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Technology Applications in Waste Management across Southeast Asia: A Bibliometric Analysis over the Past Decades

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Abstract: Using technology in waste management in the current era is crucial in enhancing efficiency, sustainability, and positive environmental impact. Therefore, this research aims to understand publication trends related to technology applications in waste management from 2013 to 2024 across Southeast Asia through bibliometric analysis. In this analysis, VOSviewer software and the bibliometric analysis applications RStudio and biblioshiny were employed to analyse the bibliographic data obtained graphically. After filtering, 553 documents from the Scopus database were analysed. The results revealed fluctuating trends in the number of publications, with the Journal of Cleaner Production being the highest contributor with 33 documents. Malaysia ranked first in the number of documents, with 452 focusing on technology utilisation in waste management. Additionally, Universiti Teknologi Malaysia and the National University of Singapore were the most productive affiliations, each contributing the highest number of publications, with 58 each. Two institutions within the top twenty also represented Indonesia as the most relevant affiliations, namely (1) Bandung Institute of Technology and (2) Universitas Sebelas Maret. According to the research findings, 68 Indonesian researchers contributed to the analysed theme, with the top author originating from the Czech Republic with 13 documents. The globally most cited documents, published in the Journal of Resources, Conservation, and Recycling, have been cited 535 times. Visualisation of research trends revealed popular topics aligned with research and discussion, including waste management, sustainable development, recycling, waste disposal, solid waste, municipal solid waste, anaerobic digestion, waste treatment, biogas, pyrolysis, and environmental impact. These findings aid researchers in guiding future analyses and determining research themes, especially in waste management technology, while also assisting in resource allocation and evidence-based strategy formulation to enhance

waste management efficiency and sustainability. Nonetheless, the study recommends further research using diverse data sources, bibliographic connections, and qualitative analysis.

Keywords: Bibliometric analysis, Technology, Waste management

Introduction

Waste management is a critical challenge, particularly in developing nations, where the infrastructure for waste collection often falls short (Sandeep et al., 2018). Addressing this issue requires multifaceted approaches that mitigate environmental degradation and foster sustainable practices. Agricultural waste, a significant contributor to ecological harm, has the potential to be transformed into valuable resources such as organic fertiliser through vermicomposting, thereby promoting sustainable agricultural production(Talukdar et al., 2018). However, a holistic strategy is indispensable to tackle the enormity of waste management challenges. This is where the 3R approach (Reduce, Reuse, Recycle) comes into play, as emphasised by (Kinantan et al., 2018). This strategy emphasises optimising garbage collection and transportation and underscores the imperative to minimise waste generation in the first place.

The scale of the waste management challenge is staggering, with a staggering 4 billion tons of waste generated annually worldwide, necessitating a fundamental shift in approach (Trivedi et al., 2019). Recognising this urgency, researchers and innovators increasingly turn to digital technologies to revolutionise waste management practices. Indeed, as Sadinov and Rajabov (2023) note, the application of digital technologies in waste management is burgeoning, offering promising avenues for repurposing waste and devising innovative solutions. Central to this technological revolution is IoT-based architecture, enabling real-time monitoring of waste volume and composition and dynamic optimisation of waste collection routes (Aleyadeh & Taha, 2018).

Technology integration in waste management is pivotal in ensuring efficient and sustainable practices. Adam et al. (2018) and Kumari et al. (2019) elucidate the significance of technology in enabling real-time monitoring of waste containers, allowing for precise tracking of waste levels, composition, and collection frequencies. This real-time data empowers waste management authorities to optimise their operations, allocating resources more effectively and responding promptly to fluctuations in waste generation. Furthermore, technology enhances the overall throughput of waste management operations by streamlining processes such as route optimisation for waste collection vehicles, thereby reducing fuel consumption, emissions, and operational costs.

Expanding on this notion, Sadinov and Rajabov (2023) underscore the vast potential of digital technologies in repurposing waste and fostering innovation within waste management projects. By leveraging digital platforms and advanced analytics, waste materials can be transformed into valuable resources, such as biofuels, compost, or recycled materials, contributing to environmental conservation and economic growth. Additionally, digital tools facilitate collaboration among stakeholders, enabling the co-creation of innovative solutions to address specific waste management challenges within local communities. Gupta et al. (2019) further emphasise the indispensability of modern technology, particularly artificial intelligence and machine learning, in facilitating smart waste management and bolstering recycling efforts. These advanced technologies enable predictive analytics and automated decision-making, allowing waste management systems to anticipate demand, optimise resource allocation, and improve sorting accuracy at recycling facilities. Moreover, artificial intelligence-driven algorithms can continuously learn and adapt based on evolving waste composition patterns, enhancing the efficiency and efficacy of recycling processes over time.

Collectively, these studies underscore the profound impact of technology in driving enhancements across various facets of waste management processes, from real-time monitoring and optimisation to waste repurposing and recycling. Embracing technological advancements improves operational efficiency and resource utilisation and fosters innovation and resilience within waste management systems, ultimately contributing to a more sustainable and environmentally responsible future. Moreover, the integration of smart waste management systems empowered by IoT, machine learning, and Android applications is reshaping the landscape of waste collection and processing(Varudandi et al., 2021). These advancements, coupled with the incorporation of artificial intelligence, cloud computing, and intelligent transport systems, are driving the emergence of sophisticated waste management frameworks(Karunambiga & Sathiya, 2023). Nevertheless, while digital technologies offer immense potential, adopting waste-to-energy technologies remains a cornerstone of waste management efforts in Southeast Asia.

In this region, diverse waste-to-energy technologies such as incineration, landfill gas capture, and anaerobic digestion are gaining traction, presenting opportunities for renewable energy generation(Tun et al., 2020). However, challenges persist, particularly in construction and demolition waste management, where data scarcity and institutional gaps hinder progress (Hoang et al., 2020). Bangladesh, for instance, grapples with the imperative to enhance waste management practices while concurrently addressing unemployment, underscoring the multifaceted nature of the challenge (Dinnar et al., 2021). Nonetheless, strides are being made towards low-carbon emission development strategies, exemplified by initiatives such as composting for organic waste and robust environmental management systems (Lee et al., 2018).

A bibliometric analysis sheds light on the evolving landscape of waste management research, highlighting a pronounced focus on waste-to-energy technologies and treatment methodologies (Ndou & Rampedi, 2022). This sentence emphasises the importance of bibliometric analysis, a quantitative method for examining patterns and trends in scholarly literature. In this context, the analysis provides valuable insights into the prevailing research themes and areas of emphasis within waste management, particularly regarding waste-to-energy technologies and treatment methods. By systematically reviewing a vast body of literature, bibliometric analysis offers a comprehensive overview of the research landscape, aiding in identifying key research directions and gaps.

Southeast Asia's trajectory mirrors this global trend, with an increasing emphasis on waste-to-energy solutions (Tun et al., 2020). Here, the sentence highlights the regional perspective, demonstrating how the findings of the bibliometric analysis apply to the specific context of Southeast Asia. The mention of waste-to-energy solutions underscores the relevance of the analysis to address pressing environmental and energy challenges in the region. By recognising regional trends and patterns, policymakers and stakeholders can tailor interventions and strategies to meet the unique needs and priorities of Southeast Asian countries. Notably, the proliferation of waste classification technologies, particularly in nations like China, underscores a concerted effort towards enhancing recycling and resource recovery (Yang et al., 2021). This statement emphasises the role of waste classification technologies in promoting sustainability and resource efficiency. The reference to China highlights a specific example of a country actively investing in waste management infrastructure and technologies to address environmental concerns. The analysis underscores opportunities for knowledge sharing and collaboration among countries striving to improve their waste management practices by identifying such advancements.

Nevertheless, gaps persist, as evidenced by the limited exploration of cleaner transport sector opportunities within the waste-to-energy discourse (Boloy et al., 2021). This sentence acknowledges the limitations and areas for further research identified through the bibliometric analysis. The analysis provides valuable guidance for future research endeavours by pinpointing gaps in the existing literature. In this case, the reference to cleaner transport sector opportunities underscores the importance of considering broader systemic factors and interconnections within waste management systems. As such, while technological innovations hold immense promise for revolutionising waste management practices, concerted efforts and interdisciplinary collaborations are essential to realise their full potential in Southeast Asia and beyond. This concluding statement emphasises the overarching goal of the bibliometric analysis: to inform and guide efforts aimed at harnessing the transformative potential of technology in waste management. By advocating for collaborative approaches and interdisciplinary engagement, the analysis encourages stakeholders to work together towards sustainable and inclusive solutions to the complex challenges of waste management. Based on the existing body of literature, it is evident that there is a need for bibliometric research on the application of technology in waste management, particularly in Southeast Asian developing countries. The primary objective of this study is to thoroughly investigate the application of technology in waste management by employing a bibliometric approach to address existing research gaps. This study addresses the following specific research questions:

RQ1: What are the publication trends and research patterns regarding the application of technology in waste management across Southeast Asia over the past few decades?
RQ2: Which leading academic journals specifically address the application of technology in waste management in the Southeast Asian region?
RQ3: How is the network of collaboration among Southeast Asian countries in research on the application of technology in waste management?
RQ4: Who are the most frequently cited authors in research on the application of technology in waste management in Southeast Asia?
RQ5: Which publications significantly influence research on the application of technology in waste management in Southeast Asia?
RQ6: What are the primary research areas of focus in studies on the application of technology in waste management in Southeast Asia?

Method

Data Source, Study Boundary and Search Strategy

Bibliometric analysis proves valuable in comprehending and charting the collective scientific knowledge and evolutionary intricacies of established disciplines by organising vast amounts of unstructured data through rigorous methodologies (Donthu et al., 2021). As part of a systematic literature review, the bibliometric review is characterised by clarity, transparency, and replicability in developing the review database (Donthu et al., 2021; Hallinger & Suriyankietkaew, 2018; Kho & Brouwers, 2012). When conducting a bibliometric review, it is essential to clearly define the scope of the study and elucidate the techniques used to track down relevant sources. The current study extracted bibliometric data from the Scopus database. Scopus is a comprehensive database encompassing abstracts and citations for scholarly journal articles (García-Ávila et al., 2023; Mesdaghinia et al., 2015; Mongeon & Paul-Hus, 2016; Sweileh et al., 2016). It covers various academic fields, such as medical, technical, social, and scientific studies, which are highly relevant for investigating and advancing waste management systems (Punj et al., 2023). Compared to Web of Science, Scopus provides approximately 20% more coverage, while Google Scholar yields results with varying levels of accuracy (Falagas et al., 2008; Mesdaghinia et al., 2015).

The bibliometric analysis methodology is utilised to summarise a compilation of bibliographic data. This technique visualises the structural, social, and author networks, as well as the prevailing analytical focuses within a specific research domain (Ha et al., 2020; Karakus et al., 2019; Suprapto et al., 2021; Zupic & Čater, 2015). Furthermore, this approach encompasses statistical evaluations of published articles and their citations to gauge their pertinent impacts and assess emerging gaps or subjects of interest (Maditati et al., 2018; Saregar et al., 2022). Additionally, bibliographic analysis leverages pertinent data from online databases, facilitating scientific investigations and offering a global outlook on related areas of inquiry (Secinaro et al., 2020). Figure 1 delineates the execution of these five steps, underscoring the utilisation of bibliometric methodologies.

Figure 1. Bibliometric methodology

Study Design

This study design was executed by formulating research questions and selecting keywords and databases. It indicated the existence of six questions investigating the following features: annual publication trends, document sources, subject areas, and countries; affiliations; most productive authors; contributions of Indonesian experts; highly cited papers; and future experimental opportunities related to the application of technology in waste management. The design also demonstrated that the applied search keywords were "Technology" AND "Waste Management," with the Scopus database chosen as the bibliometric source.

Data Collection

The data collection process from the Scopus database utilised a title search strategy employing the keywords "Technology" AND "Waste Management" within the publication year range of 2013-2024. The timeframe selection from 2013 to 2024 is considered a robust decision due to its encapsulation of the most recent developments in the field. This temporal scope enables the research to effectively track the evolution of technology, research trends, and their consequential impact on waste management, consistently aligning with the research objectives. Moreover, utilising a relatively recent timeframe ensures that the acquired data is representative of the latest advancements in scholarly literature, thereby offering a more precise portrayal of the current status and future directions in waste management. With a specific focus on the Southeast Asian region, this timeframe facilitates a deeper understanding of regional developments within the broader global context. The data collection process yielded 553 documents for 2013-2024, sourced from journals published in Southeast Asian countries, adhering to the final publication stage and utilising English. Furthermore, the documents were obtained in Comma-Separated Values (CSV) and Research Information System (RIS) formats, enabling the extraction of article titles, authors, references, and keywords.

Data Analysis

Data analysis began with importing CSV, BIB, and RIS data from the Scopus database into Microsoft Excel, VOSviewer, and RStudio/Biblioshiny. This initial step was pivotal for facilitating subsequent data processing. The analysis sought to delineate and comprehend various trends, encompassing characteristics of publication output, document sources, affiliations by country and institution, dissemination across subject categories, and identification of top authors and citations. This information underwent detailed and comprehensive scrutiny to enhance understanding of the prevailing research landscape, specifically focusing on the period from 2013 to 2024.

Data Visualisation

After completing the data processing and analysis, the next phase involved visualising the data. This visualisation process utilised VOSviewer, RStudio/biblioshiny, and Microsoft Excel. Specifically, VOSviewer was employed to translate the processed CSV metadata into network, overlay, and density visualisations. Additionally, Microsoft Excel was utilised to present the data in tables and diagrams, aiming to provide a clearer and more comprehensible overview of the observed research trends.

Interpretation

Following data visualisation using VOSviewer, a meticulous analysis and interpretation of the visual representations ensued. This stage encompassed a thorough examination of various facets, including identifying clusters within the network, juxtaposing earlier and contemporary studies, and scrutinising density patterns, which yielded insights into the saturation of research topics and delineated prospective avenues for future experimentation. The significance of these visualisations lies in their capacity to offer nuanced insights into the intricate patterns and trajectories underlying research within the field. By rigorously discerning and interpreting these visual depictions, researchers can glean profound insights into the prevailing dynamics and trends, thus informing subsequent research endeavours and strategic decision-making processes in a scholarly context.

Result

Publication Trends

The trend of publication productivity spanning a decade (2013-2024), as derived from the Scopus database, reveals notable fluctuations. Specifically, the analytical trajectory concerning the application of technology in waste management across diverse disciplines exhibited variability over this ten-year period. This is evidenced by an upward trend in the number of documents observed in 2019, 2020, 2021, 2022, and 2023, with 43, 56, 81, 99, and 109 publications, respectively, followed by a subsequent decline in 2024, with only 17 publications. It is important to note that this decrease is typical, as it represents the initial segment of the year. Figure 2 provides a visual representation of the annual publication trend.

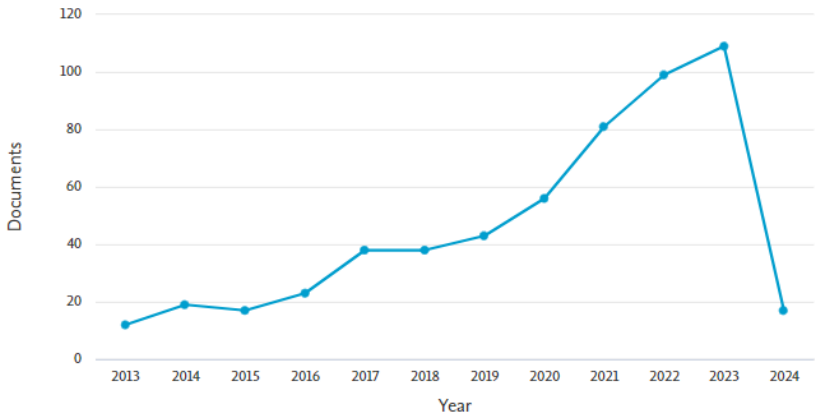

Figure 2. Annual publication trends for the period 2013-2024

Main Source Document

The article documents were sourced from a diverse array of journals, encompassing a wide spectrum of waste management topics across various academic disciplines such as environmental science, engineering, energy, social science, chemical engineering, and material science. Among these journals, some are indexed in Scopus with Q1 (16 journals and 187 articles), Q2 (1 journal and 9 articles), and Q3 (3 journals and 25 articles) rankings, as illustrated in the accompanying figure (figure 3).

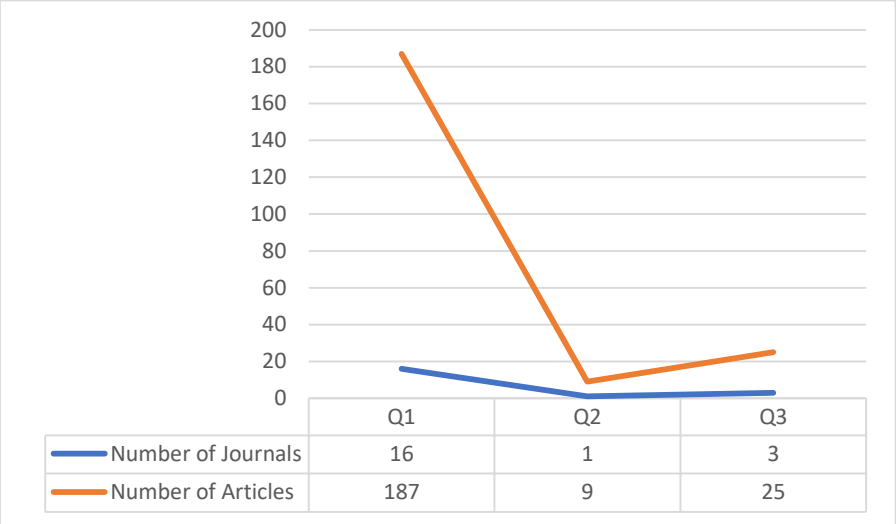

Figure 3. Distribution of indexed journals and articles categorised as Q1, Q2, and Q3

Additionally, Table 1 provides a detailed explanation of the top twenty journals that are highly prolific in publishing articles related to waste management technology.

Table 1. Distribution of documents by related sources from 2013-2024

Sources	SJR Index (Scimagojr 2022)	Articles
Journal of Cleaner Production	1.98 (Q1)	33
Sustainability (Switzerland)	0.66 (Q1)	21
Resources, Conservation and Recycling	2.68 (Q1)	18
Science of the Total Environment	1.95 (Q1)	16
Waste Management and Research	0.87 (Q1)	16
Chemical Engineering Transactions	0.24 (Q3)	14
Waste Management	1.75 (Q1)	14
Chemosphere	1.73 (Q1)	11
Energy	1.99 (Q1)	9
Journal of Environmental Management	1.68 (Q1)	9
Journal of Material Cycles and Waste Management	0.64 (Q2)	9
Environmental Science and Pollution Research	0.94 (Q1)	8
Journal of Hazardous Materials	2.57 (Q1)	7
Bioresource Technology	2.47 (Q1)	6
Environment and Natural Resources Journal	0.25 (Q3)	6
Environmental Pollution	2.11 (Q1)	5
Environmental Research	1.64 (Q1)	5
Recycling	0.69 (Q1)	5
Renewable and Sustainable Energy Reviews	3.23 (Q3)	5
Applied Energi	2.91 (Q1)	4

Documents based on Subject Area

A comprehensive total of 553 publications focusing on the utilisation of technology in waste management were gathered from documents spanning the years 2013 to 2024, with a particular emphasis on subject areas falling under the umbrella of environmental science. Notably, the subject areas of "Environmental science",

"Engineering", "Energy", "Psychology", "Social sciences", "Computer science, Business, and Chemical engineering", "Chemistry", "Agricultural and biological science" were represented by 352, 166, 149, 69, 66, 60, 55, 36, and 34 publications, respectively. Figure 4 provides a visual representation of the document classification highlighting subject areas.

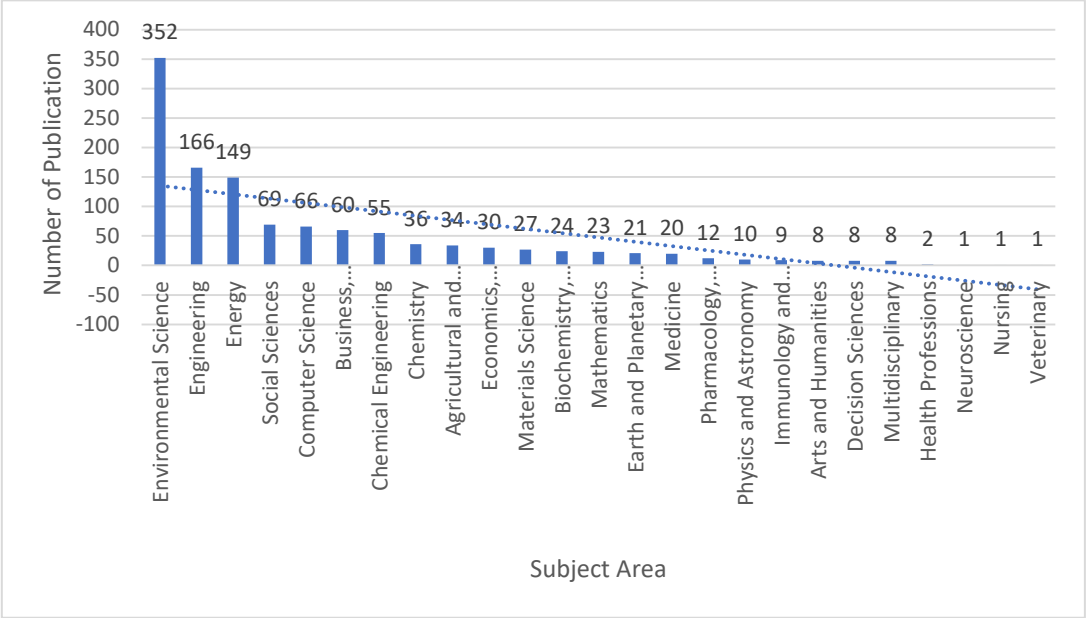

Figure 4. Document by subject area

Top Publications by Country

According to country classification, a total of 553 documents were distributed, with the majority originating from Malaysia, Indonesia, Thailand, China, Singapore, Vietnam, and India, accounting for 233, 108, 94, 84, 77, 55, and 40 articles, respectively. This distribution underscores Indonesia's active involvement in the research trend pertaining to the analysis of technology applications in waste management, showcasing its prominent role among Southeast Asian countries. Figure 5 visually delineates the top 10 distribution of Southeast Asian countries in publications concerning the application of technology in waste management.

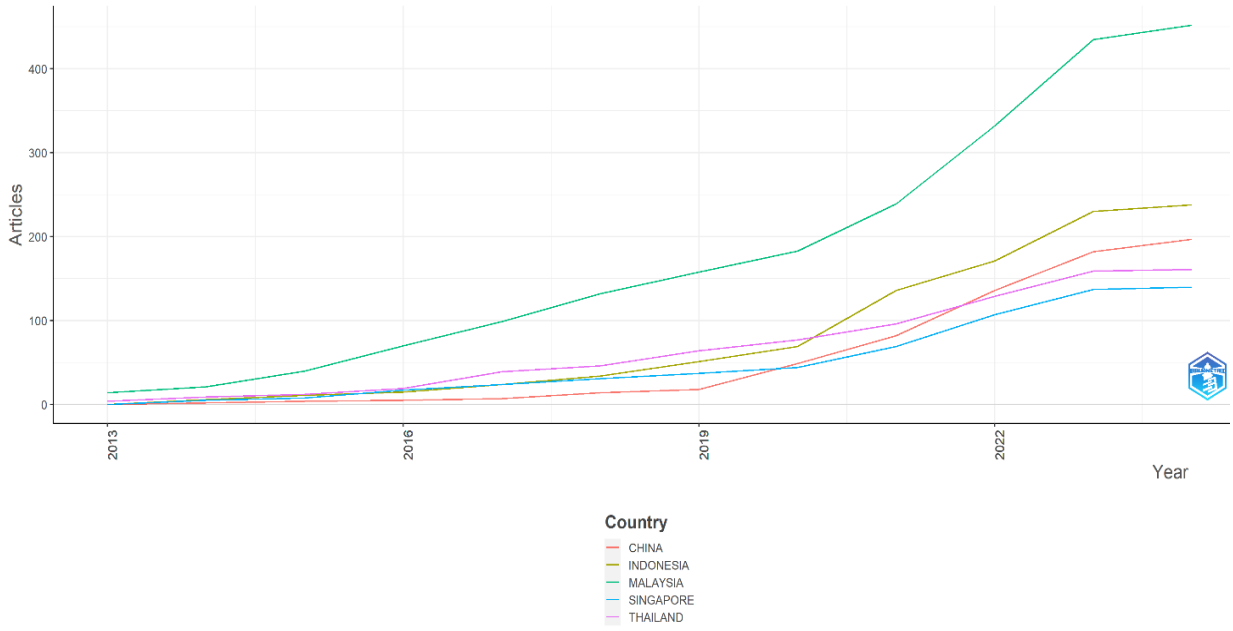

Figure 5. Country production over time

University Affiliation

Figure 6 presents the distribution of the top 20 university affiliations, emphasising their involvement in the application of technology in waste management. The distribution reflects a diverse array of university affiliations, spanning Malaysia, Singapore, Indonesia, and Thailand. Notably, Universiti Teknologi Malaysia and the National University of Singapore emerge as the most prolific institutions, contributing 58 documents each to the Scopus database. Following closely are Nanyang Technological University, University Kebangsaan Malaysia, and Chulalongkorn University, with 33, 32, and 30 articles, respectively. The analysis also highlights Indonesia's significant contribution, with three institutions making it to the top 20 affiliations, namely (1) Bandung Institute of Technology, (2) Universitas Sebelas Maret, and (3) Universitas Gajah Mada, collectively accounting for 44 publications. However, it is noteworthy that universities in Malaysia and Singapore continue to dominate the top 20 publications on the application of technology in waste management.

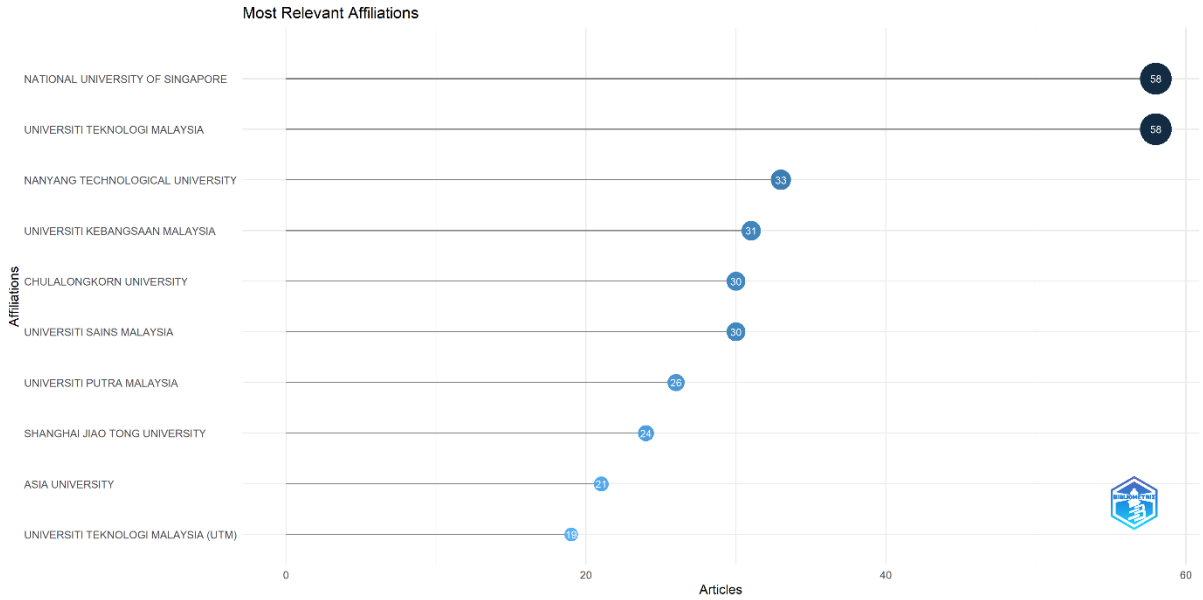

Figure 6. Most relevant affiliation

Top 10 Authors

Figure 7 highlights the most pertinent authors in this field, with Klemes JJ from the Czech Republic leading with 13 documents. Following closely are Lee CT and Tseng ML, each contributing 11 documents, along with Tong YW and Wang CH, who have authored 10 documents each.

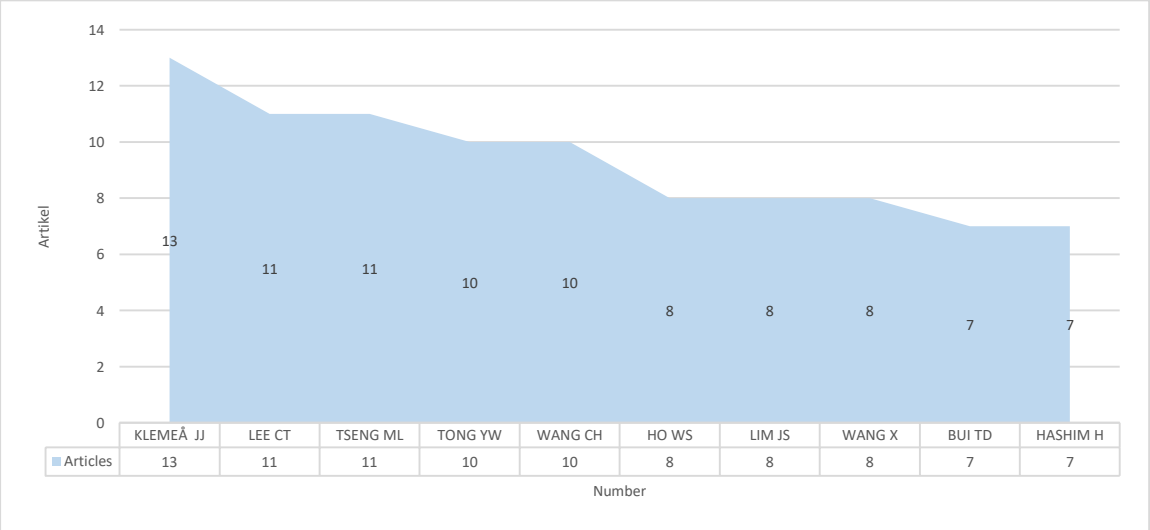

Figure 7. Top 10 authors

Document Citation

Based on the data retrieved from Scopus, the top 10 most cited documents per year are as follows: Huang (TC=535), Mehmood (TC=459), Fatimah (TC=276), Tan (TC=274), Ilyas (TC=258), Chand (TC=197), Hantoko (TC=191), Aranconrad (TC=187), Yun (TC=178), and Khoo (TC=162).

Table 2. A breakdown of the top 10 documents on Scopus by number of citations

Author/Year	Paper	DOI	Total Citations	TC per Year
Huang et al. (2018)	Construction and demolition waste management in China through the 3R principle	10.1016/j.resconrec.2017.09.029	535	76.43
Mehmood et al. (2017)	Internet-of-Things-Based Smart Cities: Recent Advances and Challenges	10.1109/MCOM.2017.1600514	459	57.38
Fatimah et al. (2020)	Industry 4.0 based sustainable circular economy approach for smart waste management system to achieve sustainable development goals: A case study of Indonesia	10.1016/j.jclepro.2020.122263	276	55.20
Tan et al. (2015)	Energy, economic and environmental (3E) analysis of waste-to-energy (WTE) strategies for municipal solid waste (MSW) management in Malaysia	10.1016/j.enconman.2015.02.010	274	27.40
Ilyas et al.(2020)	Disinfection technology and strategies for COVID-19 hospital and bio-medical waste management	10.1016/j.scitotenv.2020.141652	258	51.60
Chand Malav et al. (2020)	A review on municipal solid waste as a renewable source for waste-to-energy project in India: Current practices, challenges, and future opportunities	10.1016/j.jclepro.2020.123227	197	39.40
Hantoko et al. (2021)	Challenges and practices on waste management and disposal during COVID-19 pandemic	10.1016/j.jenvman.2021.112140	191	47.75
Arancon et al. (2013)	Advances on waste valorisation: New horizons for a more sustainable society	10.1002/ese3.9	187	15.58
Yun et al. (2018)	Metallurgical and mechanical methods for recycling of lithium-ion battery pack for electric vehicles	10.1016/j.resconrec.2018.04.025	178	25.43
Khoo (2019)	LCA of plastic waste recovery into recycled materials, energy and fuels in Singapore	10.1016/j.resconrec.2019.02.010	162	27.00

Mapping Technology Application in Waste Management with VOSviewer

The classification of study subjects pertaining to the application of technology in waste management is notable, with a total of 5463 keywords identified, of which 134 meet the threshold. Subsequently, this number was refined to 123 terms after merging identical terms. Network visualisation reveals the presence of 5 clusters, comprising 5042 links with a combined bond strength of 15719. Within these clusters, the red, green, blue, yellow, and purple clusters prioritise waste management, sustainable development, municipal solid waste, recycling, and waste disposal, respectively, with frequencies of 327, 91, 90, 84, and 79, respectively. Larger circles in the visualisation indicate higher frequencies of keywords in the documents (Zhang et al., 2024). Figure 8 presents the network visualisation using VOSviewer, accentuating the most frequently occurring keywords and networks.

Overlay Visualisation

The overlay visualisation is symbolised by colours indicating yearly experimental trends, where purple and yellow prioritise years of study and recent analysis, respectively. These recent trends focus on the following

terms: sustainable development, wastewater management, circular economy, resource recovery, machine learning, municipal solid waste management, environmental impact, pyrolisis, plastic waste, sustainable development, biofuel, environmental sustainability, waste to energy and wastewater treatment. The overlay visualisation of co-occurrence is depicted in Figure 9.

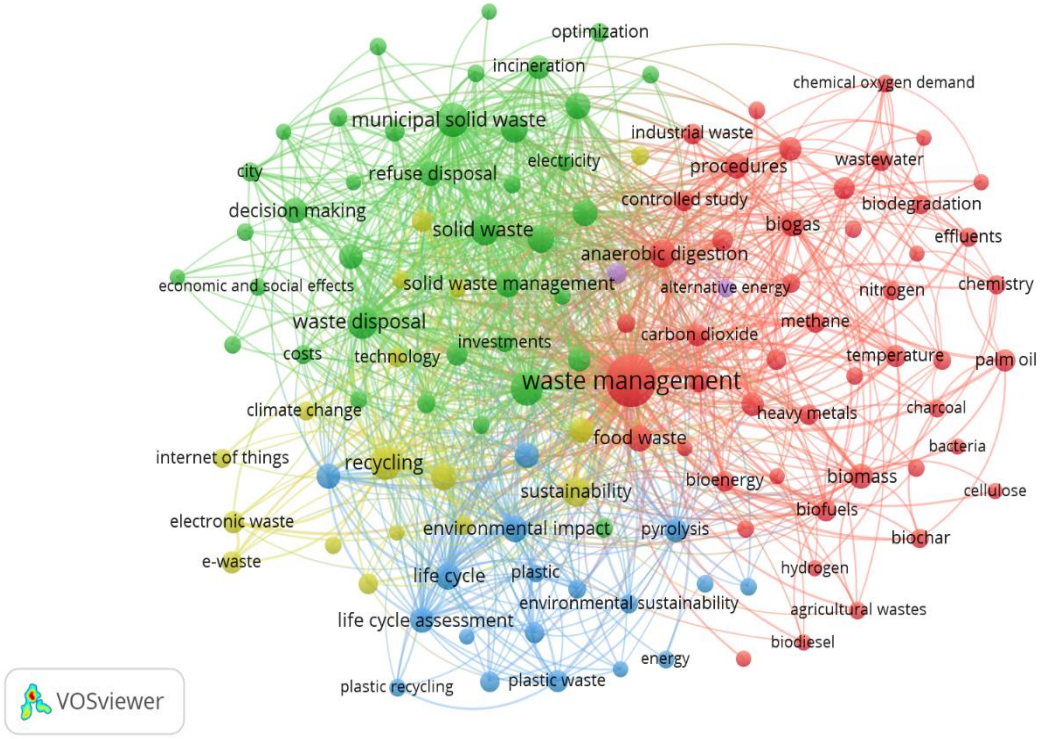

Figure 8. Network visualisation of co-occurrences with index keywords

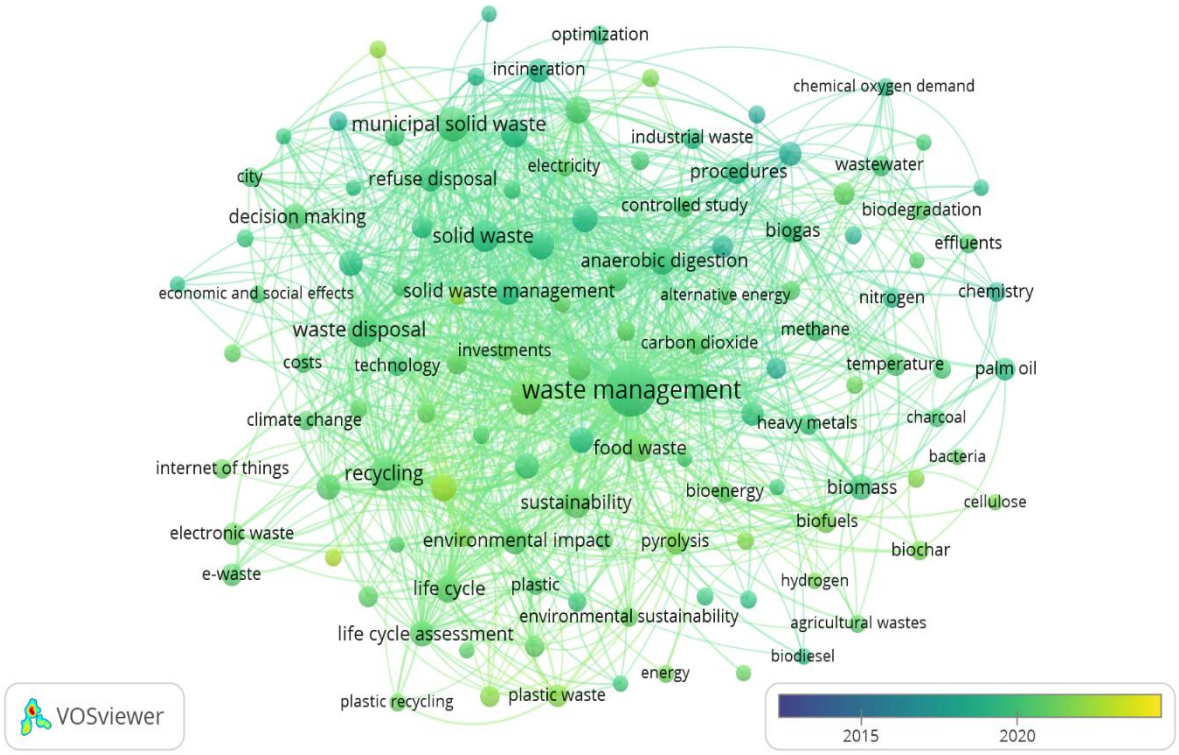

Figure 9. Overlay of visualisation of co-occurrences with index keywords

Density Visualisation

Density visualisation illustrates the saturation level of a topic, with colours such as red, blue, yellow, and green representing yet-to-be-analysed, rarely-studied, and highly evaluated areas, respectively. Brighter colours indicate a higher frequency of the analysed term in relevant experiments. The distribution of keyword density also reveals the frequency of research topics (van Eck & Waltman, 2010). For instance, terms like waste management and sustainable development are often analytically implemented, while rarely analysed and relevant terms focus on waste technology, waste disposal, sustainability, plastic waste, environmental impact analysis, creativity, life cycle, biofuel, composting, environmental sustainability, waste to energy, wastewater treatment and electronic waste. Figure 10 presents the density visualisation technology application in waste management based on keyword indexing.

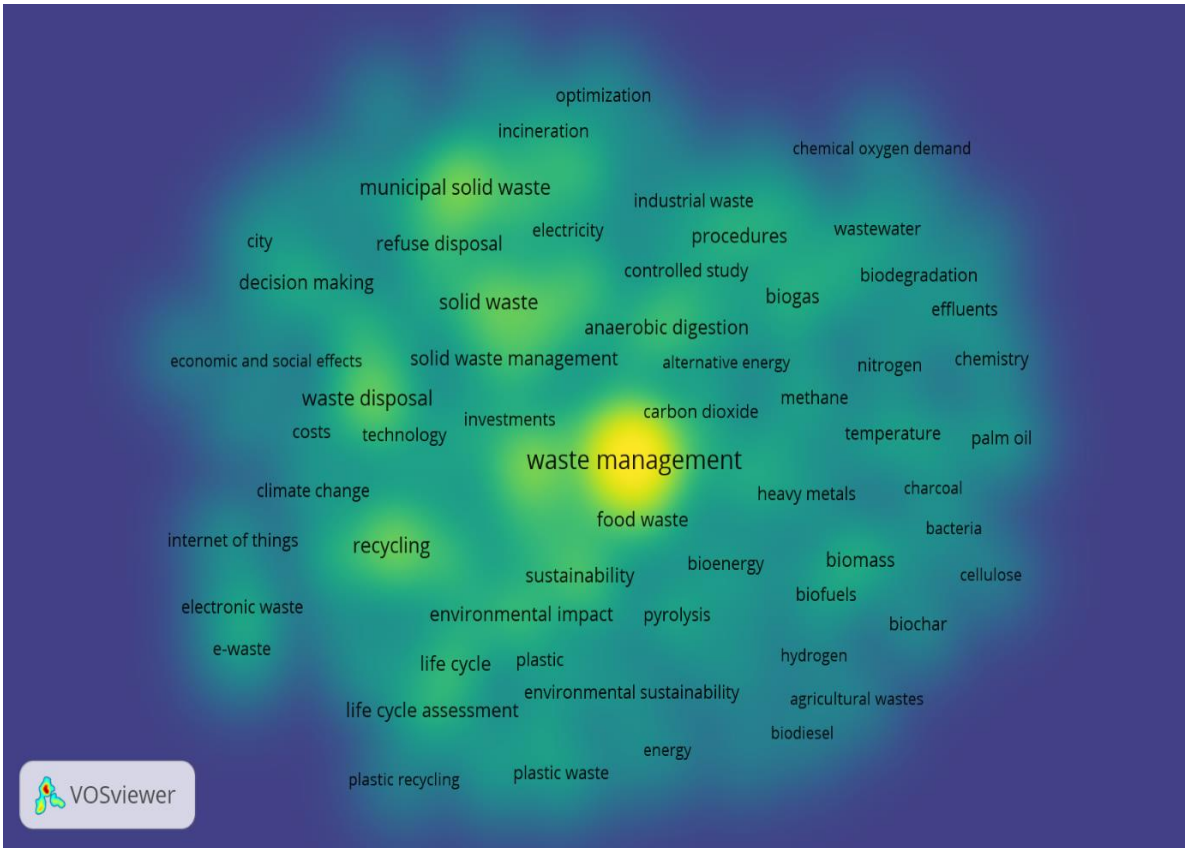

Figure 10. Density visualisation of technology application topics in waste management based on keyword indexing

Discussion

The utilisation of VOSviewer for bibliometric analysis has emerged as a valuable instrument for investigating research trends and contributions across diverse domains. Kirby (2023) and McAllister et al. (2021) emphasise its efficacy in initial research stages and visually representing publication interconnections, specifically within the realm of technology applications in waste management, this software has played a pivotal role in detecting fluctuations in publication figures, signalling an increasing interest in this area. Nonetheless, further inquiry is necessary to comprehend the decrease in recent publications (Rafdhi et al., 2023). Machado et al. (2022) also highlight VOSviewer's potential in identifying research voids, such as the necessity for environmentally-friendly technology in small and medium-sized manufacturing enterprises. This approach enables a comprehensive examination of publication productivity over the decade spanning from 2013 to 2024, revealing distinct fluctuations in publication numbers across different years. An upward trajectory was observed from 2019 to 2023, indicative of heightened interest and research focus in this domain, likely driven by technological advancements and emerging environmental concerns. However, the decline in publications in 2024 may seem unexpected; yet, it's essential to recognise that this data encompasses only the early months of 2024, thus

representing preliminary trends rather than the complete annual pattern. Further investigation and data collection are warranted to ascertain whether this decrease is temporary or indicative of a sustained trend.

Bibliometric analysis facilitates the evaluation of contributions from different countries and institutions in waste management research, offering insights into leading nations and academic entities driving knowledge generation. This comprehensive assessment sheds light on international collaboration dynamics and knowledge dissemination within the research community. The utilisation of VOSviewer in bibliometric analysis provides a nuanced understanding of research trends and contributions in technology application for waste management, aiding in the identification of areas necessitating further attention and understanding of the evolution of research in this domain. The analysis of primary document sources indicates a solid scientific foundation for waste management research, predominantly from scholarly journals spanning disciplines such as environmental science, engineering, and energy. Furthermore, subject area analysis reveals the interdisciplinary nature of technology application in waste management, with research distributed across various disciplines. Visualising document distribution based on subject areas offers a detailed perspective on research distribution across different disciplines. Specific scrutiny of contributions by countries highlights significant involvement from Southeast Asian nations like Malaysia, Indonesia, and Thailand, signalling the region's increasing focus on technology-driven waste management solutions. Visualising publication distribution by country offers a clear overview of the roles played by Southeast Asian countries in advancing research in this area.

A series of bibliometric analyses have illuminated the global landscape of waste management research. Le et al. (2023) and Shi et al. (2021) underscore the growing importance of E-waste and household waste recycling, with China and the British journal 'Waste Management' playing significant roles in these areas. Additionally, Judijanto et al. (2023) and Ndou & Rampedi (2022) highlight the interdisciplinary nature of this research, focusing on environmental sustainability in Indonesia's built environment studies and global and South African trends in municipal solid waste management. Collectively, these studies emphasise the necessity for sustainable solutions and the potential for international collaboration in addressing the challenges of waste management.

A previous bibliometric study, such as the one conducted by Mesdaghinia et al. (2015), examined waste management publications. In this study, the main focus is analysing publication trends regarding technology in waste management across Southeast Asia from 2013 to 2024. We utilised a bibliometric approach to identify institutional contributions, publication trends, and the most popular research topics. On the other hand, Mesdaghinia's research centred on publication trends related to solid waste in Iran from 1982 to 2013. These differences in time frame and geographical coverage offer distinct perspectives in understanding the evolution of waste management research. Meanwhile, the findings from both studies reveal contrasting trends. Our study highlights the highest publication contributions from Malaysia and Singapore and the most popular research topics. In contrast, the study in Iran highlights a decreasing trend in publication numbers and efforts to enhance collaboration among institutions to boost research output in this field. Thus, comparing these two studies provides diverse insights into waste management research trends in the two regions.

Within university affiliations, institutions spanning Malaysia, Singapore, Indonesia, and Thailand emerge as pivotal players in advancing research on technology applications in waste management. Prominent universities from these nations actively contribute to publications in this field, as evidenced by the detailed breakdown in the table showcasing top university affiliations. This underscores the importance of cross-country and cross-institutional collaboration in driving knowledge advancement within this domain. Additionally, noteworthy contributions come from leading authors across various countries, including the Czech Republic, Taiwan, and China, who actively engage in research on technology applications in waste management. Visualisation tools illustrate the significant impact of these authors on knowledge expansion in this area. Moreover, the analysis identifies highly cited publications, underscoring the widespread influence of specific research endeavours. Sure, researchers and authors play pivotal roles in shaping the trajectory and progression of research in this field, highlighting their significant contributions to the scholarly discourse and practical applications of waste management technology.

The most cited document in this bibliometric analysis is a study by Huang et al. (2018), which discusses the management of construction and demolition waste (CDW) in China. CDW accounts for approximately 30-40% of total waste in China, with a recycling rate of only about 5%. The study analyses CDW management in China using the principles of 3R (reduce, reuse, recycle) and discusses existing policies, challenges, and proposed solutions. Highlighted issues include the lack of information exchange between departments, immature recycling technologies, underdeveloped markets for recycled products, and inadequate supervision and management. Proposed strategies include effective circular economic models, strengthening source control, enhancing supervision and management, adopting innovative technologies and market models, and providing

economic incentives to promote CDW reuse and recycling in China. Despite CDW management regulations requiring specific recycling rates for full waste disposal cost recovery, recycling rates in cities like Beijing and Shanghai remain low. Other challenges include the lack of design standards for waste reduction, low disposal costs, improper urban planning leading to high demolition rates, and ineffective systems for CDW material collection, sorting, and reuse. Efforts to promote the principles of reduce, reuse, and recycle (3R) in CDW management in China face various obstacles that must be addressed. The extensive citation of this document is likely attributed to its comprehensive examination of construction and demolition waste management issues in China, offering valuable insights and practical solutions for addressing challenges in the field.

The VOSviewer network visualisation is a valuable tool for understanding the structure and connections among frequently occurring keywords in research, particularly in the domain of technology application in waste management. Through cluster analysis techniques, VOSviewer aids in identifying groups of keywords that commonly co-occur in literature, thereby offering insights into central themes and research trends. VOSviewer network visualisation emerges as a valuable asset in comprehending keyword structures and relationships within waste management research (Gorzeń-Mitka et al., 2020; Han & Gong, 2021; Yalçıntaş et al., 2023; Zhu et al., 2021). This visualisation method enables the identification of keyword clusters, shedding light on primary focuses and evolving research trends within the field. Moreover, the application of VOSviewer reveals clusters of keywords related to waste management technology, waste disposal, and environmental impact analysis, which frequently appear together, indicating the significance of these topics in the literature. Overlay and density visualisations further enrich our understanding of experimental trends and ongoing research focuses. Different colours highlighting annual trends and density levels offer insights into how research interests evolve and where research hubs are situated. For instance, an increase in yellow denotes a growing interest in specific topics in recent research, while blue indicates less-explored areas. This information is pivotal for planning future research endeavours. By comprehending existing research trends and focuses, researchers can pinpoint areas that have been extensively studied and those requiring further attention. For instance, identifying clusters of keywords that have been less explored empowers researchers to delve deeper into those topics and contribute meaningfully to the scientific discourse. Thus, network, overlay, and density visualisations collectively provide a holistic view of research trends and directions in technology application in waste management. Building upon the insights gained from the bibliometric analysis of waste management research, future studies could explore several novel avenues to advance knowledge in this field. One potential area of investigation involves examining the impact of emerging technologies, such as artificial intelligence, machine learning, and the Internet of Things (IoT), on waste management practices. By leveraging these technologies, researchers can develop innovative solutions for optimising waste collection, sorting, recycling, and disposal processes, enhancing efficiency and sustainability.

Furthermore, future research could delve into the socio-economic aspects of waste management, including the role of public awareness, community engagement, and policy interventions in promoting sustainable waste practices. Studies focusing on the socio-economic dimensions of waste management underscore the necessity of adopting a comprehensive approach that encompasses economic viability, public acceptance, and technological progress. The impact of socio-economic status on waste quantity and composition, alongside the significance of public awareness and community involvement, is emphasised (Lakioti et al., 2017). Within healthcare settings, socio-economic and institutional factors emerge as pivotal drivers of sustainable waste management. Additionally, examining the socio-economic ramifications of waste management delves into the interplay between waste practices and sociocultural influences (Tudor, 2007). These investigations highlight the criticality of integrating socio-economic considerations to foster sustainable waste management practices.

Understanding the drivers of waste generation and disposal behaviour among different demographic groups can inform the design of targeted interventions to reduce waste generation, promote recycling, and foster a culture of environmental stewardship. Another promising avenue for future research is the exploration of circular economy principles in waste management. By adopting a circular economy approach, which emphasises the minimisation of waste and the maximisation of resource efficiency, researchers can develop strategies for closing the loop on material flows, reducing reliance on finite resources, and promoting sustainable consumption and production patterns. Additionally, future studies could investigate the environmental and health impacts of emerging waste streams, such as electronic waste (e-waste), plastic waste, and hazardous waste. By quantifying the environmental footprint and health risks associated with these waste streams, researchers can inform policy decisions and industry practices to mitigate their adverse effects on ecosystems and human health. Moreover, interdisciplinary research initiatives that bring together experts from diverse fields, including environmental science, engineering, economics, social sciences, and public health, can facilitate holistic approaches to addressing complex waste management challenges. By fostering collaboration and knowledge exchange across

disciplines, such initiatives can catalyse innovation and drive transformative change in waste management practices.

Future research endeavours in waste management should integrate cutting-edge technologies, socio-economic considerations, circular economy principles, and interdisciplinary collaboration to develop holistic and sustainable solutions for managing waste in an increasingly resource-constrained world. Through these efforts, researchers can contribute to advancing knowledge and developing evidence-based strategies to address the pressing environmental challenges associated with waste management. From the visualisation using VOSviewer, it is evident that waste management technology is still not fully explored in scholarly literature. This indicates that waste management remains a highly complex issue that has been inadequately addressed in various countries. However, from the overlay visualisation, promising opportunities for further development and research in the application of waste management technology can be identified. For instance, researchers are still relatively underexplored in technologies such as pyrolysis, biofuels, biogas, and waste to energy. By harnessing the potential of these technologies, innovative solutions can be developed to address challenges in waste management. Pyrolysis, for example, is a thermal process that can convert organic waste into biochar or biofuel, which can serve as alternative energy sources. Developing biofuels and biogas from organic waste can also help reduce reliance on fossil fuels and mitigate greenhouse gas emissions.

The pressing need for enhanced solid waste management strategies is apparent in existing literature, with studies by Gouveia (2012) underlining the necessity to mitigate environmental and public health risks. These strategies encompass improving recycling methods, reducing waste disposal in landfills, and promoting sustainable consumption habits. Nevertheless, further investigation into the potential health impacts of waste management technologies is warranted whilst acknowledging the significant role of independent waste collectors in sustainable waste management. Developing cost-effective and economically beneficial waste management approaches is also paramount. Furthermore, solid waste management remains relatively unexplored in academic literature despite its critical importance. By formulating efficient technologies and strategies for managing solid waste, we can alleviate its detrimental effects on the environment and public health. This involves enhancing recycling methods, minimising waste disposal in landfills, and advocating for sustainable consumption habits. Considering the findings from VOSviewer and overlay visualisation, it becomes apparent that numerous opportunities exist for further research and advancement in the application of waste management technology. Utilising existing technological capabilities and investigating overlooked areas will be pivotal in addressing waste management challenges and progressing towards a more environmentally sustainable society.

Conclusion

Several key findings can be identified based on the bibliometric analysis using VOSviewer. Over ten years (2013-2024), fluctuations in publication productivity regarding the application of technology in waste management are evident, with an increase in publications from 2014 to 2023 but a decline in 2024. The primary documents are obtained from various sources such as journals, proceedings, book chapters, reviews, and books, with the majority focusing on waste management across various fields such as environmental science, engineering, energy, and psychology. Although most publications originate from Malaysia, Indonesia also plays a significant role in this research trend. Universiti Teknologi Malaysia and the National University of Singapore emerge as the most productive institutions in publications. However, three institutions from Indonesia are also included in the top twenty list. The most relevant author on this topic is Klemes JJ from the Czech Republic. Visualisations with VOSviewer reveal research trends and focuses, with various clusters and patterns emerging, highlighting the most analysed and least studied topics in research. This indicates a strong interest in advancing knowledge about waste management and technology implementation in this field. This research implies that the use of technology in waste management has the potential to yield more effective and sustainable solutions in the future. With a better understanding of research trends and study focuses in this field, researchers and practitioners can identify areas that need further attention and develop innovative technologies. This research also indicates a shift towards a multidisciplinary approach in waste management, emphasising the importance of interdisciplinary collaboration to address complex waste-related challenges. Furthermore, with significant contributions from Southeast Asian countries, the implication is that there is potential to enhance regional cooperation in developing and implementing technological solutions for waste management. Considering the themes revealed in this research, policymakers and stakeholders can prioritise investments in research and technology development that support sustainable waste management, which can contribute to sustainable economic development and environmental protection in the future.

Recommendation

The findings suggest several vital recommendations for improving Southeast Asian waste management practices and research. Firstly, fostering interdisciplinary collaboration among researchers across fields like environmental science, engineering, and social sciences can lead to innovative solutions for complex waste management challenges. Secondly, promoting international cooperation and knowledge sharing can accelerate progress by exchanging best practices and resources. Investing in research capacity building is crucial to cultivating a skilled workforce equipped to tackle emerging challenges. Encouraging open-access publishing ensures wider dissemination of research findings, fostering collaboration and informed decision-making. Prioritising research on emerging technologies like pyrolysis and biogas can unlock sustainable waste treatment solutions. Integrating stakeholder engagement ensures research efforts align with real-world needs, enhancing the relevance of outcomes. Lastly, supporting longitudinal studies enables tracking of evolving trends and assessment of long-term impacts, facilitating informed decision-making for sustainable waste management practices. Implementing these recommendations can lead to more efficient, sustainable, and environmentally friendly regional waste management practices.

Scientific Ethics Declaration

The authors declare that the scientific, ethical and legal responsibility of this article published in EPSTEM Journal belongs to the authors.

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