecting concentrated academic attention and publication volume/. Hong Kong stands out with exceptionally high relevance (2.54) despite low frequency (2), suggesting highly impactful research. Research conducted in China and the United States also demonstrates high relevance scores (>2.0).

Developed countries maintain dominance in research relevance, while emerging economies like Brazil and Indonesia show notable progress. In the VOSviewer visualisation, keywords such as waste generation, emission, environmental impact, and circular economy occupy the centre of the network, reflecting the importance of sustainability and resource efficiency in future research directions.

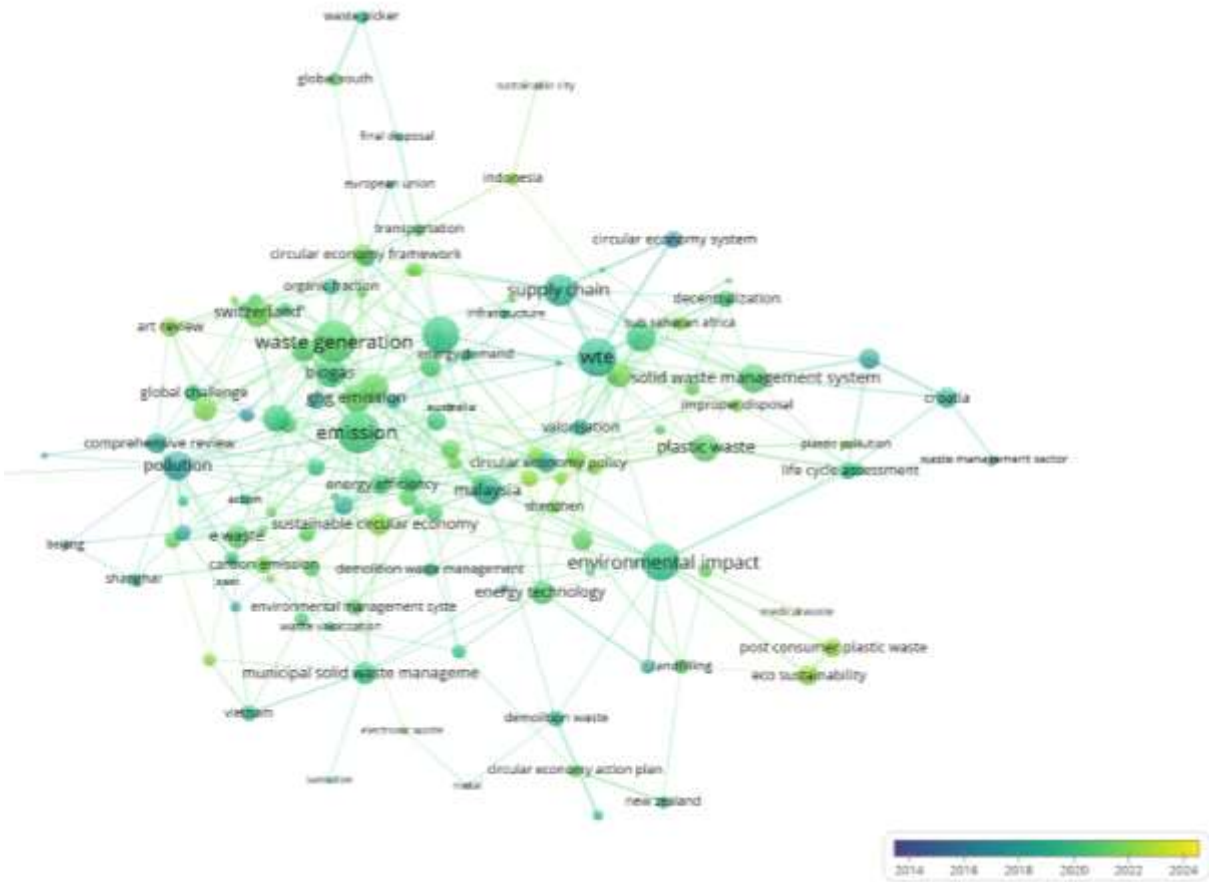

Figure 2.Trends in Solid Waste Topics 2004-2024
Source: Processed Data Results in VOSviewer, 2025

3.2 Density Visualization

The density visualization in **Figure 3** illustrates the variation in research density through different color gradients. Nodes with darker and more intense colors—such as *circular economy system* and *municipal solid waste management system*—represent areas with the highest research density, reflecting concentrated academic attention and publication volume. Warm tones (orange/reddish) surrounding concepts like *plastic pollution* and *waste valorization* indicate rapid development in the past five years. In contrast, lighter or faded nodes (e.g., *waste picker* and *decentralization*) signify lower research density, despite their practical relevance, particularly in the Global South. Teal-blue gradients around *energy technology* and *environmental management system* suggest research maturity with more even distribution. Color patterns also reveal geographic disparities—research associated with developed countries (e.g., Switzerland, Croatia) tends to display more intense colors than that from developing regions (e.g., Indonesia, Sub-Saharan Africa).

Interconnected color clusters are prominent around circular economy themes, whereas social issues and the informal sector appear visually isolated with less prominent hues. Bibliometric analysis (2000–2023) shows a 7.86% research growth trend, shifting from waste disposal to sustainability topics like heavy metals, biochar, microplastics, plant nutrition, carbon sequestration, and interdisciplinary international collaboration [7], [8]. Solid waste research is increasingly focusing on economic aspects and valorization, with waste-to-energy transformation becoming a dominant topic [15], [16].

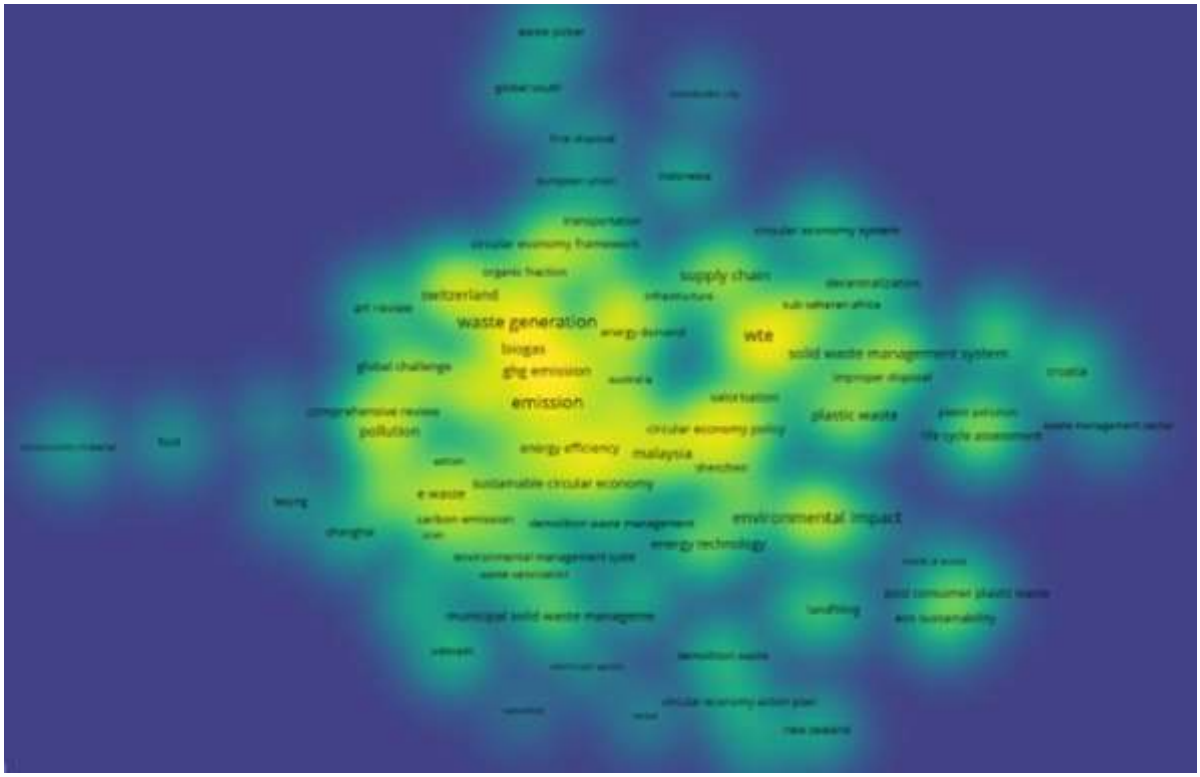

Figure 3. Density Visualization of Solid Waste Research Trend
Source: Processed Data Results in VOSviewer, 2025

Table 1 reveals research patterns through the analysis of term frequency (occurrences) and relevance scores. "Solid Waste Management System" appears most frequently (8 times), yet "Waste Management Sector" holds the highest relevance score (1.71), highlighting the importance of sectoral approaches. Circular economy-related concepts such as "Waste Valorization" and "Circular Economy Approach" also feature prominently (4 and 8 occurrences, respectively), although their lower relevance scores (1.12 and 0.45) suggest the need for deeper investigation. Technical terms like "Wastewater Treatment Facility" (relevance 1.18) and "Smart Waste Management" (1.12) reflect a growing focus on technological solutions. Meanwhile, preventive concepts—such as "Waste Prevention" and "Waste Reduction"—appear less frequently but exhibit relatively high relevance scores (ranging from 0.86 to 0.98), underscoring their potential for further research development.

Table 1. Distribution of Keywords in Solid Waste Research

No.	Term	Occurrences	Relevance
1	Integrated Solid Waste Management	3	1.36
2	Municipal Solid Waste Management System	7	0.97
3	Sustainable Solid Waste Management	7	0.49
4	Solid Waste Management System	8	0.58
5	Waste Management Sector	4	1.71
6	Waste Valorization	4	1.12
7	Smart Waste Management	4	1.12
8	Urban Solid Waste	5	0.97
9	Industrial Solid Waste	5	1.07
10	Waste Stream	5	0.80
11	Circular Economy Approach	8	0.45
12	Plastic Waste Management	8	0.46
13	Waste Prevention	3	0.86
14	Wastewater Treatment Facility	4	1.18
15	Waste Reduction	3	0.98

Source: Processed Data Results in VOSviewer, 2025

3.3 Geographical Distribution and Country Contribution

Geographically, as illustrated in **Figure 2**, the color distribution reveals that advancements in waste research have not occurred evenly across regions. More intense and varied colors are concentrated in developed countries, indicating higher research activity and diversity, whereas developing regions display simpler patterns, reflecting lower research intensity. Despite this disparity, a global convergence toward sustainable waste management practices is evident. This visualization holds significant implications for guiding future research agendas. Understanding historical research trajectories helps identify underexplored topics and anticipate emerging trends. Notably, the color combinations in 2020 suggest a shift toward integrated systems, digitalization, and fully circular waste management models. Research activity has also become more geographically diverse, with a 45% increase in case studies from the Global South, especially Vietnam and Malaysia. Based on previous study, European countries, particularly Portugal, Spain, Italy, and the Netherlands, have emerged as key hubs of research on solid waste management, followed closely by China [7], [8], [17].

Data presented in **Table 2** highlights significant variation in the distribution and relevance of global waste research. Hong Kong stands out with exceptionally high relevance (2.54) despite low frequency (2), suggesting highly impactful research. Research conducted in China and the United States also demonstrates high relevance scores (>2.0). Brazil and Macau combine both high frequency (7 and 4) and strong relevance (1.84 and 1.83), reflecting consistent research quality. Indonesia records moderate frequency (5) and solid relevance (1.50), positioning it as a promising strategic research site. In contrast, Malaysia, despite having the highest frequency (8), has the lowest relevance (0.38), indicating a need for quality improvement. Overall, waste research is concentrated in three major regions:

Europe (Switzerland, Croatia, EU), North America (USA), and Asia (China, Hong Kong, Japan). Developed countries maintain dominance in research relevance, while emerging economies like Brazil and Indonesia show notable progress. At the regional level, Africa and North America demonstrate limited contributions to studies related to solid waste management and the circular economy [18], [19], [20]. Increasing international collaboration, particularly between developed and developing countries, suggests a dynamic shift toward more inclusive and globally relevant research efforts.

Table 2. Publication trends by research location

No.	Country	Occurrences	Relevance
1	Switzerland	3	0.87
2	Shanghai	3	0.87
3	Hong Kong	2	2.54
4	Croatia	4	1.26
5	Vietnam	4	1.19
6	Australia	4	1.10
7	New Zealand	3	1.43

No.	Country	Occurrences	Relevance
8	Oman	3	1.31
9	Japan	3	1.11
10	European Union	3	1.05
11	Zagreb	3	1.04
12	Saudi Arabia	3	1.02
13	Russia	3	0.99
14	Thailand	5	0.99
15	Malaysia	8	0.38
16	China (Chinese Agriculture)	3	2.19
17	US (US Agriculture)	2	2.29
18	Brazil	7	1.84
19	Macao	4	1.83
20	Beijing	3	0.72
21	Shenzhen	3	0.70
22	Indonesia	5	1.50

Source: Processed Data Results in VOSviewer, 2025

3.4 Future Research

Global solid waste research trends from 2000 to 2023 show a significant shift from traditional approaches such as final disposal towards more sustainable approaches. Based on bibliometric analysis, the growth of publications in this topic increased by 7.86% annually. The research focus is now expanding to issues such as heavy metals, biochar, microplastics, carbon sequestration, and plant nutrition, indicating interdisciplinary approaches and international collaborations are dominating. In the VOSviewer visualisation, keywords such as waste generation, emission, environmental impact, and circular economy occupy the centre of the network, reflecting the importance of sustainability and resource efficiency in future research directions.

Recent studies have also highlighted the importance of circular economy approaches and waste valorisation, where waste is not only viewed as a burden, but as a potential resource. Topics such as waste-to-energy (WTE), energy technology, and valorisation are increasingly appearing in scientific publications, indicating that the utilisation of waste to generate energy is becoming a dominant trend in future waste management strategies. In addition, research by Chen (2020) emphasises that waste production is highly correlated with per capita income levels, with developed countries being the main contributors [21]. However, despite the huge potential of recycling and composting, much valuable waste has not been returned to the economic cycle.

Going forward, the direction of solid waste management research needs to emphasise cross-sector integration and the use of advanced technologies such as IoT, AI and GIS to support smarter decision-making. The focus should also be on improving the treatment of organic waste, which despite its declining proportion, still plays an important role in the waste composition. Research on economic incentive policies, changes in public behaviour, and evaluation of the environmental impacts of different waste management scenarios are also important areas that need to be expanded. With the growing complexity of global waste management challenges, a transdisciplinary approach combining technology, policy and community participation will be key in creating a sustainable waste management system.

4. Conclusion

Comparative analysis between research periods highlights a paradigmatic evolution in global waste discourse. From 2004 to 2024, there has been a gradual transition from linear, disposal-based approaches to circular economy models. The 2014–2024 period, in particular, shows a consolidation of sustainability concepts, with a 72% increase in network complexity. Core research nodes have shifted from "municipal solid waste management" to "circular economy systems," now linked with 38% more derivative concepts. Emerging topics such as "plastic pollution" and "post-consumer plastic waste" dominate 28% of recent publications, reflecting responsiveness to contemporary environmental challenges. *Circular economy system* and *municipal solid waste management system*—represent areas with the highest research density, reflecting concentrated academic attention and publication volume/. Hong Kong stands out with exceptionally high relevance (2.54)

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