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WASTE MANAGEMENT: A STATE-OF-THE-ART LITERATURE REVIEW

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ABSTRACT: The purpose of the paper is to systematise scientific research on waste management in order to identify key thematic clusters. A systematic literature review was applied based on bibliometric analysis of publications indexed in Web of Science from 1990 to 2022. Using appropriate filtering criteria, a total of 6,415 publications containing the phrase "waste management" in the title were selected for analysis. The analysis identified trends in publications, the most important publications, journals, countries, authors, collaboration networks in the thematic area and the main thematic research clusters. Through co-word analysis, five thematic research clusters in the field of waste management were identified. These include: (1) waste management methods across various industries, (2) circular economy approaches to closed-loop waste systems, (3) life cycle assessment as a prominent tool for evaluating municipal solid waste management, (4) optimization strategies for solid waste systems, and (5) hazardous and medical waste management, particularly in the context of the COVID-19 pandemic. Moreover, we concluded a framework of existing literature revealed that research interest in waste management has increased over the years; the researchers tended to use more comprehensive methodologies or combined methods to conduct their works, they often used the Life Cycle Assessment; waste management is a key element of the circular economy, aiming to maximize the use of resources by extending the life of a product and the emergence of new sustainable business models driven by recycling. The contribution of this work is to extend current literature and serves as areference to scholars and practitioners for future research and operation in the waste management field. The obtained data can support policymakers and researchers in planning future research activities and implementing sustainable development strategies in Europe.

KEYWORDS: waste management, literature review, bibliometric methods, VOSviewer, research clusters

Introduction

Among the many problems facing humanity today are those related to waste (Michelini et al., 2017). These issues stem from the wastefulness promoted by contemporary society, which in turn is a major cause of the depletion of natural resources. The increase in population and consumption (Maaß, Grundmann, 2018), as well as urban development, imposes disproportionately large waste streams on the economy, generating waste management costs and limiting the ability to properly dispose of these materials. This leads to groundwater contamination (Tian et al., 2019), increased greenhouse gas emissions (Domagała, 2021), the spread of diseases, and the exhaustion of waste disposal options due to high per capita waste production (Šomplák et al., 2019).

Overall, waste becomes a problem as soon as it is generated and not properly processed. Poor waste management also negatively impacts the urban environment and human health, leading to decreased productivity and economic development (Serge Kubanza & Simatele, 2020). The need to ensure sustainable patterns of production and consumption has been particularly emphasised in the UN Sustainable Development Goals (SDGs), specifically in Goal 12.5 (UN WOMEN, 2022). This goal aligns with the concept of Circular Economy (CE). Proper waste management is a crucial step toward transitioning to a CE, as it helps maximise the recovery and reuse of materials, thereby reducing pressure on the use of new natural resources (Castellet-Viciano et al., 2022).

Effective waste management is a complex and challenging issue. It involves legal, environmental, social, economic, cultural, and institutional factors. In a CE, the value of products and goods is maintained for as long as possible. Waste and resource consumption are minimised, and when a product reaches the end of its life, it is reused to create value. This brings numerous economic benefits that contribute to innovation, economic growth, and job creation (Kirchherr et al., 2018; Domagała & Kadłubek, 2023).

Given the substantial research dedicated to this field, a systematic analysis is essential to monitor the geographical distribution of knowledge generation and research trends in waste management (WM). One effective approach to address this need is through bibliometric analysis of the existing literature on waste management. This paper utilises bibliometric analysis focused on selected keywords to identify trends, patterns, and gaps in the analysis of waste management (WM). The purpose of the research is also to identify influential scientists, publications, and journals in the WM field. The findings may serve as a valuable resource for practitioners and researchers, providing insights into the current research landscape and potential future directions in waste management.

Waste management in European Union

The statistics below illustrate the scale of the waste management problem in the EU. In 2006, 2.28 billion tons of waste were generated in the European Union (EU). In subsequent years, the amount of waste generated fluctuated, but did not exceed the 2004 value. It was not until 2018 that nearly 2.35 billion tons of waste were generated, which could be related to increasing consumption and economic growth in Europe between 2012 and 2017 (Dossche & Martinez-Martin, 2018). In 2020, the amount of waste dropped to 2.15 billion tons. Researchers, including Rodgers et al. (2021) and Sharma et al. (2020), pointed to a direct link between the economic slowdown caused by the COVID-19 pandemic and the decline in waste generation.

In the EU, Germany and France generate the largest amount of waste (Figure 2). In 2022, these countries generated more than 300 million tons of waste. Italy (190 million tons) and Poland (175 million tons) were also in the lead. The least waste was generated by small countries: Cyprus, Malta and Latvia. These differences in waste generation may be influenced by factors such as industrial development, population size, and GDP (Abubakar et al., 2022).

In the EU, it is also common to track statistics on the amount of waste generated per person (per capita), which are more reliable. This allows one to observe, for example, consumption patterns. In 2004, the average European produced about 5180 kg of waste per year (Figure 3). As with the total amount of waste generated, this figure fluctuated in subsequent years. During periods of economic recession (2008 and 2020), the amount of waste generated per capita fell below 5,000 kg.

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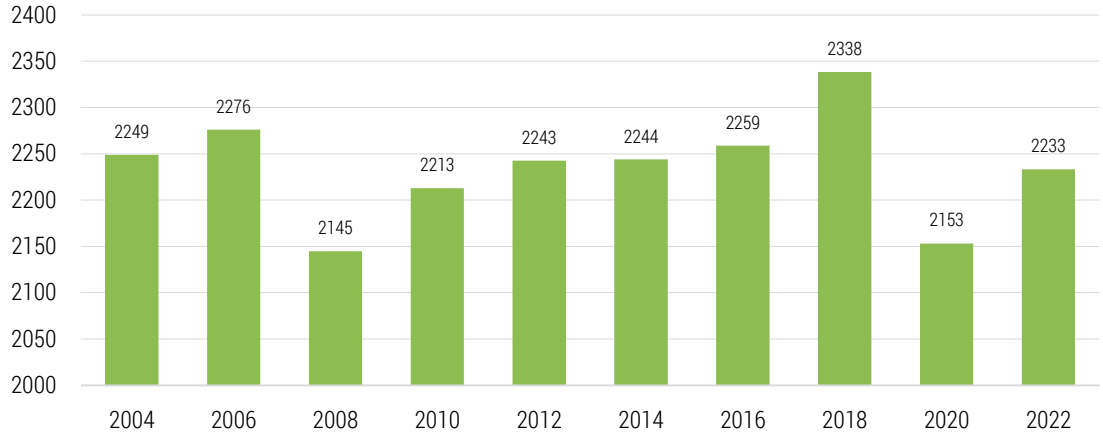

Figure 1. Total waste generation in EU 2004-2022 (million tons)

Source: authors' work based on Eurostat 2024.

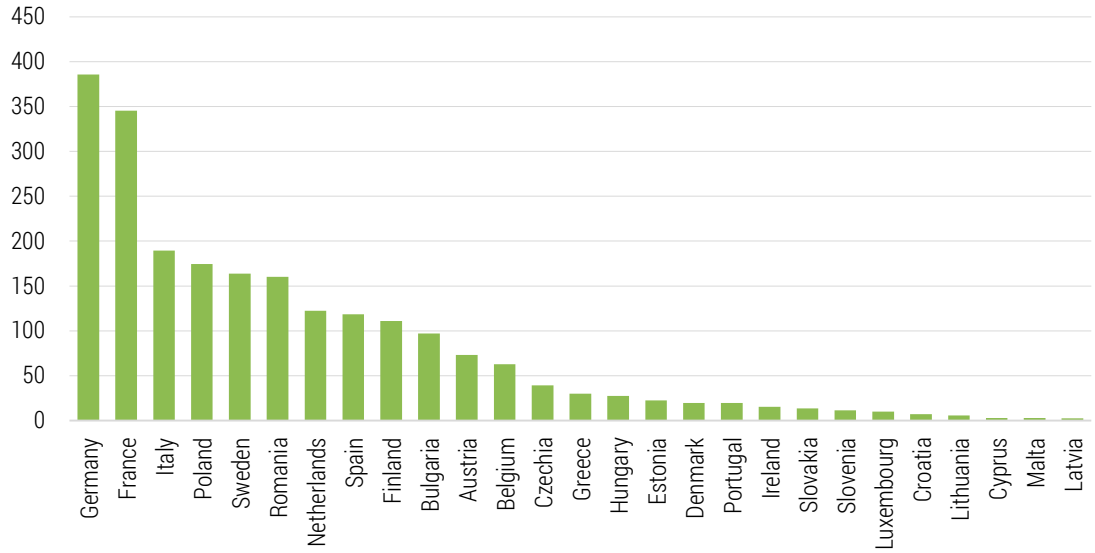

Figure 2. Total waste generation in European Union countries in 2022 (million tons)

Source: authors' work based on Eurostat 2024.

Results of waste generation by country in the EU show that Finland, Estonia, Sweden and Luxembourg produced the most waste per capita, and the average amount of waste generated was more than 15,000 kg annually (Figure 4). However, it should be mentioned that the results for Finland and Sweden were influenced by the extraction and processing of raw materials, which produce a large amount of industrial waste (Espo & Pirtonen, 2021). The largest European countries, e.g. Germany, France, and Poland, resulted in close to the European average, i.e. about 4900kg of generated waste per capita.

The EU's policy in the area of waste management is related not only to the reduction of the amount of waste generated but also to the way it is managed and disposed of (European Council, 2023). Figure 5 presents the variation in waste treatment methods across European Union countries in 2022, expressed as percentages of the total mass of waste generated. This structure reflects the level of economic development, technological advancement, and the effectiveness of environmental policy implementation in each Member State. At the EU level, the dominant waste management methods were recycling (approximately 40% of the total waste mass) and landfilling (also about 40%). Recovery of raw materials and energy accounted for 19%, while incineration without energy recovery represented only 1%.

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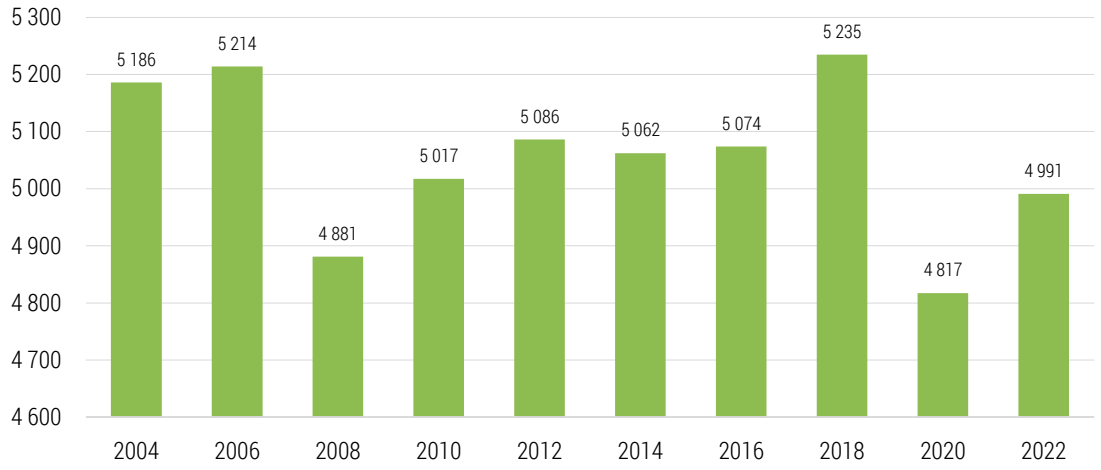

Figure 3. Total waste generation per capita in the European Union 2004-2022 (kilograms per capita)
Source: authors' work based on Eurostat 2024.

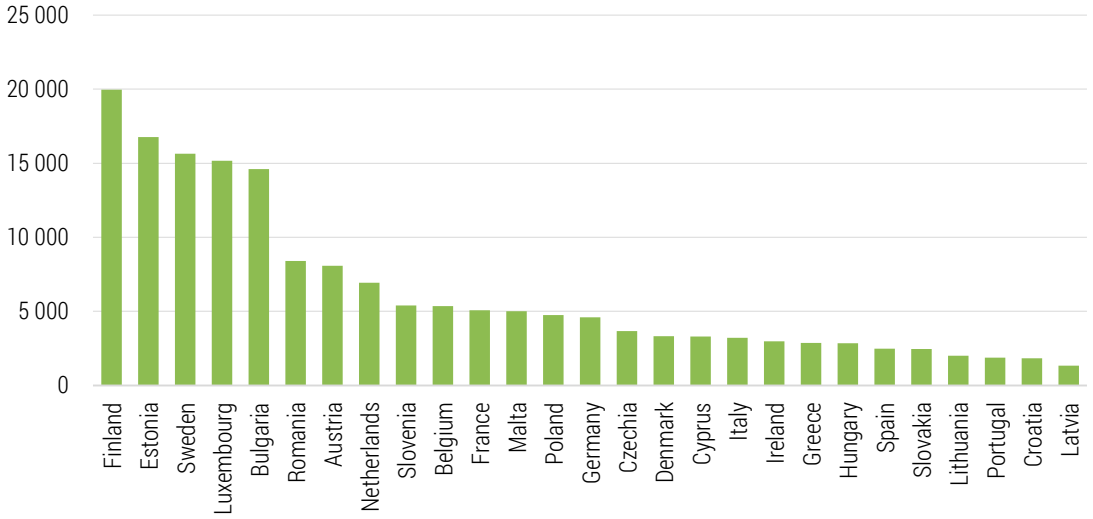

Figure 4. Total waste generation per capita in European Union countries in 2022 (kilograms per capita)
Source: authors' work based on Eurostat 2024.

Energy recovery refers to converting waste into energy, typically through incineration with heat or electricity generation. This approach allows the energy content of waste to be harnessed rather than lost, reducing reliance on primary energy sources and decreasing the amount of waste sent to landfills. It is considered more sustainable than landfilling or incineration without recovery because it provides both waste volume reduction and energy production benefits. According to Figure 5, the share of energy recovery in waste treatment varies significantly among EU countries. Economically developed nations such as Denmark and Ireland display high proportions of energy recovery. These countries have invested heavily in advanced waste-to-energy infrastructure and operate efficient district heating systems that benefit directly from incineration with energy recovery. In contrast, several Eastern and Southern European countries show a minimal share of energy recovery in their waste management structure. This is largely due to limited technological capacity and insufficient funding for modern waste treatment facilities.

Figure 5 clearly illustrates disparities between highly developed economies and those with lower environmental infrastructure capacity. Economically advanced countries, such as Belgium and Denmark, are characterised by a significant share of recycling and energy recovery, with minimal landfilling. Italy, for instance, achieved the highest recycling rate in the EU in 2022 – approximately 83%. In

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contrast, in Romania and Bulgaria, landfilling remains the predominant method of waste management, due to limited investment capabilities, weaker regulatory frameworks, and lower public environmental awareness.

From the perspective of the waste management hierarchy, the presented structure indicates that despite progress in many Member States, the significant share of landfilling still requires intensified efforts to develop recycling technologies and energy recovery solutions, particularly in less developed regions. The figure, therefore, serves not only as an illustrative but also as a diagnostic tool, identifying areas that require priority intervention in EU waste management policy.

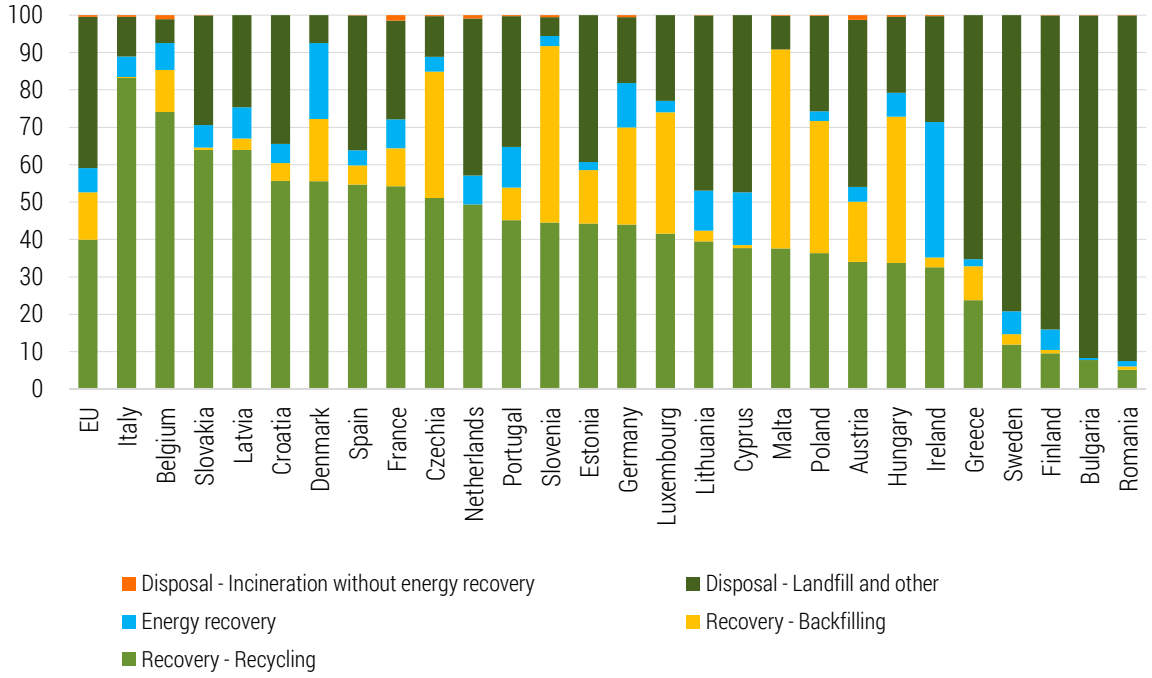

Figure 5. Waste treatment in European Union countries in 2022 (%)

Source: authors' work based on Eurostat 2024.

Material and methods

The methodology presented in this paper employs bibliometric analysis. The planned analyses will adopt a descriptive approach, which is instrumental in exploring trends in scientific research and recognising key researchers or research institutions. This approach will facilitate a comprehensive analysis of the literature and enable the identification of significant advancements in the field of waste management. A range of tools and techniques was employed for the bibliometric analysis. Trend analysis was utilised to examine the variation in the number of publications and citations throughout the study period. Additionally, citation analysis was conducted to explore substantive relationships between publications. A higher impact factor suggests a greater level of interest from other authors in a given publication. Citations also indicate the extent of knowledge transfer and dissemination by authors affiliated with different research institutions. Furthermore, the study incorporated the co-word analysis method, which counts the frequency of word pairs within the analysed texts. The co-occurrence of words may indicate the presence of sub-disciplines or highlight foundational premises that could guide the future development of a specific research area. The VOSviewer software was used to perform the cluster analysis for the purposes of this study. Authors also used the data analysis tools available in the Web of Science (WoS) database. On February 10, 2024, the Web of Science database hosted the study's data.

A significant challenge in conducting database queries is the effective identification of keywords that encompass all publications pertinent to specific research objectives. To address this, a targeted search was executed in the Web of Science (WoS) database using the keywords "waste" and "manage-

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ment." This search was structured to focus on article titles. To ensure the relevance and quality of the retrieved data, the literature type was restricted to "journal article", the language was limited to "English" and the years of publication were limited to "from 1990 to 2022". Articles that did not focus on the topic of WM were eliminated. This refined search yielded a substantial collection of 6,415 publications, which were subsequently subjected to further analysis. Figure 6 illustrates the methodology for selecting publications related to waste management research based on specific filtering steps applied in the Web of Science database.

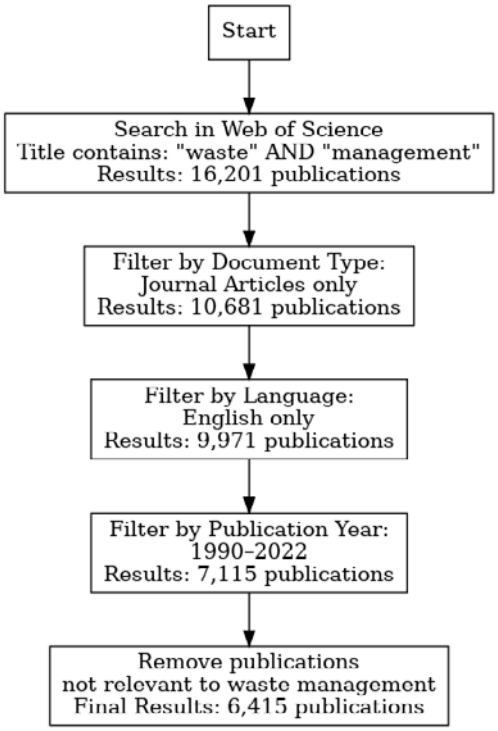

Figure 6. Methodology for selecting publications for research

The search strategy applied in this bibliometric analysis – limited to publications containing the terms "waste" and "management" in the title field of the Web of Science database – inevitably introduces certain semantic and scope-related limitations. On the one hand, this approach ensured a coherent and thematically focused dataset, capturing studies in which waste management constitutes a central research topic. On the other hand, it may have led to the omission of relevant publications.

In the literature on waste-related research, various alternative or more specific terms are frequently used – such as "refuse", "garbage", "trash", "waste disposal", "resource recovery", or "circular waste systems". Studies using such terminology may not have been captured if those terms did not appear explicitly in the title, even if the work addressed waste management issues. Furthermore, limiting the search exclusively to article titles – without scanning abstracts or keywords – may have introduced selection bias, particularly affecting interdisciplinary or emerging areas of research.

Another limitation arises from the inclusion of English-language publications only. This may have resulted in the exclusion of important studies published in other languages, especially those focusing on national or regional waste management contexts. However, due to practical constraints and the authors' inability to systematically analyse non-English texts, this decision reflects a commonly adopted practice in bibliometric research. English remains the dominant language of scientific communication, especially in internationally indexed databases such as Web of Science.

These limitations illustrate the typical trade-off between precision and comprehensiveness in bibliometric studies. While the chosen search parameters aimed to maximise thematic clarity and relevance, they may have impacted the completeness and representativeness of the publication sample. Despite this limitation, the authors were able to identify relevant thematic clusters and the publications associated with them.

Therefore, future research in this field is encouraged to adopt broader keyword strategies, utilise controlled vocabularies or thesauri, and extend searches to include additional metadata fields such as abstracts and author keywords. Where possible, incorporating non-English publications – supported by appropriate language tools and resources – may further enhance the inclusiveness and robustness of bibliometric analyses in the domain of waste management.

Based on the prepared set of publications, five key research questions were formulated to provide a structured framework for the analysis of literature on waste management:

- What is the overall trend in terms of publications?
- Which authors/researchers, based on the analysed data, are most influential?

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- Which journals, according to the data analysed, are most significant for publishing research findings related to WM?
- Which scientific research centres or countries play a pivotal role in advancing WM research?
- What are the primary research areas and themes within the broader topic of waste management?

Collectively, these questions will provide a comprehensive framework for understanding the field of waste management research, facilitating deeper insights into its development and future directions.

Results

General trend in publications

The annual distribution of 6415 papers on waste management was examined. As shown in Figure 7, the number of articles rises from 49 in 1990 to 724 in 2022. The amount of published material increased rapidly starting in 2007. The quickly increasing significance of WM challenges in multiple countries could be the reason for this trend. Certain European nations faced difficulties like a scarcity of landfill sites, potential water pollution, risks of climate change, and issues related to public health. This led to the initiation of the circular economy (CE). Key events that spurred increased interest in waste management included the introduction of the 2015 European Community Agenda 2030, the COVID-19 pandemic, the implementation of the Green Deal in 2020, and the publication of the C40 Mayors' Agenda amid the need for a just recovery and a transition to a more sustainable economy, which influenced the recent growth of research.

The obtained results indicate that there has been a recent increase in interest in the topic of WM, confirming the usefulness of systematic literature review, summarising the key findings on the topic, and identifying future research directions that could develop the field further. Category analysis can identify the disciplines involved in a particular knowledge domain. Environmental Sciences accounted for the highest proportion, followed by environmental engineering. In addition, the largest number of publications corresponded to such research topics as green sustainable science technology, energy fuels, engineering chemistry, and public environmental and occupational health.

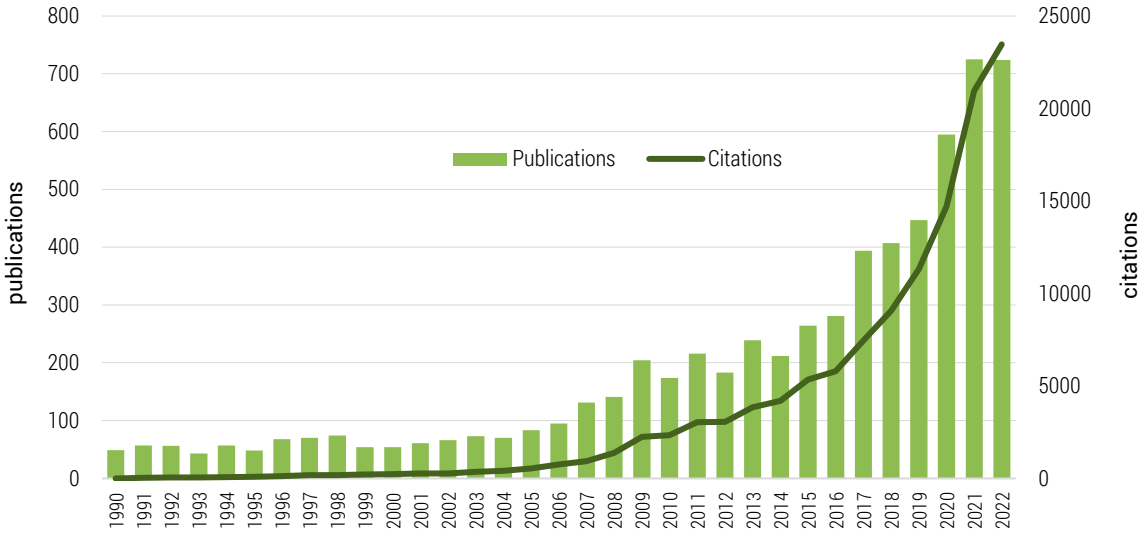

Figure 7. Citations and number of publications related to waste management in the period 1990–2022 in WoS

Source: authors' work based on the created database.

Figure 8 displays the performance of each country individually. Developed countries have made the largest contributions to the current treasury of WM knowledge. Nevertheless, only 23 nations exceeded 50 research outputs. The USA, China, UK, Italy, Canada, and Spain have the most contributions. Additional articles originated from emerging nations like India, Brazil, Iran, Malaysia, Thailand, and Indonesia, in that order (Figure 8). Poland held the 14th position in the ranking with a total of 169 publications.

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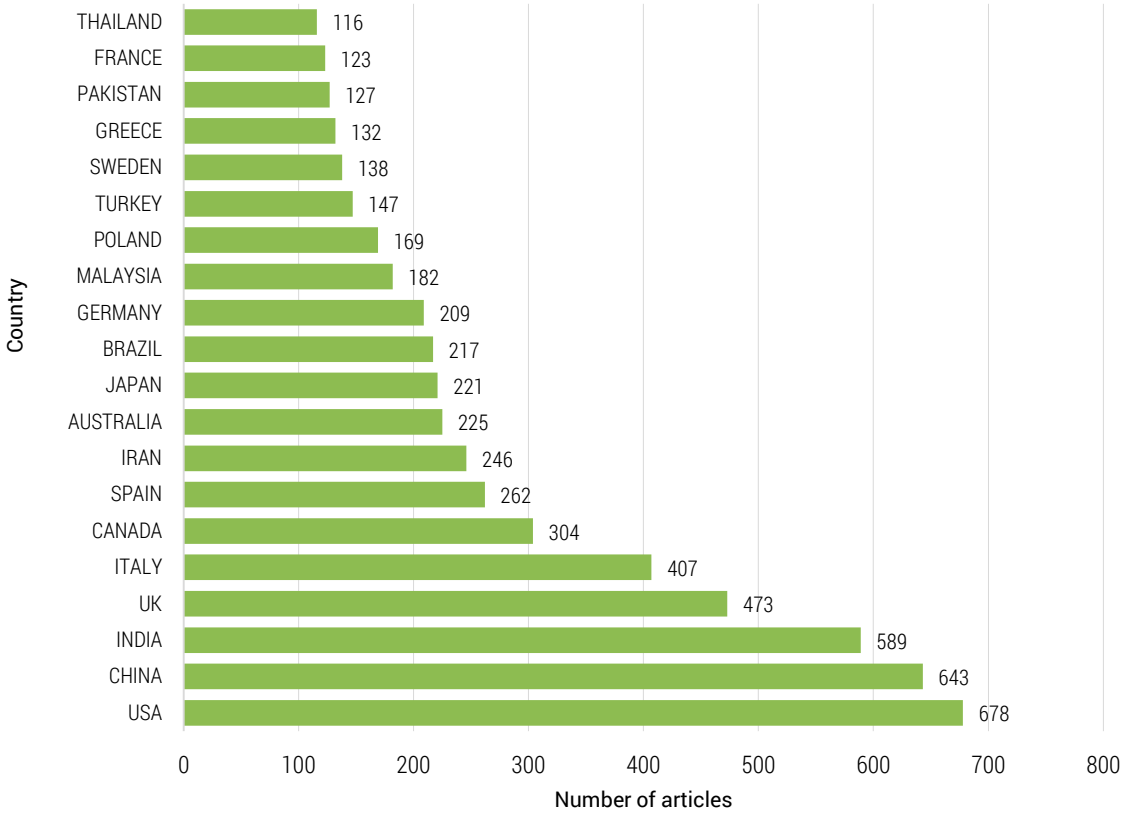

Figure 8. Top 20 countries with the most scientific publications on WM

Source: authors' work based on the created database.

The examination also highlighted the level of collaboration among nations. Researchers from China demonstrated the highest level of international collaboration. Researchers from the UK, the USA, India, and Canada showed slightly lower levels of cooperation.

Within the collaboration, seven clusters were identified based on geographical criteria (Figure 9). All countries with the highest number of publications (China, the USA, and India) were grouped within the same cluster, confirming strong scientific cooperation among researchers in these nations.

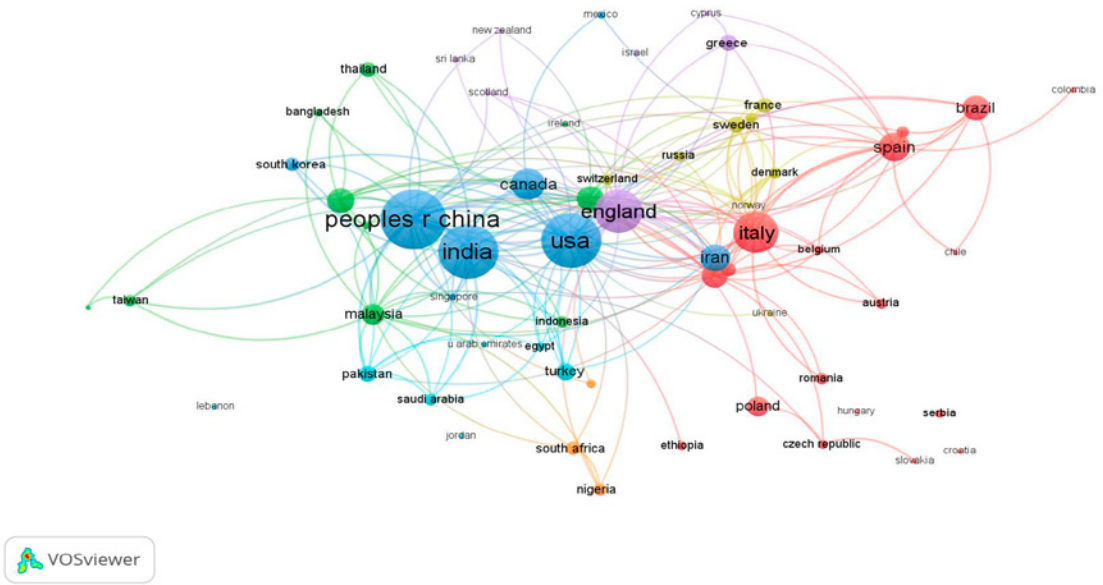

Figure 9. Visualization of the volume of research at the national level and international collaboration

Source: authors' work based on the created database.

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Analysis of authorship, collaboration and research center

In the next step, the distribution of authors' scientific productivity was examined. 65 authors published more than 10 articles, while most authors (16711) published less than 10 articles. The largest number of publications about WM was published by Huang G.H., and it was 111 articles (Table 1).

Table 1. Most productive authors by number of papers

Ranking by number of publications		
Author	**Institution / Country**	**No. of papers in WoS**
Huang G.H.	McMaster University, Hamilton, Ontario, Canada	111
Li Y.P.	Beijing Normal University, China; University of Regina, Canada	36
Chang N.B.	University of Central Florida, USA	34
Christensen T.H.	Technical University of Denmark, Denmark	27
Al-Khatib I.A.	Birzeit University, Palestine	20
Pires A.	NOVA University Lisbon, Portugal	20

Source: authors' work based on the created database.

The contribution of individual authors to the development of waste management research was primarily evaluated based on the number of citations of their publications in the database. As shown in Table 2, the most cited paper was published in 2014 by Papargyropoulou et al., got the highest number of citations (721), followed by the paper by Sharholy et al. (510 citations) in 2008.

The geographic spread also indicates the research hubs with the highest number of publications by authors on the topic being studied. A broad range of scientific output was noted in terms of the institutions where it is carried out and subsequently published. Table 3 displays the most powerful science centres. The University of Regina and the Indian Institute of Technology System, both having over 100 articles published, are seen as more efficient from this viewpoint.

Table 2. The most cited articles

Authors	Title	Source	Publication Year	Total Citations
Papargyropoulou, E.; Lozano, R.; Steinberger, J. K.; Wright, N.; bin Ujang, Z.	The food waste hierarchy as a framework for the management of food surplus and food waste	Journal of Cleaner Production	2014	721
Sharholy, M.; Ahmad, K.; Mahmood, G.; Trivedi, R. C.	Municipal solid waste management in Indian cities – A review	Waste Management	2008	510
Barr, S.	Factors influencing environmental attitudes and behaviors – A UK case study of household waste management	Environment and Behavior	2007	483
Wilson, D.C.; Velis, C.; Cheeseman, C.	Role of informal sector recycling in waste management in developing countries	Habitat International	2006	477
Huang, G; Baetz, B.W; Patry, G. G	A gray linear-programming approach for municipal solid-waste management planning under uncertainty	Civil Engineering Systems	1992	432

Source: authors' work based on the created database.

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Table 3. Institutions of authors most frequently publishing in the area of the waste management

Research center	No. of papers in WoS
University of Regina	112
Indian Institute of Technology System (IIT System)	111
University of Tehran	70
North China Electric Power University	68
Swiss Federal Institutes of Technology Domain	61

Source: authors' work based on the created database.

Analysis of publication sources

The analysed papers were published in reputable international journals, indicating that waste management has become a popular topic for many journals. The top five journals in the field of waste management, based on the number of publications in the WoS database, are Waste Management, Waste Management Research, Journal of Cleaner Production, Sustainability, and Resources Conservation and Recycling (Table 4). These journals have each published between 253 and 469 articles on the topic of Waste Management.

Table 4. Journals with the largest number of publications on WM issues in the WoS database

Title of the journal	No. of papers in WoS
Waste Management	469
Waste Management Research	406
Journal of Cleaner Production	339
Sustainability	256
Resources Conservation and Recycling	253

Source: authors' work based on the created database.

The main research areas

A keyword co-occurrence map reveals not only the frequency of specific keywords appearing in titles, abstracts, and keywords, but also which terms appear together within a single paper. The size of each circle reflects the occurrence rate of a given word, while the line thickness shows how frequently these words are paired within a paper. This diagram also visually represents the subject area being analysed (Figure 10).

Through co-word analysis, five research clusters concerning WM were identified.

- Cluster 1 (red) – Waste management methods in various industries
- Cluster 2 (blue) – Closed-loop waste management (Circular Economy)
- Cluster 3 (violet) – Life Cycle Assessment as a popular method for assessing municipal solid waste management
- Cluster 4 (yellow) – Optimisation of solid waste management
- Cluster 5 (green) – Hazardous and medical waste management, with particular emphasis on the COVID-19 period

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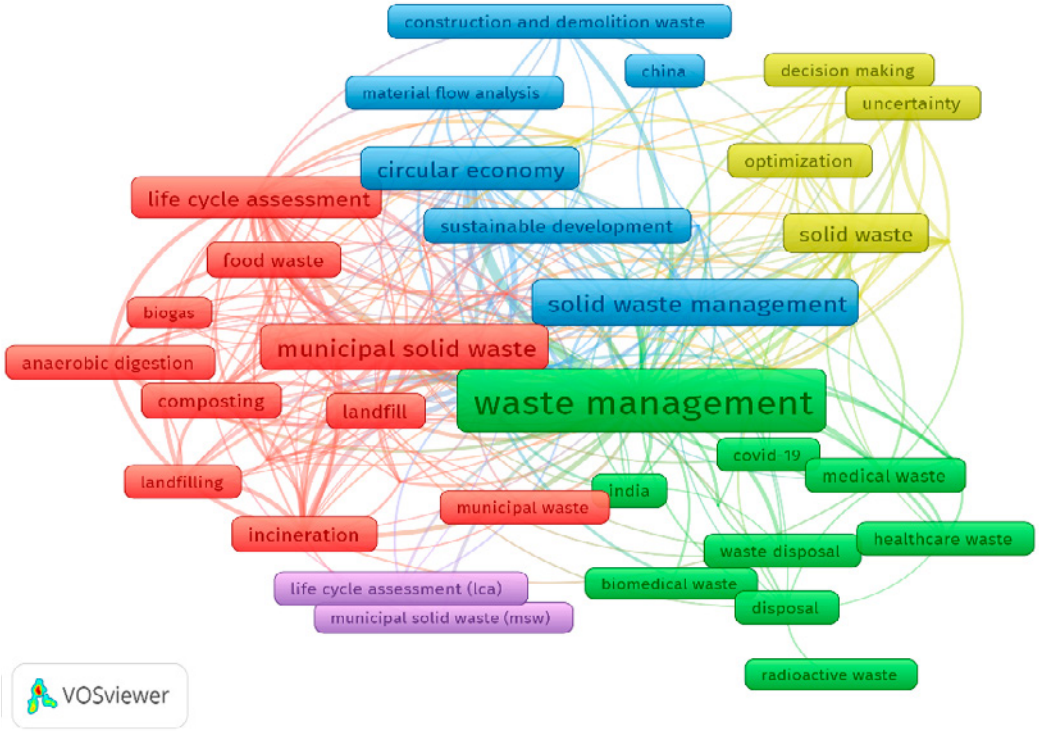

Figure 10. Co-word cluster map

Source: authors' work based on the created database.

Discussion

The first highlighted cluster refers to waste management methods in various industries. In 2008, the European Union introduced a waste management hierarchy, which outlines a specific sequence of actions to prevent waste generation: waste prevention, preparation for reuse, recycling, other forms of recovery, and disposal (Zhang et al., 2022). Demirbas (2011) discussed these methods in economic, social, and environmental terms, emphasising composting, energy recovery, and the recovery of secondary resources from solid waste as preferable solutions. Galvez-Martos et al. (2018) applied the circular economy framework to Construction and Demolition Waste (CDW) in Europe, while Bourtsalas et al. (2022) linked waste management with the energy sector in both the USA and the EU, pointing to benefits for emission reduction and energy security. These examples highlight a notable regional divide: regions with advanced infrastructure and stable policy frameworks, such as Northern and Western Europe, tend to adopt high-efficiency solutions like anaerobic digestion or thermal recovery. In contrast, countries with limited technical capacity, decentralised governance, or challenging climatic conditions may find it difficult to operate at the upper levels of the hierarchy (Maphosa & Maphosa, 2020). Eriksson, Strid, and Hansson (2015), in their study of food waste in Sweden, confirmed that landfill is consistently the least favourable option, while donation, anaerobic digestion, and energy-recovery incineration yield the most positive environmental outcomes. These patterns suggest that the waste hierarchy's practical implementation is strongly conditioned by regional economic capacity, governance models, and technology availability, leading to persistent disparities in environmental performance across the globe.

Closed-loop waste management is another thematic cluster identified through thekeywords. The concept of circular economy gained traction through European Commission legislation in 2015, with the introduction of initial recommendations and objectives for sustainable development within the EU (European Commission, 2024). It is important to note that the implementation of circular economy principles varies significantly across countries and regions, influenced by spatial factors such as local infrastructure, regulatory frameworks, waste collection systems, and urban-rural dynamics. Research in the field of circular economy is being conducted across various industries, including the

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food (Papargyropoulou et al., 2014; Sehnem et al., 2021), construction (Ghaffar et al., 2020; Huang et al., 2018), and packaging sectors (Rutkowski, 2020). For example, Haupt et al. (2017) conducted a thorough examination of paper, cardboard, aluminium, tinplate, glass, and polyethene terephthalate (PET) recycling from municipal solid waste (MSW) in Switzerland. Results show that the recycling rates of most separately collected materials are substantially lower than officially reported. Papargyropoulou et al. (2014) based on insights from food waste specialists, distinguished between food surplus and waste, avoidable and unavoidable waste, and the roles of prevention versus management. They advocate for sustainable production and consumption practices across supply chains as a first step, proposing a waste hierarchy framework that prioritizes minimizing surplus and redistributing food to those in need before considering animal feed conversion. In Europe, CE is supported by comprehensive policies like the European Green Deal and Circular Economy Action Plan, enabling its integration into industrial and urban systems. In contrast, many Sub-Saharan African countries – such as Ghana – operate within a predominantly linear waste economy, hindered by low public awareness, limited infrastructure, and weak political commitment (Debrah et al., 2022; Nijman-Ross et al., 2023). In such contexts, CE practices often emerge informally, driven by necessity rather than formal governance. These disparities illustrate that CE diffusion is not simply a matter of policy transfer but requires alignment with socio-economic realities and institutional maturity.

Another identified cluster relates to Life Cycle Assessment (LCA). LCA is a widely recognised and utilised method for evaluating the environmental impacts of waste management systems. As a vital analytical tool for environmental decision-makers, LCA is instrumental in assessing the environmental burdens associated with products and processes throughout their entire lifecycle. This analysis spans from the extraction of raw materials through production, use, and eventual disposal (Grzesik, 2006; Rebitzer et al., 2004; Oztas et al., 2022). The growing role of LCA reflects a fundamental shift in environmental assessment from focusing on isolated process stages or single indicators to a holistic perspective encompassing all phases of a product's or service's life cycle. This approach captures potential shifts in environmental burdens between stages, providing a more complete basis for addressing challenges such as economy-wide decarbonisation and resource-use optimisation. LCA's integration with complementary tools like Life Cycle Costing (LCC) and Social LCA enables multidimensional evaluations that combine environmental, economic, and social dimensions, thereby supporting informed and balanced decision-making in line with sustainable development goals. The method's standardisation under ISO 14040/14044 ensures that results are comparable across sectors and regions, a crucial factor in globalised supply chains and transparent environmental reporting. Recent advances in computational capacity, the availability of high-quality datasets such as Ecoinvent, and the development of user-friendly software like SimaPro, OpenLCA, and GaBi have significantly lowered technical barriers, broadened its applicability, and increased the robustness of results, contributing to the method's accelerated uptake among policymakers, researchers, and industry practitioners worldwide.

Kulczycka et al. (2015) evaluated two LCA software tools: IWM-2, specifically designed for municipal solid waste, and SimaPro, a more general and widely used LCA tool. The study highlighted the strengths and limitations of each software, using a case study from Poland to analyse waste management scenarios. The research demonstrated that even with identical initial inventory data, based on the same assumptions, system boundaries, and LCA methods, different software tools may yield varying outcomes. Sarigiannis et al. (2021) conducted a comparative LCA of various waste disposal strategies in eastern Attica and Thessaloniki. The study assessed options such as landfilling (with and without landfill biogas recovery), biogas and compost production through anaerobic digestion and composting, as well as waste incineration, using a multi-method, multi-scale approach. Mushtaq et al. (2022) applied LCA to evaluate the environmental impacts of different hospital waste management strategies. Jensen, Møller, and Scheutz (2016) analysed organic household waste management in the Danish–German border region through LCA, revealing significant differences between the systems used in each country. The Danish region relies solely on incineration, while the German side employs a combination of biogas production, composting, mechanical and biological treatment (MBT), and incineration. These examples illustrate how regional contexts and policy frameworks influence the selection and application of LCA methods. While Western and Northern European countries often employ advanced, multi-scale LCA tools, other regions may still face implementation challenges due to differences in infrastructure or regulatory maturity.

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The fourth thematic cluster concerns optimisation of solid waste management. For example, Nabavi-Pelesaraei et al. (2017) assessed energy consumption and environmental impacts of waste management scenarios involving incineration and landfill, employing various methods. Their study developed feed-forward back-propagation models, using the Levenberg-Marquardt training algorithm, to predict electricity usage and environmental factors relative to energy consumption in municipal solid waste management. Huang et al. (1992; 1993) introduced a novel approach to mathematical programming, known as grey fuzzy linear programming (GFLP), and a new optimisation method called grey linear programming (GLP) used for optimising analysis results. The GFLP approach was applied to a hypothetical problem in the municipal solid waste management planning area. Over time, the field has evolved from deterministic and linear mathematical models toward more complex, adaptive, and data-driven approaches. Early models focused primarily on cost and capacity constraints, while more recent studies incorporate environmental criteria, uncertainty, and stakeholder preferences using artificial intelligence, fuzzy logic, and multi-objective optimisation (Rathore & Sarmah, 2020). This shift parallels broader technological trends, where increased computational capacity and machine learning techniques enable more nuanced balancing of environmental, economic, and social objectives. Yet again, regional differences emerge: high-income countries deploy these advanced tools to fine-tune already-efficient systems, while lower-income regions often prioritise basic service expansion, with optimisation remaining a secondary concern.

The final thematic cluster addresses hazardous, medical, and food waste management, especially during the COVID-19 period. With pandemic-related shifts in consumer behaviour and increased single-use products in food and plastics, the circular supply chain has been notably impacted. The United Nations Environment Programme (UNEP) highlights the urgent need for standardised medical waste management linked to pandemic control (UNEP, 2020). Research by Sharma et al. (2020) found that while household food waste may decrease due to conscious purchasing, supply chain disruptions could lead to waste increases. The study underscores the importance of resilient supply chains for future pandemics. Vanapalli et al. (2021) and Hantoko et al. (2021) reached similar findings regarding plastic waste generation and management impacts. Ilyas et al. (2020) emphasised that improper COVID-related waste handling poses a global health and environmental threat, while Kulkarni and Anantharama (2020) examined the surge in medical waste affecting municipal waste systems. The COVID-19 pandemic served as a turning point in the discourse on hazardous and medical waste management, exposing systemic vulnerabilities across different geographic regions. Silva et al. (2020) stressed that rising plastic waste during the pandemic necessitates stronger policies to mitigate environmental impacts. Although the pandemic was global in nature, its waste-related consequences varied significantly across regions, depending on geographic, functional, and economic factors. For example, highly urbanised and industrial regions experienced an increase in medical and packaging waste due to higher population densities and concentrated healthcare services. In contrast, tourist-dependent countries, particularly those with seasonal economies such as Mediterranean or island nations, experienced sharp declines in commercial, food service, and airport-related waste during lockdowns (Papanikos, 2020; Provenzano & Volo 2021).

Summary and conclusions

With the rise of industrialisation, urbanisation, and the associated waste generation, there is a growing need for effective waste management strategies. The study aimed to identify current research directions related to the issue of waste management. The analysis confirms that waste management is closely linked to the concept of the circular economy and remains not only a relevant but also a dynamically evolving field of scientific inquiry. Research activity has intensified in recent years, as reflected by the steady increase in the number of publications, particularly between 2015 and 2022. This growth aligns with the adoption of the European Union's 2030 Agenda and reflects the scientific community's engagement with global sustainability objectives. The increase in publications during 2019–2020 reflects European countries' commitment to promoting the decoupling of economic growth from natural resource use. This trend was influenced by the COVID-19 health crisis, the European Green Deal, and the C40 Mayors' Agenda, which all highlight the need for a just recovery and a transition toward a more sustainable economy. Nevertheless, the research highlights existing

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gaps between developed and developing countries. Developed countries lead with the largest number of articles published on waste. Among the leading journals on waste management, the following stand out: Waste Management, Waste Management Research, Journal of Cleaner Production, and Sustainability. Among the articles with the greatest impact, that is, the most cited, is the paper by Papargyropoulou et al. (2014).

This study offers a comprehensive review and summary of the waste management literature, highlighting key trends within the field. The bibliometric analysis of 6,415 publications indexed in the Web of Science enabled the identification of five major research clusters in the field of waste management: (1) waste management methods across various industrial sectors, (2) circular economy approaches and closed-loop systems, (3) life cycle assessment (LCA) as a tool for evaluating municipal solid waste systems, (4) optimization strategies for solid waste management, and (5) hazardous and medical waste management, including pandemic-related challenges during COVID-19.

The findings are expected to serve as a foundation for future research by both academics and industry professionals, with important implications for evidence-based policymaking at the EU and global levels. By identifying emerging trends, thematic gaps, and research priorities, this analysis can support policymakers in designing more effective, targeted, and forward-looking waste management strategies. For policymakers, the results provide a robust evidence base for informed decision-making in environmental governance, helping to identify the technologies, methods, and management models most likely to enable effective and context-appropriate implementation, ensuring that regulatory interventions are grounded in the most current, consensus-driven scientific knowledge. For policy-makers, these insights serve as a robust evidence base, ensuring that regulatory interventions are informed by the most current, consensus-driven scientific knowledge. The temporal trends captured in the bibliometric data can also be used to monitor the indirect impacts of policy instruments – such as the EU Circular Economy Action Plan – on research intensity and innovation uptake.

The bibliometric mapping of thematic gaps, international collaboration patterns, and high-priority research areas offers strategic value for funding agencies by enabling targeted allocation of resources to projects with the greatest environmental and socio-economic impact potential. The analysis also highlights the most influential authors, institutions, and journals, providing a roadmap for building high-impact research consortia and fostering targeted international collaboration.

In this way, bibliometric mapping not only informs the design of forward-looking waste management strategies but also strengthens the science–policy–funding interface, accelerating the translation of research into effective, measurable action at both EU and global levels.

The conducted research has certain limitations. The scope of this study was restricted to searching for information in the WoS database; therefore, it is suggested that future research include other databases, such as Scopus and Google Scholar. Further studies should apply an expanded set of keywords and include abstracts and author-provided keywords to improve coverage and reduce selection bias. Incorporating non-English publications, as well as employing alternative visualisation tools (e.g., CiteSpace, RStudio), would enhance the comprehensiveness of bibliometric analyses and capture trends in emerging interdisciplinary areas of waste management research. It is recommended that future bibliometric analyses employ a broader set of keywords and include additional metadata fields, such as abstracts and author-provided keywords, to enhance the reliability and comprehensiveness of the results. Furthermore, examining non-English-language articles could provide a different perspective on waste management.

The contribution of the authors

Conceptualisation, J.D.; literature review, J.D. and M.B.; methodology, J.D.; formal analysis, J.D. and M.B; writing, J.D. and M.B.; conclusions and discussion, J.D. and M.B.

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GOSPODARKA ODPADAMI – PRZEGLĄD NAJNOWSZEJ LITERATURY

STRESZCZENIE: Celem artykułu jest usystematyzowanie badań naukowych dotyczących gospodarowania odpadami w celu identyfikacji kluczowych klastrów tematycznych. Zastosowano systematyczny przegląd literatury oparty na analizie bibliometrycznej publikacji indeksowanych w bazie Web of Science w latach 1990-2022. Po zastosowaniu odpowiednich filtrów zidentyfikowano 6415 publikacji zawierających frazę „waste management" w tytule. Analiza pozwoliła na określenie trendów publikacyjnych, najważniejszych publikacji, czasopism, krajów, autorów, sieci współpracy w obrębie badanego obszaru tematycznego oraz głównych klastrów badawczych. Za pomocą analizy współwystępowania słów kluczowych wyodrębniono pięć tematycznych klastrów badawczych w dziedzinie gospodarowania odpadami, obejmujących: (1) metody zarządzania odpadami w różnych sektorach przemysłu, (2) podejścia gospodarki o obiegu zamkniętym (circular economy) do systemów zamkniętego obiegu odpadów, (3) ocenę cyklu życia (Life Cycle Assessment) jako popularne narzędzie oceny systemów gospodarki odpadami komunalnymi, (4) strategie optymalizacji gospodarki odpadami stałymi oraz (5) zarządzanie odpadami niebezpiecznymi i medycznymi, ze szczególnym uwzględnieniem okresu pandemii COVID-19. Wnioski z analizy literatury wskazują, że zainteresowanie tematyką gospodarowania odpadami wzrasta na przestrzeni lat; badacze coraz częściej stosują złożone lub łączone podejścia metodologiczne, a ocena cyklu życia jest jednym z najczęściej wykorzystywanych narzędzi. Gospodarka odpadami stanowi kluczowy element gospodarki o obiegu zamkniętym, której celem jest maksymalizacja wykorzystania zasobów poprzez wydłużenie cyklu życia produktów oraz rozwój nowych, zrównoważonych modeli biznesowych opartych na recyklingu. Wkład niniejszej pracy polega na poszerzeniu istniejącego stanu wiedzy i dostarczeniu punktu odniesienia dla badaczy i praktyków w zakresie przyszłych badań oraz działań operacyjnych w obszarze gospodarowania odpadami. Uzyskane dane mogą wspierać decydentów politycznych i naukowców w planowaniu przyszłych działań badawczych oraz wdrażaniu strategii zrównoważonego rozwoju w Europie.

SŁOWA KLUCZOWE: gospodarka odpadami, przegląd literatury, analiza bibliometryczna, VOSviewer, klastry badań

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