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Systematic Review of Advancements in Sustainable Solid Waste Management System in the era of Industry 4.0

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Abstract

Solid waste generation has witnessed a significant global upsurge, necessitating a shift from traditional handling methods to more intelligent approaches aligned with the contemporary paradigm of Industry 4.0(I4.0). Traditional techniques of solid waste management (SWM) pose challenges in adequately coping with the burgeoning volume, demanding the adoption of smarter solution. Achieving sustainability, encompassing economic, social, and environmental facets, is hindered by the persistent reliance on manual processes in waste management. This article aims to address these issues by conducting a systematic literature review on the application of I4.0 in SWM considering sustainability. This study also suggests a path for future research through in-depth content analysis. The findings contribute valuable insights for policymakers, practitioners and researchers aiming to develop strategies for intelligent and sustainable solid waste management in the current global landscape.

Keywords
Solid Waste Management, Sustainability, Industry 4.0, Systematic Literature Review, Content Analysis

1. Introduction
In a period characterized by accelerated urbanization, augmenting population dimensions, and economic expansion, solid waste management (SWM) has emerged as critical global concern by 2050, with projections foreseeing an anticipated 3400 million tonnes of solid waste (SW) (Hashemi-Amiri et al., 2023). The rising SW rates lead to widespread dumping, adversely affecting property values and community well-being. Addressing these challenges requires integrating sustainability into SWM, which is crucial for source reduction, mitigating environmental pollution from disposal, promoting recycling, and promoting the harmonious development of humanity and nature (Pati and Agrawal, 2022; Yang et al., 2023). SW is categorized into various types, including electronic, municipal, hazardous, industrial, and, distinguished based on their sources and compositions. The synergistic application of Industry 4.0 (I4.0) alongside physio-chemical technologies elevates resource recoveries, ensuring effective management and yielding valuable outputs (Vyas et al., 2023). Leveraging I4.0 for efficient handling of value chain data for executing cognitive action and implementing at the local level not only enhance SWM but also contribute to sustainable economic growth (Chowdhury et al., 2022). In addition, it aspires to essentially convert conventional businesses into smart industry by bringing self-maintenance and personality traits, serving as the cornerstone of future network technologies where knowledge is intelligently transmitted and shared without human intervention.

SWM involves predicting SW generation, segregating waste, managing collection, transportation, and recycling. Addressing the intricacies of these processes can be achieved by employing computational designs that emulate human cognitive skills, allowing for the resolution of complex engineering problems with numerous input/random variables (Ihsanullah et al., 2022). With the advent of unparalleled data accessibility and technological progressions, models are increasingly favoring the application of methods based on artificial intelligence (AI), machine learning (ML), cyber-physical system, cloud computing, block chain, big data, Internet of things (IoT), and equivalent methods. I4.0 interventions play a pivotal role in elevating waste management, fostering high resource efficiency and optimizing SWM planning, monitoring and execution for the sustainable society as shown in Figure 1. The survey performed on a global scale by the International solid waste association, underscores that merely 14% of the experts taking part in the interview process feel adequately knowledgeable about the opportunities presented by I4.0 (Kanojia,2021). To obtain more insights and trends role of I4.0 in SWM for achieving sustainability, it appears that comprehensive systematic literature review is the prominent approach to utilize. The content analysis is carried out to present the futures areas of research drawn from the gap of past literature.

The remainder of this article comprises three sections. Section 2 delves into past studies, while Section 3 discusses the research method. Section 4 presents the discussion, and lastly, Section 5 outlines the study's conclusions, limitations and future scope.

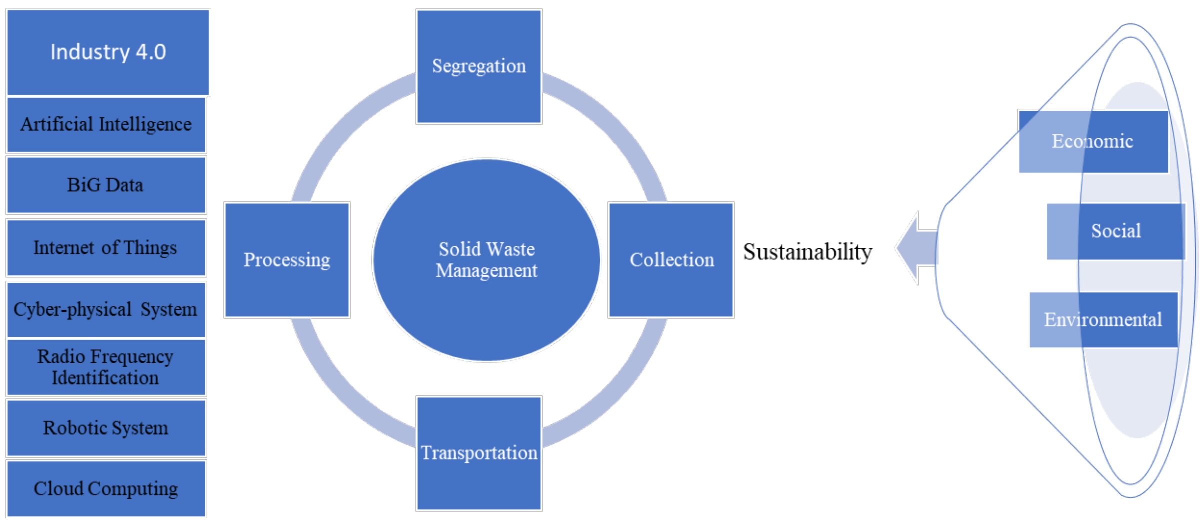


Figure 1. Integrating Industry 4.0 techniques for advancing sustainable solid waste management.

2. Related Work

SWM, recognized as the process of handling SW from its generation to processing, acts as a pivotal role in obtaining environmental economic and social aspects of sustainability. Even though the enactment of SWM system holds promise for this endeavor, scholars emphasize the crucial role of technologies in enhancing its effectiveness. Digitalisation and automated workflow systems have long been cutting-edge technologies in various sectors. Their primarily objective is to minimize the requirement for physically demanding tasks and enhance process efficiency for workers (Sarc et al., 2019). I4.0 offer substantial potential for modernizing and improving SWM implementation through its associated technologies (Tanveer et al., 2022). In their study, Sharma et al., (2020) reveal the primary obstacle to smart city waste management, as the absence of regulatory guidelines, norms and policies, followed by challenges such as lack of uniformity and insufficient internet connectivity. Addressing these obstacles requires governmental support through the implementation of policies, norms, and IT-enabled infrastructure as suggested by Razip et al., 2022. Similarly, Zhang et al., (2023) discusses the casual driver of smart waste management lie overcoming the supply chain operational challenges across acquisition, manufacturing, distribution, and consumption processes. These challenges can be alleviated by emphasizing the utilization of by-products and waste, alongside prioritizing cost efficiency and social acceptability.

Recent research suggests innovative approaches leveraging I4.0 principles to address the challenges of SWM. For example, Aytac and Korcak, (2021) advocate for fully automated intelligence utilization, harnessing the potential of IoT to reduce food waste generation at its source. They provide a case study focussing on restaurants to illustrate this approach. Similarly, Anagnostopoulos et al., (2018) proposed an another IoT application involving the installation of actuators and sensors in both trucks and bins. Their study involved stochastically reassigning trucks to collect waste from bins over a two-year period, assuming a distribution of waste bins and the service area coverage of trucks. Ali et al., (2022) introduced a decision-making framework for optimal managing of SWM, showcasing the potential of process network synthesis and ML. Various ML model were employed, with the multilayer perceptron neural network chosen for further development due to its superior performance on testing data. Additionally, Sen Gupta et al., (2022) demonstrate blockchain's role to the improvement of waste management, using smart contract to track trash and incentivize waste sorting efforts. Muthusamy et al., (2022) compare ML algorithms, such as, long short-term memory algorithm (LSTM) and k-Nearest neighbor's algorithm (k-NN) for smart bin tracking which is integrated with IoT, with k-NN yielding highest accuracy in bin level predictions. Through cloud IoT connectivity, real-time monitoring and predictive analytics, these approaches optimize solar e-waste management processes, ensuring efficient collection and accurate data analysis (Table 1).

Table 1. Overview of literature review studies in waste management

Author	Objectives	Journal	Time horizon	Method
Abdallah et al., 2020	Conducts analysis of past studies focusing on utilizing AI for effective SWM.	Waste Management	2004-19	Systematic literature review
Andeobu et al., 2022	Investigates AI's application for promoting sustainable SWM practices.	Science of the Total environment	2005-2021	Systematic literature review
Cheah et al., 2022	Explores the current landscape of I4.0 technologies and their potential contributions to enhancing SWM processes.	Environmental research	Not mentioned	Literature review
Fang et al., 2023	Examines studies concerning the integration of AI tools for optimizing waste management system.	Environmental Chemistry letters	Not mentioned	Literature review
Hassoun et al., 2023	Examines I4.0's use for addressing challenges specific to sea food waste management.	Current research in food science	Not mentioned	Narrative review
Ihsanullah et al., 2022	Discusses various AI methodologies aimed at forecasting and enhancing the performance of SWM system.	Chemosphere	Not mentioned	Literature review
Lu et al., 2023	Maps out existing studies focusing on the automation of e-waste disassembly processes within the context of I4.0 principles.	The international journal of advanced manufacturing Technology	2000-2021	Systematic literature review
Singh et al., 2023	Analyzes the challenges presented by IoT, ML, GPS, and blockchain in the realm of waste management	Archieves of Computational methods in engineering	Not mentioned	Systematic literature review
Tanveer et al., 2022	Examines literature focussing on circular practices in waste management, with particular emphasis on green technologies.	Environmental science and pollution research	2000-2021	Bibolometric analysis, text mining, content analysis

While numerous literature reviews have been conducted to enhance the understanding of SWM research, Table 1 provides insights gleaned from previous literature review studies in this domain. However, the existing literature primarily focuses on specific aspects of I4.0 in SWM, such as IoT-enabled or AI-based models, leading to a fragmented comprehension of overall landscape (Abdallah et al., 2020; Ihsanullah et al., 2022; Mohammed Aarif et al., 2022; Singh et al., 2023). I4.0 have potential to utilize the holistic and interdisciplinary nature of sustainability encompassing economic, social and environmental dimensions, prior literature often fails to adequately address the integration of sustainability principles into I4.0-driven SWM (Andeobu et al., 2022; Fang et al., 2023; Tanveer et al., 2022). This paper seeks to bridge these gaps by constructing a holistic understanding of the diverse SWM systems to achieve sustainability in era of I4.0 documented in the past studies.

3. Materials and methods

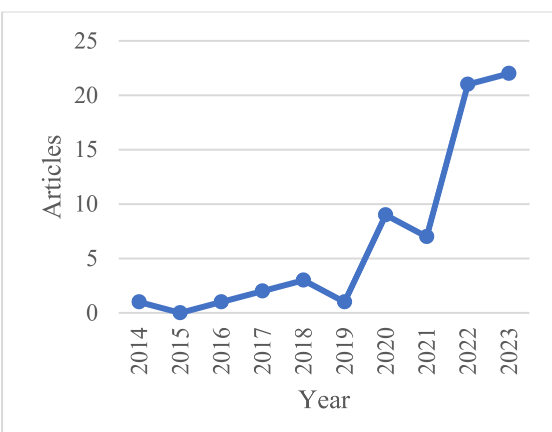
In the initial phase, we meticulous screened papers from reputable sources to better understand the landscape of sustainable SWM landscape in the I4.0 era. We sought for articles within databases such as web of science and scopus, paying particular attention to specific keywords, including: 'digitalization', 'block chain', 'smart waste', 'artificial intelligence', 'industry 4.0', 'internet of things', 'waste management', 'solid waste management', 'sustainability', and 'sustainable waste management'. We established criteria to refine the search, focusing on journals, book chapters, and conference papers, with an emphasis on English language publications from 2014 to 2023. Subsequently, we identified 292 pertinent publications, providing a comprehensive overview of the intersection between I4.0, sustainability, and SWM. Further refinement was achieved through abstract review and relevance screening, narrowing the selection down to 67 articles for detailed analysis. To effectively evaluate the articles, we devised a classification framework encompassing six key categories: publication trends over time, leading publishers and journals, authorship distribution by country, methodological approaches, and key contributors. This classification scheme offers a structured approach to comprehending research trends and exploring potential future avenues within sustainable SWM and I4.0.

Furthermore, we conducted a cluster-based content analysis to identify prevalent themes and trends among the selected documents. This method served to distil key insights and identify patterns, facilitating the recognition of persuasive articles within each cluster. These findings led to spotting research voids and we proposed prospective research paths by formulating research questions for each cluster. The analysis illuminated the theoretical underpinnings of I4.0 and sustainability in the context of SWM.

3. Results and Analysis

3.1 Publication trends over time

Figure 2 illustrates the variation in articles related to "SWM in the context of sustainability and I4.0" over a span of 10 years (2014–2023). Initially, scholars showed minimal interest in integrating I4.0 and sustainability into SWM practices. However, starting around 2019, both developing and developed countries began recognizing the significance of sustainability in SWM and expressed an acceptance to incorporate I4.0 techniques. Consequently, there has been a noticeable increase in the frequency of article publications since 2019. Discussions on the integration of I4.0 and sustainability in SWM can be observed across various types of waste (Figure 3).



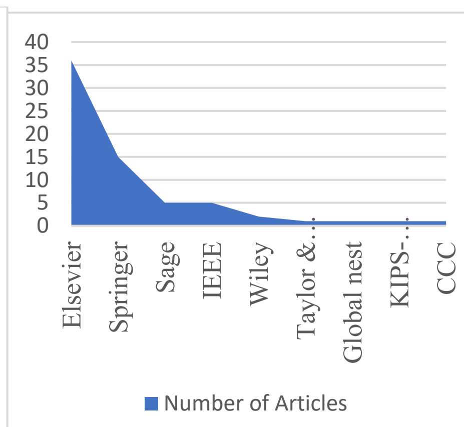


Figure 2. Evolution of articles from 2014 to 2023 Figure 3. Publisher distribution

3.2 Leading publishers and journals

When examining the distribution of articles by publishers concerning, Elsevier emerged as the leading contributor, with 36 articles in the current context, followed by Springer (15), IEEE (5) and Sage publication (5). Additionally, Wiley (2), Taylor and francis (1), KIPS-CSWRG (1), Global nest (1) and CCC (1) contributed to the body of literature. The publisher-wise distributions are graphically represented in Figure 3.

The literature search across these publishers revealed a broad spectrum of research areas within the SWM domain. Regarding the allocation of articles across journals, a diverse range of areas such as engineering, environmental science, science technology and management. Among these journals, the Journal of Cleaner Production accounted for largest share of articles (13.43%). This journal consistently disseminates a wide spectrum of scholarly works aimed at augmenting awareness of the subject among academic and stakeholder communities. Waste Management secured the second highest percentage (10.44%), underscoring the pivotal role played by diverse I4.0 technologies in propelling sustainability within SWM system. Environmental science and pollution research ranked third with an 8.95% article share. Furthermore, Waste management and research captured the fourth-highest proportion (7.46%). IEEE Access closely trailed in fifth position (4.47%). Figure 4, furnishes a visual depiction of journals categorized by publication percentage.

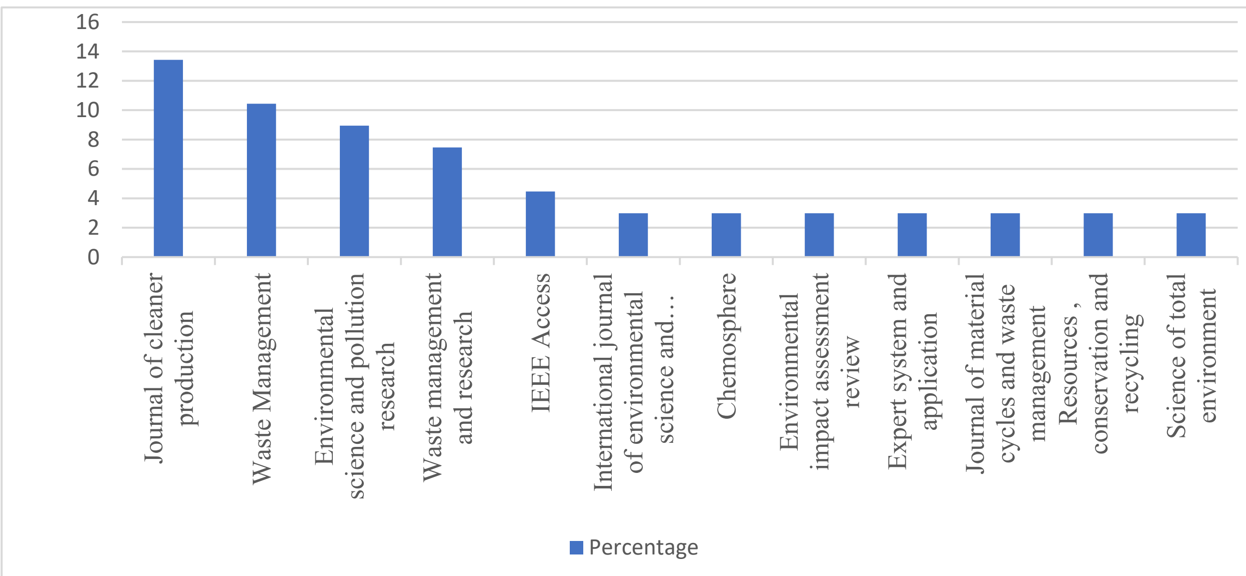


Figure 4. Distribution of publications across journals

3.3 Authorship distribution by country

The examination of the chosen articles reveals the widespread dissemination of research on SWM, sustainability and I4.0 across 43 countries globally. Figure 5 provides a detailed breakdown of these articles according to their country of origin, categorized based on author collaboration patterns: either involving contributors from multiple countries or originating from single country. Collaborative networks facilitate knowledge exchange, resource sharing, and joint research endeavors, thereby contributing to the global dissemination of research findings. Notably, China leads in multi-country collaborations, accounting for 22.38% of publications, while India stands out for its highest contribution in single-country collaborations, comprising 10.44% of the total. Furthermore, India, UK, Malaysia, Pakistan and Australia possess the latter on position in the multiple country collaboration, whereas China, Greece, Italy, Turkey and Australia possess the latter on position in the single author category.

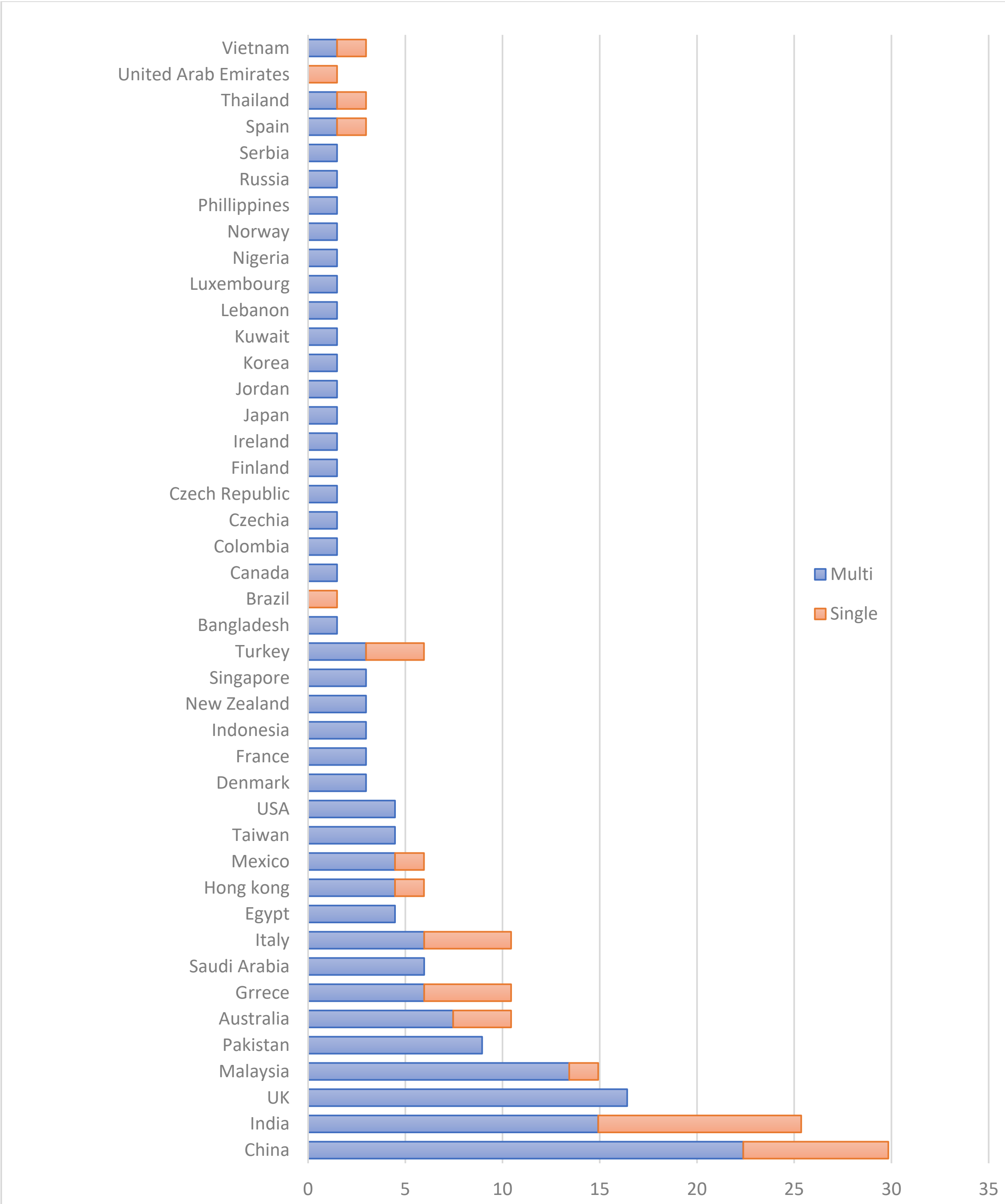


Figure 5. Classification of articles by country-wise collaboration

3.4 Methodological approaches

We have conducted a thorough analysis to identify the research methods in each shortlisted article, as illustrated in Figure 6. Our analysis reveals that the highest proportion of articles, totalling 35, employ mathematical modelling with case study-based approaches. It is noteworthy that researchers have shown a significant interest in comprehensively exploring the applications within these case studies. This is followed by reviews (22), which indicates significant findings of research gaps and opportunities for proposing future research directions. Subsequently, there are fewer articles focusing on theoretical assessments (6) and experimental evaluations (4), suggesting ample scope for research in integrating existing theories and hypothesis testing.

3.5 Key contributors

Understanding the researchers actively contributing to knowledge through their research is essential in every classification study. An early-stage researchers may find it challenging to explore the most esteemed research endeavors and viewpoints within a specific domain. Hence, it would be beneficial for the next wave of researchers to examine the most notable research published by identified top contributors. This approach can help them explore novel research concepts. In the current study, a total of 262 writers contributed to the assessment of 67 articles. Figure 7 showcases the list of top authors contributing to Sustainable SWM research considering I4.0. Leading this list is Hajiaghaei-Keshteli, Mostafa, with a total of four articles. Other top contributors with notable research credentials include Colombaroni, Chiara ; Fusco, Gaetano; Mohammadi, Mostafa ; and Rahmanifar, Golman.

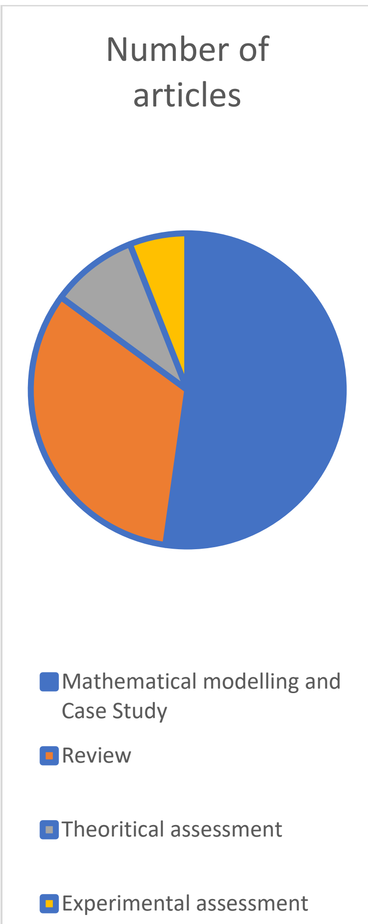


Figure 6. Methodological approach

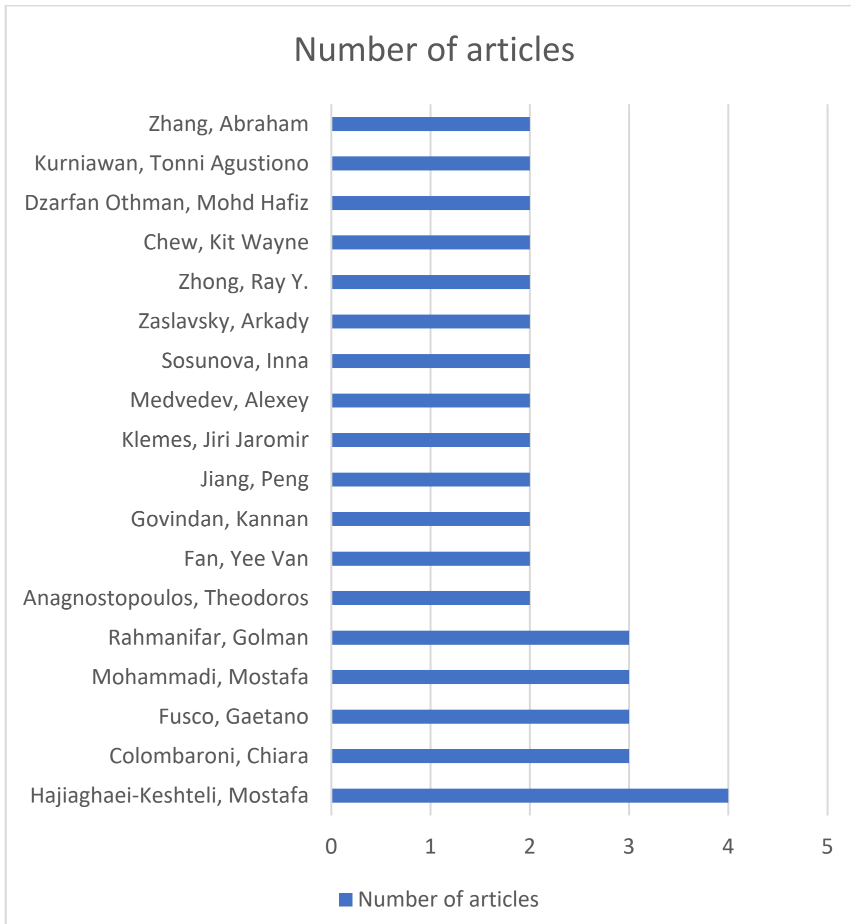


Figure 7. Ranking of leading authors

4. Discussion

This study performed content analysis on 67 screened articles. The methodology employed content analysis to systematically capture large datasets in an organized manner. Examining the keywords used by authors in their studies, we identified similarities within the realm of study, leading to the identification of three major clusters: sustainable and circular development, smart solid waste management, and decision-making model.

4.1 Cluster 1: Sustainable and circular development

This cluster encapsulates a spectrum of keywords such as cleaner production, environmental pollution, green technology, resource recovery, recycling, reuse, sustainable waste management, sustainable circular economy, waste to energy and zero waste. It is emphasized that sustainability aspects embedded within SWM strategies not only mitigate the detrimental environmental impacts associated with SW but also confer added value to products, as noted by Salehi-Amiri et al., (2022). Furthermore, the integration of I4.0 technologies holds immense promise in enhancing sustainable SWM practices by curbing natural resource consumption through waste reuse, recover and recycle before reaching their end of life, as highlighted by Kanojia et al., (2021) and Qammar et al., (2023). The adoption of I4.0 methodologies unlocks three pivotal circular economy (CE) opportunities for organizations, as elucidated by Andeobu et al., (2022), Kurniawan et al., (2023) and Tanveer et al., (2022). These opportunities encompass: Facilitating new product development conducive to CE principles, integrating historical data with real time information, online interactions among data, individuals, processes and devices, and optimization of processes associated with product sorting, recycling, remanufacturing and disassembly. This underscores the transformative potential of I4.0 in fostering sustainable and circular development pradigms within SWM frameworks, ultimately contributing to the advancement of environment, social and economic aspects.

4.2 Cluster 2: Smart solid waste management

This cluster formed with keywords including digital waste management, machine learning, rewaste4.0, blockchain technology, smart solid waste systems, big data, industry 4.0, internet of things , artificial intelligence, radio frequency identification, smart bin, waste tracking. The integration of I4.0 into traditional SWM system enables data acquisition, offering dynamic approach and deploying technologies to enhance waste generation, collection, transportation, segregation and disposal processes (Rahmanifar et al., 2023; Yu, 2021). Previous studies reveal several opportunities with smart WM system include: reliable information about collection, monitoring the tracking of vehicles, (c) improve efficiency with real time data, efficient response to breakdowns and efficient disposing process (Ihsanullah et al., 2022 ; Wawale et al., 2022). However, the discussed systems have their limitations such as dependency on proper infrastructure for data communication (Qureshi et al., 2023). Moreover, smart SWM systems offer additional benefits, including environmental protection through waste utilization and the attainment of sustainability goals (Vijayalakshmi et al., 2023).

Table 2. Identification of research gaps and proposed research question for each cluster

Cluster	Research Gap	Proposed Research Questions
Sustainable and circular development	The synergy between sustainable smart solid waste management and circular economy remains unexplored.	1. How can the impact of CE principles on sustainable SWM practices in the context of I4.0 be systematically evaluated? 2. What strategies can be employed to address the social, environmental, and economic challenges inherent in SWM to facilitate the integration of circular economy principles, thereby aligning the system with I4.0 objectives?
Smart solid waste management	The study on I4.0-driven technologies in the different phases of SWM is lacking.	3. How can the implementation of I4.0-associated technologies be utilized across different phases of SWM, including generation, collection, transportation, segregation and processing?
Decision making model	There is limited exploration on the development of novel decision-making frameworks tailored to unique requirements of I4.0 integrated sustainable SWM.	4. How can novel decision-making models be developed to effectively address the dynamic complexities and evolving requirements of I4.0 integrated sustainable SWM?

4.3 Cluster 3: Decision making model

This cluster focusing on keywords such as optimization, multi criteria decision-making, meta-heuristic, stochastic and fuzzy decision-making. SWM processes are inherently complex, characterized by non-linear parameters and intricate operations, influenced by various interconnected factors such as demographic and socio-economic dynamics (Xia et al., 2022). The integration of I4.0 into SWM endeavors to address non-linearity of historical data and cope with substantial volume of generate data, enabling organizations to make data-driven decisions through advanced analytics, artificial neural network ,machine learning, support vector machine, decision trees, genetic algorithm, linear regression, modified multi criteria decision making technique (Abbasi and El Hanandeh et al., 2016; Mishra et al., 2022; Seker, 2022). Specifically, I4.0 technologies prove instrumental in predicting bin fill levels, waste generation rate, waste sorting, and processing possibilities (Cicceri et al., 2023). It has additionally been utilized to optimize waste collection routes, frequencies, economic value, and mitigating emission (Hashemi-Amiri et al.,2023; Nidhya et al., 2020). These technological insights have the potential to significantly enhance decision-making processes, facilitate predictive maintenance strategies, optimize resource allocation, and drive process innovation within the domain of sustainable SWM (Abdallah et al., 2020; Thao, 2023). Table 2 highlights the research gaps and proposed research question for each cluster.

5. Conclusion, limitation and future scope

The objective of this study was to offer perspectives on sustainable SWM practices within the context of I4.0 while also presenting an overview of current state of research in this domain. By examining publication trend, contributing journals, publishers, countries, leading authors, and methodology associated with the domain, as well as the identified gaps, this study has delineated three primary research cluster: sustainable and circular development, smart solid waste management system and decision-making models. These clusters serve as foundational frameworks for further inquiry into the intersection of sustainability and SWM within the era of I4.0, thereby guiding future research endeavors.

However, this study has certain limitations. Firstly, the clustering of data was based on bibliometric coupling, suggesting a potential bias in the selection and categorization of articles. Future studies are encouraged to integrate surveys with interviews a methodology to mitigate the limitation. Additionally, the absence of a proposed theoretical framework limits the depth of contextual understanding provided in this study. Therefore, it is recommended that future studies can develop comprehensive theoretical framework to better describe the current landscape of sustainable SWM within the framework of I4.0.

Declaration of Competing Interest

The authors declare no conflict of interest.

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