



Research article

Toward a cleaner and more sustainable world: A framework to develop and improve waste management through organizations, governments and academia[☆]



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ABSTRACT

Waste production is expected to reach 3.40 billion tons annually in 2050. To decrease its negative impacts on the environment generated by human activities, waste management (WM) aims to increase the products life cycle and reduce the use of energy and space. Thus, this work aims to propose a framework with actions to develop and improve WM in the Triple Helix (TH) sectors: organizations, governments, and academia. The framework was developed based on the benchmarking of the technical-scientific scenario and the opportunities and challenges of WM added to the authors' experiences. This study was conducted using a combined method of the literature review and content analysis of articles present in the Scopus database, patents identified in the Orbit database, and governmental actions. As a result, 32 actions have been proposed through the framework, distributed among the TH sectors. The countries analyzed were China, India, and the United States, which highlighted because of the h-index and number of patents published. The main scientific contribution of this work is to add empirical elements coming directly from public and private institutions to the theory about WM, forming a block of knowledge with characteristics closer to reality. The major applied contribution of this work is the proposition of actions to the TH sectors, enabling the development of solutions and technologies to improve WM.

1. Introduction

Waste generation rates are increasing in a worrying way around the world. Since 2016, cities have generated more than 2 billion tons of solid waste per year. With rapid population growth and urbanization, this generation is estimated to increase by 70%, with the potential to reach 3.40 billion tons by 2050. Thus, increasing waste production and inadequate waste management (WM) are drivers of disease vectors and global climate change (Araújo et al., 2021; Espuny et al., 2021; World Bank, 2019).

The difficulties in WM have begun to intensify, especially after the industrial age when the extraction of resources and the production of goods were expanding to meet society's consumption needs. A range of products such as textiles and electronics, once treated as luxury items, has come to be regarded as everyday products. Production processes have become complex and often use composite and hazardous materials, which leads to the generation of several types of waste that can be

harmful to the environment (Ugwu et al., 2020; Zaman, 2015). These residues demand sustainable management, which avoids damage to the planet and does not compromise the supply of raw material to the supply chain of economic sectors, such as construction, food, clothing, and others (Ugwu et al., 2020; Zaman, 2015).

Sustainability can be defined as providing for the needs of the present generation without interfering with the conditions for the survival of future generations (Alhaddi, 2015; Elkington, 1994). The Triple Bottom Line framework, which includes the economic, social, and environmental pillars, can be used to measure the sustainable performance of the activities conducted by the organizations (Alhaddi, 2015; Elkington, 1997). It is possible to relate to each of these pillars to WM. The activity performed by recyclers, who generate income by buying and selling waste, and a lean and efficient budget of public services for waste treatment and disposal are related to the economic pillar. Better hygiene conditions and a high life expectancy through a WM that avoids the contamination of society are related to the social pillar. The preservation of water and soil

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by strategically planning landfill areas that do not impact water table or produce methane gas by imposing explosion risks in the surroundings, contribute to the environmental pillar (Tseng, 2011). Among the articles that involve solid waste in the context of sustainability, the main issues mentioned are finite natural resources and riches that can be exploited from the waste (Pan et al., 2020; Tan et al., 2014).

The concept that waste is a pollutant is progressively changing to the idea that waste is a recoverable, reusable, recyclable resource, or even an energy source (Laurent et al., 2014b). The goals of WM are to protect people and the environment, increase the life span of products, and reduce the use of energy and space. These actions contribute to the reduction of negative impacts on the environment that occurs because of human activities (Allesch and Brunner, 2014; Brunner and Rechberger, 2015; Laurent et al., 2014a). Among the main residues and the ones most studied in the literature are: municipal solid (Ghiani et al., 2014; Gupta et al., 2015; Yay, 2015), food (Salemdaab et al., 2017; Thi et al., 2015), hospital (Windfeld and Brooks, 2015), construction and demolition (Butera et al., 2015; Dahlbo et al., 2015), electro-electronic (Sarath et al., 2015), and high-level radioactive (Sellin and Leupin, 2014).

Municipal Solid Waste (MSW) is generated by residences, commercial establishments, industries, and public bodies. It is composed of items from street sweeping and daily use, such as product packaging and clothing, excluding waste from municipal wastewater treatment (Yay, 2015; Liu et al., 2014). Knowledge of its composition is essential for the implementation of the most appropriate policies to reduce waste generation and to choose the most convenient processes for its treatment and disposal. Its composition and quantity vary according to location, climate, socioeconomic conditions, waste collection and disposal methods, and other factors (Gupta et al., 2015; Vazquez et al., 2020; Yay, 2015). Through proper municipal solid waste management, the city becomes cleaner and less vulnerable to the spread of diseases. The effectiveness of the municipal solid waste management (MSWM) system can be an indicator of appropriate governance. Therefore, it increases the chances of receiving external investments by showing a reliable local government (Wilson et al., 2015).

Food waste is the wastage that occurs during the food production and consumption phase, usually caused by retailers' mismanagement or consumers' bad habits (Thi et al., 2015). The European Commission has developed guidelines through the food waste hierarchy law to indicate the best options for treatment and final disposal (Figure 1) (Salemdaab et al., 2017).

In Figure 1, it is determined that the rulers should take actions for reducing food waste; its redistribution to those who suffer from food insecurity, such as the homeless; its recycling as animal feed or use in composting; its recovery as energy through anaerobic digestion and its disposal to landfills (Rastogi et al., 2020; Salemdaab et al., 2017). It is worth noting that these guidelines must be adapted to regional or local contexts (Eriksson et al., 2015).

Hospital Waste (HW) is the waste generated in the diagnosis, treatment, or immunization of humans or animals and can be infectious or non-infectious. The United States Medical Waste Tracking Act adds that HW can also be generated in research related to living beings or in the testing and production of biological drugs (Windfeld and Brooks, 2015). Exposure of healthcare workers, waste handlers, patients, and the general community to HW can cause risks of contamination from diseases and injuries from the workplace. This type of waste can also lead to environmental pollution and degradation of the environment (Makajic-Nikolic et al., 2016). The best way to mitigate these impacts is the separation of infectious from non-infectious HW. Infectious ones should be treated according to their specificity and non-infectious ones should be sent for treatment together with MSW (Windfeld and Brooks, 2015).

Construction and Demolition Waste (C&DW) are generated in renovation activities and building new infrastructure. It can be generated from works performed by small families to large construction companies (Dahlbo et al., 2015; Wu et al., 2017). This type of waste can be classified according to its chemical characteristics as inert and non-inert. The main difference between inert materials (such as concrete and brick) and non-inert materials (such as wood) is that in the first group, there is no solubility in water (Wu et al., 2017). The main obstacles to recycling are the high availability and low cost of virgin raw materials, which decreases the demand for recycles and interest in developing businesses from recycling (Dahlbo et al., 2015).

Waste Electrical and Electronic Equipment (WEEE) is the component and subassembly of electronic and electrical equipment that is considered obsolete or unwanted by users. It can come from telecommunications, lighting, and automatic systems (Lu et al., 2014). This type of waste, besides containing valuable resources, such as noble metals and rare earth elements, has many toxic materials, such as heavy metals. The high generation and mismanagement of WEEE can cause risks to human health and the environment, and instability of the technological industry of this sector, due to the scarcity of mineral resources. Therefore, the implementation of recycling is essential for the preservation of human health, ecosystems, and natural resources (Zeng et al., 2017).

High-Level Waste (HLW) is generated by reprocessing nuclear fuel after uranium and plutonium extraction (Stefanovsky et al., 2016). Its management is principally concerned with the processing of HLW solutions for the recovery of valuable actinides such as uranium and plutonium; removal of minor actinides and other long-lived fission products (Sengupta and Gupta, 2017). For the destination of this waste, geological disposal is conducted, which consists of isolating and containing radioactive material in such a way that there is no need for long-term monitoring by future generations and that there is a reduction of risks for human beings. The procedure is done through a system that isolates the waste from the biosphere for a long period to ensure that its concentrations in the atmosphere are insignificant compared to the natural level of radioactivity (Sellin and Leupin, 2014).

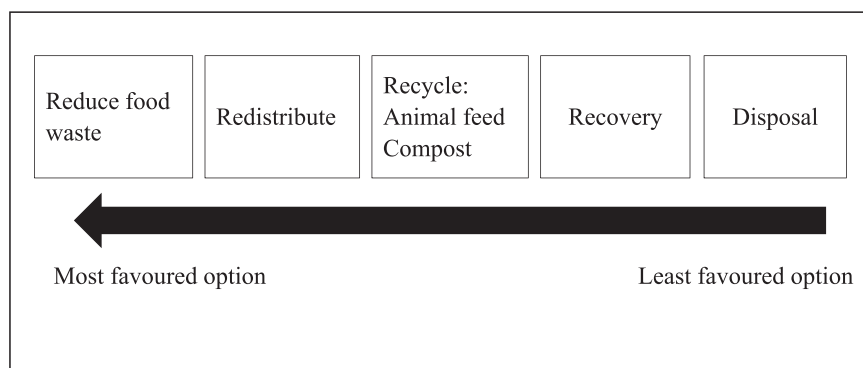


Figure 1. In the food waste hierarchy, the sequence of priorities are: reduction, redistribution, recycling as animal feed, reuse, and as a last option, disposal in landfills.

There are some important studies on WM that use the literature review research method like this work. Among the most influential, [Malinauskaite et al. \(2017\)](#) have studied national MSW and waste-to-energy systems in the context of the circular economy in some European countries; [Qambrani et al. \(2017\)](#) have presented a review of the concepts involved in biochar production (charcoal) from the pyrolysis of biomass from cattle manure and feed waste, specifying its qualities and applications; [Czajczyńska et al. \(2017\)](#) have studied fast, intermediate, and slow pyrolysis of organic waste and mixtures of inorganic and organic household waste; [Yong et al. \(2016\)](#) have studied the more efficient use of energy from cleaner fuels and biofuels and WM; [Rajaeifar et al. \(2017\)](#) have identified the main difficulties of electricity generation from MSW.

This study differs from the above-mentioned studies in that it goes beyond a literature review, in other words, a comprehensive benchmarking is conducted that broadens the horizon of the theme. In this review, the development of patents, initiatives of startups, development of laws, governmental actions, and experience of the authors are added to increase the literature that fosters a more efficient WM. The novelty of this article is precisely the proposition of the framework based on the WM technical-scientific scenario, considering the spheres of the Triple Helix ([Figure 2](#)). The Triple Helix contemplates the contributions of organizations, governments, and academia. This tripartite structure covers actions for a more favorable environment for innovation that amplifies and deepens the results of other studies ([Etzkowitz, 2003](#); [Santos et al., 2021](#)).

Organizations are the place of production of goods and services; governments are the source of legal guarantees among the interactions and exchanges between the other two sectors; and academia is an environment of creation of modern technologies and knowledge ([Etzkowitz, 2003](#)). In this context, the research question that guided the development of this work is: what are the main actions that can be developed by organizations, governments, and academia for the application and improvement of WM? To answer it, the objective of this paper is to propose a framework based on the technical-scientific scenario that proposes actions to develop and improve WM in organizations, governments, and academia.

The proposition of this framework contributes to filling the following research gaps: the development of a framework to promote the implementation of WM ([Wilson et al., 2015](#)); lack of appropriate strategic solid WM plans by rulers ([Kumar et al., 2017](#)); and the need for decision-making methods that combine expert and stakeholder opinion in MSW ([Vučijak et al., 2016](#)). Thus, the motivations for this article are twofold, and they are: to reduce the deficit and delay in treating solid waste in landfills; and to contribute to the reduction of disease contagion caused by accumulating garbage, improving the cleanliness and hygiene of urban areas. The results of this work contribute scientifically to add

empirical elements from public and private institutions to the literature on WM, thus forming a new block of knowledge with characteristics like reality. The main applied contribution of this work was to provide actions to the sectors of the Triple Helix, enabling the development of solutions and technologies for improving WM, so that, these sectors work separately and jointly.

2. Research method

This study was conducted using the combined research methods of literature review and content analysis. The literature review was used to collect and evaluate existing materials on WM, aiding in the understanding of the subject and identifying existing research gaps ([Jupp, 2006](#)). Content analysis was used to identify trends in WM publications based on systematic interpretation of data ([Nunhes et al., 2021](#)). Thus, the combination of these two methods enables the proposition of policies and initiatives through the qualitative approach of evaluating publications, allowing to generate relevant insights that contribute to the development of the topic ([Snyder, 2019](#), [Bhatt et al., 2020](#)). This literature review and content analysis of articles, patents, documents, and others, enables the interpretation and understanding of WM, allowing an elaboration of a framework for its development ([Costa et al., 2021](#)).

The research was divided into five steps: I – Definition of the objectives and method; II – Definition of criteria, data collection, and data analysis; III – Research development; IV – Results and discussions; V – Conclusion. These steps are divided into phases and indicated in the methodological flow in [Figure 3](#).

In Step I, the research objectives and methods were defined. Step II was conducted in three phases: A - Search criteria definition; B - Data collection; C - Data Analysis. In Phase A, the search criteria were defined for the data collection conducted in the Scopus and Orbit databases. The articles used for the preparation of the technical-scientific scenario and the grouping of the challenges and research opportunities were taken from the Scopus database in April 2020, with the term "waste management" present in the title of the article, in English, and published in the period from 2015 to 2019. Scopus was chosen because it is the largest and best database for this article, providing metrics for citation analysis and covering most of the material available in other databases ([Elsevier, 2022](#); [Santos et al., 2021](#); [Oliveira et al., 2019](#)). The patents selected for developing the technical-scientific scenario were selected from a search on the Orbit database in August 2020. This platform was chosen because it offers access to the largest accurate patent database, with over 100,000 users ([Questel, 2021](#)). To select the patents, the term "waste management" was used in the title and object of the invention of the groups of patents published in the period from 2015 to 2019. This period was chosen for searches in both databases because it includes the latest technologies and most modern developments in WM. It can be noted that the patents and articles selected in this period already consider the innovations and theoretical references from previous years.

In Phase B, information was collected from 1956 articles in the Scopus database and 1816 patents on the Orbit platform that met the search criteria of Phase A. In Phase C, the information collected in Phase B was analyzed, with the objective to rank the main countries in relation to the number of patents published and the h-index, as shown in [Figure 4](#). The h-index is an important parameter to evaluate the quality of publications of authors, institutions, journals, and countries, considering the number of citations of each article. To calculate this parameter, it is checked whether "X" articles contain the same or a higher minimum number of "X" citations in each document ([Nunhes et al., 2021](#)). Initially, the 10 countries with the most patents published and the 10 countries with the highest h-index were ranked. It is important to emphasize that countries with the same h-index, obtained the same score value, as can be seen in the case of the United States (US) and Spain (h-index 18 and 5 points, according to ranking). Then, the countries that were in both columns were identified and the index composed of the average of the positions between the Patent Position and H-Index Position variables was used.

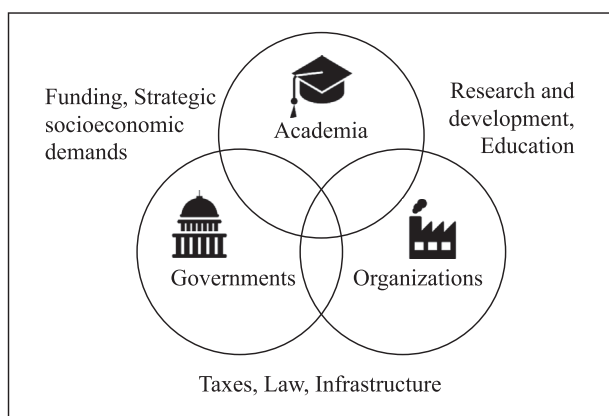


Figure 2. The Triple Helix Model is composed of Academia, Governments, and Organizations and their interactions aim to accelerate innovation and generate knowledge to solve contemporary challenges.

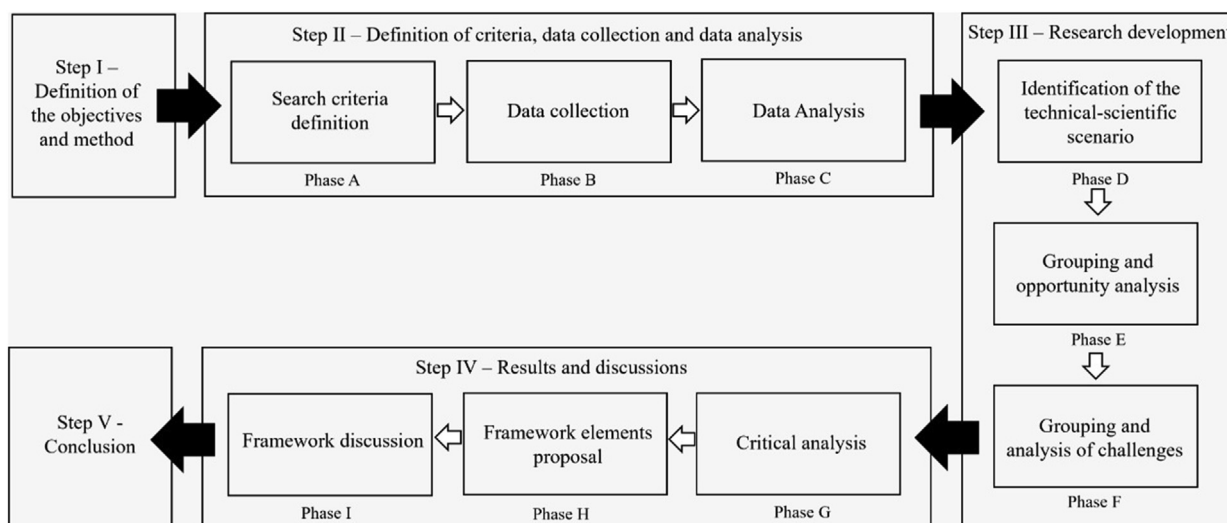


Figure 3. The research method flow is composed of five phases. Phase1: Objectives and method definition; Phase 2: Research criteria definition, data collection, and organization; Phase 3: Technical-scientific scenario mapping; Phase 4: WM framework elaboration; Phase 5: Conclusion and final text writing.

Patent Position			H-Index Position			Final Position Index				
Nº	Countries	Patents	Nº	Countries	H-Index	Final Position	Main Countries	Patents	H-Index	Publications Number
1	United States	273	1	China	26	1.50	China	271	26	157
2	China	271	2	India	23	2.50	India	178	23	309
3	India	178	3	Italy	23	3.00	United States	273	18	136
4	South Korea	120	4	United Kingdom	22	7.50	Japan	99	15	73
5	Canada	100	5	United States	18	7.50	Australia	74	16	66
6	Japan	99	5	Spain	18	7.50	Brasil	50	17	97
7	Australia	74	7	Brazil	17					
8	Brazil	50	8	Australia	16					
9	Mexico	40	9	Japan	15					
10	Singapura	27	10	Malaysia	13					

$$Final\ Position\ Index = \frac{H - Index\ Position + Patent\ Position}{2}$$

Figure 4. The country ranking was developed to select three relevant countries, considering the average number of patent registrations and the H-index of scientific publications. According to this criterion, the selected countries were China, India, and the USA.

This logic considers the balance between the H-index and patent publication and has already been validated and successfully used by Nunhes et al. (2021) and Reis et al. (2021).

This index indicates that the lower the average value between the variables, the better positioned the country is, as observed in the Final Position Index in Figure 4. It was identified that the top three countries had 40% of all patents published and were among the highest h-index. Considering these criteria, the selected countries were China, India, and the USA. Step III consists of the development of the research, which was conducted in three Phases: D - Identification of the technical-scientific scenario; E - Grouping and analysis of opportunities; F - Grouping and analysis of challenges. In Phase D, the content analysis was conducted to compile the main innovations and organizational, governmental, and academic initiatives of the selected countries to compose the technical-scientific scenario of WM based on the TH model. Official documents were analyzed, such as governmental websites, reports from national and international agencies of the selected countries. The articulation of this

set of documents made it possible to systematize the framework for public and private authorities to develop the WM.

In Phase E and F, the opportunities for development and the challenges of WM were identified and grouped, respectively, based on the 30 most cited articles and their gaps, which were selected in Phase B (Table 1).

The technical-scientific scenario, the opportunities and the challenges added to the experiences of the authors of this work subsidized the formulation of the framework for WM development (Step IV), as shown in Figure 5.

Step IV was conducted in three phases. In Phase G, critical analyses were performed by the authors of this paper for the elaboration of the framework. In phase H, the main initiatives, opportunities, and challenges for developing WM were selected. In phase I, the actions proposed in the framework were discussed. Step V presents the fulfillment of the objectives proposed in this work, the main contributions, limitations, and suggestions for future work.

Table 1. 30 most cited articles about Waste Management.

Title	Authors	Source	Scopus Citation	Scientific Gaps
Waste to energy – key element for sustainable waste management	Brunner, P.H., Rechberger, H.	Waste Management	168	Development of collection structures aimed at specific parts of technological items
Multiple stakeholders in multi-criteria decision-making in the context of Municipal Solid Waste Management: A review	Soltani, A. et al.	Waste Management	131	The application of game theory to reconcile stakeholder interests in solid waste
An overview of food waste management in developing countries: Current status and future perspective	Thi, N.B.D., Kumar, G., Lin, C.-Y.	Journal of Environmental Management	126	Development of integrative food waste management systems in developed countries
Municipal solid waste management and waste-to-energy in the context of a circular economy and energy recycling in Europe	Malinauskaitė, J. et al.	Energy	122	Development of a platform that allows communication between industries and waste management and energy waste agencies
Biochar properties and eco-friendly applications for climate change mitigation, waste management, and wastewater treatment: A review	Qambrani, N.A. et al.	Renewable and Sustainable Energy Reviews	105	Development of biomass-based charcoal product on a large scale
Application of life cycle assessment (LCA) for municipal solid waste management: A case study of Sakarya	Erses Yay, A.S.	Journal of Cleaner Production	97	The application of source-separation of waste to improve waste to recycling activities
Municipal solid waste characterization and quantification as a measure towards effective waste management in Ghana	Miezhah, K. et al.	Waste Management	94	Insertion of models on generation and composition of municipal solid waste
Environmental and health impacts of using food waste as animal feed: a comparative analysis of food waste management options	Salemdeeb, R. et al.	Journal of Cleaner Production	91	Investment in the collection of food waste for use as animal feed
Cleaner energy for cleaner production: Modelling, simulation, optimisation and waste management	Yong, J.Y. et al.	Journal of Cleaner Production	91	Development of technologies for low CO ₂ emission
A review on current status of municipal solid waste management in India	Gupta, N., Yadav, K.K., Kumar, V.	Journal of Environmental Sciences (China)	88	Analysis and collection of large samples of municipal solid waste to obtain statistically reliable results
Medical waste management - A review	Windfeld, E.S., Brooks, M.S.-L.	Journal of Environmental Management	86	Development of best practices for sorting hospital waste
Investigating the determinants of contractor's construction and demolition waste management behavior in Mainland China	Wu, Z., Yu, A.T.W., Shen, L.	Waste Management	85	Analysis and collection of large samples from construction and demolition waste management companies to obtain more reliable results
Carbon footprint of food waste management options in the waste hierarchy - A Swedish case study	Eriksson, M., Strid, I., Hansson, P.-A.	Journal of Cleaner Production	85	Analysis of food properties to determine the waste management required
Construction and demolition waste management - A holistic evaluation of environmental performance	Dahlbo, H. et al.	Journal of Cleaner Production	83	Applying source separation of construction and demolition waste to improve waste management
Eco-friendly waste management strategies for greener environment towards sustainable development in leather industry: A comprehensive review	Kanagaraj, J. et al.	Journal of Cleaner Production	82	Developing biodegradation methods with dye residues
Modeling of energy consumption and environmental life cycle assessment for incineration and landfill systems of municipal solid waste management - A case study in Tehran Metropolis of Iran	Nabavi-Pelesaraei, A. et al.	Journal of Cleaner Production	81	Identification and separation of waste for incineration
Construction and demolition waste management in China through the 3R principle	Huang, B. et al.	Resources, Conservation and Recycling	79	Development of effective classification for construction and demolition waste
Potential of pyrolysis processes in the waste management sector	Czajczyńska, D. et al.	Thermal Science and Engineering Progress	77	Development of technologies to enable the efficient processing of mixed waste
Household recycling knowledge, attitudes and practices towards solid waste management	Babaei, A.A. et al.	Resources, Conservation and Recycling	74	Conducting studies on the provision of municipal solid waste management infrastructure by governments and its relationship to the collection of this waste by citizens
Wasteaware' benchmark indicators for integrated sustainable waste management in cities	Wilson, D.C. et al.	Waste Management	74	Development of a database for comparison of integrated waste management
Challenges and opportunities associated with waste management in India	Kumar, S. et al.	Royal Society Open Science	73	Development of strategic plans for solid waste management by governors
Innovating e-waste management: From macroscopic to microscopic scales	Zeng, X. et al.	Science of the Total Environment	73	Control the substances in electro-electronic waste to avoid heavy metals entering new products
Electricity generation and GHG emission reduction potentials through different municipal solid waste management technologies: A comparative review	Rajaeifar, M.A. et al.	Renewable and Sustainable Energy Reviews	71	Development of a system to collect data on waste generation and management
Pyrolysis process of agricultural waste using CO ₂ for waste management, energy recovery, and biochar fabrication	Lee, J. et al.	Applied Energy	71	Applying carbon dioxide gas in the production of biochar to control atmospheric pollution
Application of TOPSIS and VIKOR improved versions in a multi criteria decision analysis to develop an optimized municipal solid waste management model	Aghajani Mir, M. et al.	Journal of Environmental Management	71	Using less degradable waste for energy generation
A comprehensive review of the development of zero waste management: Lessons learned and guidelines	Zaman, A.U.	Journal of Cleaner Production	68	Conducting studies on how to transform existing waste management systems into zero-waste systems

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Table 1 (continued)

Title	Authors	Source	Scopus Citation	Scientific Gaps
Integrated municipal waste management systems: An indicator to assess their environmental and economic sustainability	Rigamonti, L., Sterpi, I., Grosso, M.	Ecological Indicators	67	Conducting studies to define economic multipliers related to material and energy recovery
Life cycle assessment of construction and demolition waste management	Butera, S., Christensen, T.H., Astrup, T.F.	Waste Management	66	Analysis of the impacts of carbonation of construction and demolition waste to decrease global warming
Multicriteria decision making in selecting best solid waste management scenario: A municipal case study from Bosnia and Herzegovina	Vučijak, B., Kurtagić, S.M., Silajdžić, I.	Journal of Cleaner Production	64	Analysis of decision-making methods that combine the opinion of experts and stakeholders in the management of municipal solid waste
Mobile phone waste management and recycling: Views and trends	Sarath, P. et al.	Waste Management	64	Analysis of unexplored areas of the cell phone related to waste recycling to reduce the amount of waste

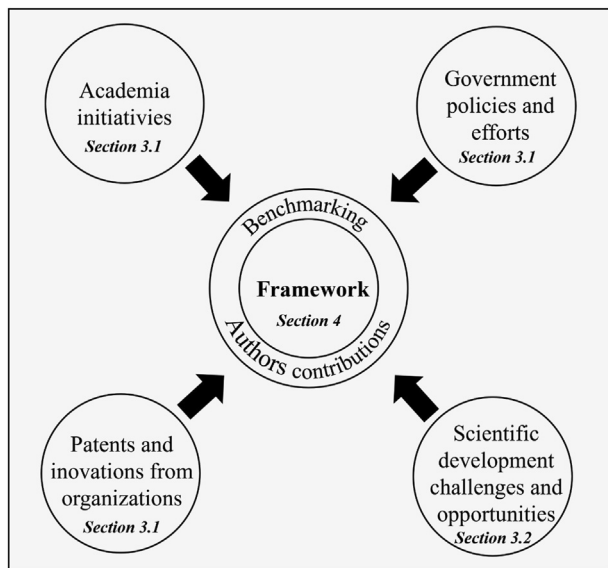


Figure 5. The WM Development Framework proposals were elaborated based on critical analysis and benchmarking of the policies, strategies, and initiatives from industries, governments and universities of the top WM technical-scientific scenario countries.

3. Research development

In this section, the development of the technical-scientific scenario and the opportunities and challenges of WM are presented, as per Figure 5 (Section 2- Research Method). This information contributes to the actions that will be presented in the Framework for Waste Management Development and Improvement (Section 4- Results and Discussion).

3.1. Technical-scientific scenario

The WM technical-scientific scenario presents the discussion of the results found in the countries that stood out most in the development of research and patent publications on the subject between 2015 and 2019. China, India, and USA were selected according to Figure 4. They are the top three waste generating countries in the world (Nanda and Berruti, 2021). The text is structured according to the sectors of the Triple Helix: organizations, governments, and academia contributing to the elaboration of the framework proposed by this work, according to Figure 5.

3.1.1. China

China is the country with the second-highest patents published between 2015 and 2019 on WM and it is the second country that published the most scientific papers on the topic with the highest h-index.

In companies, the top three companies in producing patents on WM are Envac, ConvaTec, and Henan Dizhilyu Environmental Protection Technology (Orbit, 2021). Envac is the company with the most patents published in WM in China, being the most innovative company in the waste collection industry in the world and the inventor of the pneumatic waste collection system for hospitals (Envac, 2020a). It provides intelligent WM systems for cities, hospitals, and airports (Envac, 2020b). Another technology developed by Envac is the vacuum waste technology that allows the collection to become sustainable, intelligent, and economical. After a user places a trash bag at the entrance of the electronic waste trash can, the waste is sucked through an underground pipe network to the waste collection terminal (Envac, 2020c). ConvaTec is a global medical products and technology company that created a connector system for patient urine and feces collection bags. This connector system features a simple tube connection method that directs the body waste stream into an external waste collection bag, minimizing its exposure to the environment (Jin et al., 2019; Odonkor et al., 2020). The waste collection solutions developed by Envac and ConvaTec save an expressive number of resources, since the residual materials from the human body require products such as diapers, which are discarded after use, or hospital basins that are transported internally to dispose of the fluids, becoming exposed with potential contamination and requiring washing. In populous countries like China, with continued urban growth, the implementation of these technologies becomes even more important (Mian et al., 2017). Henan Dizhilyu Environmental Protection Technology has created a separation device for plastic waste treatment systems, featuring a conveyor belt, screening system, and wheels for crushing the material. This device avoids plastic waste and reduces the energy expended during the process (Zhentang and Hualong, 2018).

Besides, the startups WeChat, Baidu, and Alipay have helped people correctly classify waste by improving search engines that identify which waste is wet, dry, toxic, or recyclable. Alipay, Alibaba's electronics payment affiliate, has a database of more than four thousand types of correctly classified waste and an app that helps users sell their recyclable materials. In addition to supporting families in disposing of waste correctly, these three startups are producing software applications to help some residential complexes in Shanghai to use QR codes. They can trace the origin of waste to make residents aware of separating waste correctly and receiving a fee for correct disposal. Each residence attaches a unique QR code to their trash bags for later tracking at the waste management station. In this way, it is possible to develop corrective actions with families that do not pay attention to the adequate separation (Liao, 2019). The adoption of these technologies enables an increase in recycled items; personalized guidance for citizens who have difficulty adhering to disposal protocols; and provides opportunities for income generation from waste (Ferri et al., 2015).

Regarding government initiatives in China, a plan has been created for proper WM that sets strategic goals, tasks, and measures for economic and social development for the period 2015–2020. It addresses food waste control and management of municipal, agricultural, and hazardous solid waste (People's Republic of China, 2016). The Cleaner Production

Promotion Law (CPPL) aims to increase the efficiency of resource use rate throughout the production process, reduce and avoid the generation of pollutants and promote the sustainable development of the economy and society (People's Republic of China, 2003). To promote CPPL by encouraging the circular economy, a law for proper waste management has been enacted to achieve sustainable development to reduce, refuse, and recycle (People's Republic of China, 2009). In 1995, the Law on Prevention and Control of Environmental Pollution by Solid Wastes was enacted to preserve human health and promote ecological safety. With this law, the state encourages scientific research and development of technologies for the adequate management of solid wastes with resources (People's Republic of China, 2005).

The first urban regulation in China applied to MSW reduction, delivery, collection, transportation, treatment, and disposal activities was enacted in the city of Shanghai in 2019 (Shanghai Municipal People's Government, 2019). To ensure the implementation of this policy, publicity actions were conducted through posters and videos, school education, and volunteers were available at the collection points to assist in the classification of MSW. An incentive system called Green Accounts was also adopted, which synchronizes the smartphone with a card that registers all the correct waste classifications and provides credits to the citizen who disposes of his waste. The credits can be exchanged for products such as food and tickets to tourist attractions (Zhou et al., 2019). In Shanghai, intelligent waste trash cans are used to perform automatic waste sorting, reduce the volume of environmental sanitation work, save expenses, improve environmental awareness, and thereby increase the efficiency of the country's resource use (Changgang et al., 2017). The government financial incentive practices have been an initiative adopted by many countries on environmental issues, although they lack legal detail (Martek et al., 2019). China's Department of Solid Wastes and Chemicals, under the Ministry of Ecology and Environment (MEE), conducts solid waste, chemical, and heavy metal pollution control; develops and implements policies, plans, laws, administrative regulations, departmental rules, standards, and relevant specifications on chemicals and solid waste; and implements environmental management systems (MEE, 2018).

In academia, publications of authors and research and education institutes that excel in WM were analyzed. As for the authors, the most prominent are Dr. Mustafa Ali, Prof. Dr. Gordon Huang, Ms. Xiujuan Chen, and Prof. Dr. Jinhui Li. Mustafa Ali has conducted research that addresses the major problems facing hospital WM in developing countries. These studies signal that safer management of this waste requires dynamic policymaking and government action to promote public awareness (Ali et al., 2017). A study of Mustafa that involves authors from universities in the United Kingdom and the Netherlands found that the combined method of waste and carbon footprint indicators can indicate shortcomings in WM (Ali et al., 2019). Gordon Huang and Xiujuan Chen have developed a study that proposes a mixed-number hierarchical fuzzy programming framework applied to MSW management in Beijing, China (Cheng et al., 2017b). In this study, there is also the identification of the significant impacts of hierarchy and heterogeneities of management practices and the need to analyze the problems caused by the lack of proper planning of solid waste management (Cheng et al., 2017a). Jinhui Li has conducted a study on the need to improve recycling technology for electrical and electronic waste because the risk of environmental pollution increases without the right strategies and operations, especially for heavy metals (Zeng et al., 2017).

Regarding research and education institutes that highlight WM are the Tsinghua University, North China Electric Power University, and Chinese Academy of Sciences. Tsinghua University operates the Beijing Key Laboratory of Radioactive Waste Treatment (Tsinghua University, 2020). Since 1984, the institution has specialized in teaching and researching technologies for the management, treatment, and disposal of hazardous waste, industrial solid waste, and domestic waste. The Division of Solid Waste Management at the School of Environment of Tsinghua University is one of the first institutions engaged in research on

the theory and technology of waste reduction, recovery, and decontamination in China (School of Environment Tsinghua University, 2010). North China Electric Power University has the Energy and Environment Research Center, which develops cost-effective and innovative technologies and strategies to face the most critical energy and environmental challenges (North China Electric Power University, 2018). To meet part of the country's need for sustainable energy, the university has created the first Renewable Energy School, which includes the Biomass Energy Research Center (North China Electric Power University, 2016). The Chinese Academy of Sciences has the Research Center of Eco-Environmental Sciences, which includes the Laboratory of Solid Waste Treatment and Recycling that aims to develop new theories and technologies for recycling. It has researched polymer waste, bio-waste, construction waste, sewage sludge, and municipal solid waste (Research Center of Eco-Environmental Science Chinese Academy of Sciences, 2015). Chinese universities should further increase the solutions directed to organic waste, especially household waste because the country mostly generates this type of waste (Liu et al., 2020). The solutions identified around energy production from biomass are an interesting solution that can reconcile a more appropriate treatment for food waste with the development of a strong energy matrix (Wijekoon et al., 2021).

The Chinese government has instituted the Fundamental Research Funds for the Central Universities to improve the investment systems with scientific research by making them more efficient so that they can innovate and promote their best talents (Tang et al., 2011). Other research funding that highlighted is the National Natural Science Foundation of China, which conducted the project "Impacts of human activity on the environment and disaster", whose main issues analyzed were characteristics, interaction, and safe disposal of industrial and MSW (NSFC, 2018).

3.1.2. India

India is the fifth country with most patents published between 2015 and 2019 on waste management and is the country that has published the most scientific papers on the topic, with the second-highest h-index.

In organizations, the top three companies in producing patents on waste management are Envac, ConvaTec, and FLSMIDT (Orbit, 2021). Envac is also active in India and is the most prominent company in patent production between 2015 and 2019 in this country. It has created a method for compacting waste that consists of collecting and transferring it to a parallelepiped-shaped container that is positioned diagonally. This container favors the action of gravity and uses the weight of the inserted waste to make it possible to store more waste (Törblom, 2019). ConvaTec is also active in India and has a medical device that allows the drainage of physiological secretions. A container stores the waste and a system of tubes that lead to a collection reservoir for minimal contamination of this fluid on the external surface (Tszin et al., 2019). FLSMIDT has developed a horizontal filter press that separates liquids from solids in steel frame chambers. In this structure, the sludge is pumped under high pressure separating the liquid phase from the solid phase through a cloth filter. When the separation is concluded the feed pumps are automatically turned off (Neumann, 2017). FLSMIDT and ConvaTec's products promote solutions that enable more effective solid waste and effluent separation, contributing to safer waste treatment and recovery (Dastjerdi et al., 2021).

In addition to these, the startup Skrap helps companies adopt sustainable practices and solutions aimed at zero waste in their offices through integrated waste management. Services provided include assessing the amount and type of waste generated in the facilities; designing a customized waste segregation infrastructure; installing a composting system; managing the collection of recyclable materials; training of cleaning team and food suppliers on waste management; and conducting waste audits to review progress in adopting sustainable practices and introducing corrective measures. Workshops and campaigns are also organized to promote employee participation in

sustainability initiatives in the workplace (Skrap, 2018). Consulting focused on environmental issues should be promoted in the corporate environment, even if the economic results are not as imminent as in the modalities aimed at production processes (Kubota et al., 2020).

India's government enacted The Environment (Protection) Act in 1986, which aims to improve and protect the quality of the country's ecosystem by reducing environmental pollution (Republic of India, 1986). The Solid Waste Management Rules made mandatory the segregation and storage of waste generated directly at the source, the inclusion of waste pickers in WM, and the implementation of a collection system by consumer goods companies that use non-biodegradable packaging. According to this law on solid waste management, the Ministry of Environment, Forest, and Climate Change was responsible for monitoring its implementation in the country, creating specific regulatory instruments for the adequate management of plastic, electro-electronic, construction and demolition, biomedical, and hazardous waste (Republic of India, 2016).

The Hazardous Substances Management Division is part of India's Ministry of Environment, Forest and Climate Change and aims to promote the management and safe use of hazardous substances, including chemical products and wastes, to prevent harm to human and animal health and the environment. The activities of division encompass chemical safety and management of hazardous, electronics, municipal solids, plastics, biomedical, and fly ash waste (Ministry of Environment Forest and Climate Change, 2017).

To support state and local governments, the Ministry of Urban Development of India's Government has created the Centre of Excellence to Centre for Environment and Development to develop strategies and frameworks for solid waste and wastewater management (India Waste Management Portal, 2014). One of these strategies is to separate waste at a source by storing it in different colored waste trash cans that are made available to households by Urban Local Bodies (Centre for Environment and Development, 2011). These actions are important to decrease the number of heavy metals in the organic fraction of waste since in Indian regions there is a significant percentage of this contamination present (Srivastava et al., 2020).

In academia, the most prominent authors who published articles on WM in the period 2015 to 2019 were Prof. Dr. Rajiv Ganguly, Prof. Dr. Sukha Ranjan Samadder, Dr. Pooja Yadav, and Mr. Nishesh Kumar Gupta. Rajiv Ganguly has conducted a study that reports on existing solid waste management practices in four major cities of Himachal Pradesh, India. It has identified that initiatives and corrective measures need to be taken by the municipalities to better improve solid waste management, including the purchase of new equipment for segregation and recycling facilities, proper maintenance of waste collection vehicles, and a system for leachate collection and removal (Sharma et al., 2018). Sukha Ranjan Samadder and Pooja Yadav have developed a study to evaluate the possible environmental impacts of existing plastic waste management in the city of Dhanbad, India. In this study, it has identified that formal and informal structures for the collection and segregation of plastic waste should work together to maximize the recycling of these materials, and recycling industries should use alternative energy sources instead of thermal energy to make the recycling process more sustainable (Aryan et al., 2019). Nishesh Kumar Gupta has conducted a study on the developments in the literature regarding biosorption for nuclear waste management. Biosorbents of bacterial, fungal, algal, plant, and animal origin are used for heavy metal retention. Its large-scale application is expected soon because it is one of the most economical methods for nuclear waste treatment (Gupta et al., 2018).

Research and education institutes that excel in WM are the Jaypee University of Information Technology, Indian Institute of Technology Indian School of Mines, and National Institute of Technology Rourkela. The Jaypee University of Information Technology has the Department of Civil Engineering, where there is research on solid waste management (JUIT, 2020a). In this institution, there is also the Department of Biotechnology and Bioinformatics, which develops research on

bioremediation of electronic and municipal solid waste (JUIT, 2020b). The Indian Institute of Technology Indian School of Mines has operated the Center of Societal Mission since 2015. This center is part of the Government of India's National Initiative, which connects institutes of higher education with local communities to accelerate sustainable growth. At this center, a program cleans the homes, streets, and surrounding areas of participating villages, making the population aware of proper waste disposal. It applies the use of bio-waste, plastic waste, and wastewater (IIT (ISM), 2020). The National Institute of Technology Rourkela has a Department of Civil Engineering that develops solutions for India's key sustainability challenges. In this department, there is research on wastewater management, air pollution, and solid waste management (NIT Rourkela, 2019).

The Department of Science and Technology of the Government of Kerala has a research fund to support scientific and laboratory infrastructure in colleges, university departments, and research centers. It also supports young researchers to undertake projects and activities in the field of science and technology (Government of Kerala, 2020). The University Grants Commission is a statutory organization of India's government that provides funds and coordinates, determines, and enforces the maintenance of quality standards of education in universities in India (University Grants Commission, 2020). This commission has guidelines for universities to adopt policies and practices to replace plastic waste with other more environmentally friendly materials (UGC, 2019). Because India is a complex country, it is important that education institutions seek solutions for WM segregation along with raising the awareness of their citizens to increase the percentage of waste processing (Paul and Paul, 2021).

3.1.3. United States

The United States is the second country with the most patents published between 2015 and 2019 on WM and the third country that has published the most scientific papers on the topic, with the fifth-highest h-index.

In organizations, the three major companies in the production of patents on WM are Rubicon, ConvaTec, and Envac (Orbit, 2021). Rubicon is the top company in patent production between 2015 and 2019 in the United States. It has created a system that generates and optimizes the best waste collection routes through a GPS-based location device that includes the necessary stops of the collection vehicle (Rodoni, 2019). ConvaTec has developed an ostomy bag system for collecting waste from an opening to the outside of the human body through the abdominal wall. Ostomy is a surgery that removes part of the bladder or small or large intestine. To deodorize the gases in the body's waste, these bags have a filter system (Oberholtzer and Lesko, 2019). Envac has registered the same patents in the United States as in China and India.

Besides these, the startup TerraCycle enables the environmentally correct collection and disposal of waste. TerraCycle's Zero Waste Box program allows for the recycling of the inorganic waste in the USA that normally has its destination in landfills. The user or company chooses the type of waste they want to recycle, buys the appropriate sized box on TerraCycle's website, collects the waste and mails it to the startup to be recycled (TerraCycle, 2020). TerraCycle's business has significant importance in developed countries since the percentage of the electro-electronic waste is high and has a high impact on environmental contamination (Nanda and Berruti, 2021). Apeel Sciences is a startup that has created a technology that makes the fruit take longer to spoil. This technology allows a thin shell of edible plant material to form on the surface of the fruit, delaying the factors that cause spoilage (Apeel Sciences, 2019).

The U.S. government has enacted the Resource Conservation and Recovery Act, which establishes guidelines for the proper management of hazardous and non-hazardous solid waste. This act gives the U.S. Environmental Protection Agency the authority to control the process of WM by developing regulations, guidelines, and policies. It ensures the management of solid and hazardous waste, and the creation of programs that

encourage the reduction of waste directly from the source and its reuse (EPA, 2020).

In the United States, twenty-seven states and the District of Columbia have at least one mandatory recycling law. The types of waste most impacted by these laws are lead-acid batteries, used oil, glass, metal and plastic containers, foil, and cathode-ray tubes. Regarding the disposal of solid waste in facilities present in the states, such as landfills and incineration, only the state of Montana has no waste that is banned from being disposed of at these sites. The most banned wastes in the states are lead-acid batteries, used oil, whole tires, untreated infectious, and cathode-ray tubes (Northeast Recycling Council (NERC), 2020). The United States is supported by a strong regulatory agency and the institution of state laws focused on solid waste because it is a country of continental proportions and with strong federalism (Lima et al., 2014).

In academia, the most prominent authors publishing articles on WM from 2015 to 2019 were Prof. Dr. Morton A. Barlaz, Dr. James William Levis, Prof. Dr. Donald Huisingh, and Prof. Dr. John J. Boland. Morton A. Barlaz and James William Levis have developed a study using a life cycle assessment that identifies the environmental implications of food waste management policies in the United States. It has indicated that it is beneficial to consider the characteristics of food waste, such as the number of nutrients, to develop policies related to its final destination (Hodge et al., 2016). The retired professor from the University of Tennessee Donald Huisingh has conducted a study covering the topics of biofuel development, carbon emission reduction, and WM. This study signal that international trade can reduce global environmental pressures by importing products manufactured with lower fossil carbon emissions and less water consumption than in domestic industries (Yong et al., 2016). John J. Boland has conducted a study that analyzes the implementation of solid waste policies in Kathmandu, Nepal. This study has identified that new policies are developed without the effective implementation of their predecessors, and the government does not present more current instruments to address the problems of solid waste management. Therefore, the creation and enforcement of local codes and the commitment of the central government are necessary to allow the free exercise of the policies created (Dangi et al., 2017).

Regarding education and research institutes that excel in WM are Ohio State University, NC State University, and Yale University. The Ohio State University has an initiative in which all events at the institution aim at zero waste. There is an indication of what materials are needed for this and a simulation of the timeline to be used for this type of event (OSU, 2020). An example is Ohio Stadium, which is the largest stadium in the USA that recycles, reuse, and composts at least 90% of the waste generated (Ohio State Buckeyes, 2020). NC State University holds waste and recycling events for students to make them aware of the importance of WM, provides WM services to be requested by departments, and a guide to what waste for recycling is accepted in trash cans of the institution (NCSU, 2020a). The university has NC State's Compost Facility and Research Cooperative, which is a place to compost waste on campus and, a reuse program to extend the life cycle of products present at the university, such as sports equipment and computers (NCSU, 2020b). Yale University has an Environmental Affairs Section that is responsible for managing the disposal of hazardous waste on campus. Those who generate them are responsible for their proper collection, handling, labeling, and storage in their work areas (Yale University, 2020). Regarding the execution of management plans within the university environment, there are universities with different budgets and staffing levels. Institutions that do not have a good structure have difficulties conducting successful implementations of waste collection and treatment. However, the provision and signage of waste garbage cans is a low investment and fundamental to any effective WM plan in the university environment (Ebrahimi and North, 2017).

The National Science Foundation subsidizes research and education in most fields of science and engineering through grants and cooperative agreements with universities, companies, and research organizations in the United States (NSF, 2020). One of its funded studies indicates that to

increase the detour of waste from landfills in a cost-effective manner and reduce greenhouse gas emissions, it is necessary to transform waste into energy, separate mixed waste, and improve its collection (Jaunich et al., 2019). The National Natural Science Foundation of China, already discussed in section 3.1.3, is the fund that most has financed studies at universities in the United States in partnership with universities in China.

3.2. Scientific opportunities and challenges for waste management

This topic will present the opportunities and challenges of research on WM, which will assist in the construction of the development framework.

3.2.1. Opportunities for waste management development

The opportunities for WM development were grouped according to their similarities based on the research gaps are indicated in Table 1. The authors and their respective clusters are shown in Table 2.

The cluster "Development of tools, systems, and methods for WM" includes opportunities to improve the collection, sorting, and infrastructure for diverse types of waste that are adapted to the realities of different countries and companies. According to Kumar et al. (2017), the problems associated with waste become more acute as the size of communities increases and this fact provides opportunities for decentralized WM by the informal sector. The development of new WM systems and facilities assist in improving this scenario, making the entire process of its management more sustainable.

The cluster "Development of modern technologies for waste treatment" refers to the opportunities that can be realized in different countries and aimed at all stages of WM, consisting of generation, collection and transportation, treatment, and final disposal. According to Malinauskaite et al. (2017), the development of energy from municipal waste is limited in some countries due to the lack of appropriate technology available. Although such limitations offer great opportunities for research and technological improvements, there is a lack of innovative studies that fit the local conditions of each country.

The changing pattern of the waste composition emphasizes the importance of segregation for the successful operation of WM facilities (Gupta et al., 2015). To be able to study the trends of waste quantity and characteristic change for improving WM, the Cluster "Utilization of statistical tools and experimental methods for waste collection process analysis and improvement" presents the opportunity to research with significant waste samples to generate more reliable results. In the experimental part, one can contribute to the decision-making process for the use of fast pyrolysis, aimed at bio-oil production, or slow pyrolysis, for charcoal production.

Table 2. Clusters of waste management development opportunities.

Clusters	Authors
Development of tools, systems, and methods for WM	Brunner and Rechberger (2015); Soltani et al. (2015); Thi et al. (2015); Windfeld and Brooks (2015); Babaei et al. (2015); Zaman (2015); Vucijak et al. (2016); Kumar et al. (2017)
Development of modern technologies for waste treatment	Sarath et al. (2015); Wilson et al. (2015); Rigamonti et al. (2016); Yong et al. (2016); Czajczynska et al. (2017); Malinauskaite et al. (2017); Rajaeifar et al. (2017)
Utilization of statistical tools and experimental methods to analyze and improve the waste collection process	Gupta et al. (2015); Wu et al. (2017)
Proposing new sustainable practices and inserting the existing ones in WM	Butera et al. (2015); Eriksson et al. (2015); Dahlbo et al. (2015); Kanagaraj et al. (2015); Miezah et al. (2015); Yay (2015); Aghajani Mir et al. (2016); Lee et al. (2017); Nabavi-Pelesaraei et al. (2017); Qambrani et al. (2017); Salemdeeb et al. (2017); Zeng et al. (2017); Huang et al. (2018)

The sustainable management of increasing amounts of waste has become a major social and environmental concern because its improper management results in public health and safety problems (Yay, 2015). Therefore, the Cluster "Proposition new sustainable practices and insertion of the existing ones in WM" is a research opportunity that aims to create throughout the WM process sustainable practices and apply existing practices such as waste separation direct from the source and energy generation from biomass, to decrease waste and contamination caused by their activities.

3.2.2. Waste management challenges

Waste management challenges were identified in the 30 most cited articles (Table 1) on the topic and then grouped according to their similarities. These groups with their respective authors are shown in Table 3.

The Cluster "Unreliable Information" indicates that the articles that compose it identified a lack of reliable data regarding the composition, indicators, generators, and WM to make more accurate diagnoses. According to Brunner and Rechberger (2015), obtaining reliable waste information is critical to WM. However, data mining and processing involve considerable costs, often resulting in superficial and uncertain information that negatively impacts proper WM.

The challenges of the cluster "Deficient Budget and Urban Structure" show the inadequacy of WM structures to the available budget. It includes the lack of policies, collection, and control of WM due to operational problems. According to Thi et al. (2015), developing countries have low budgets for segregation activities and waste treatment facilities, making it difficult to operationalize WM and achieve good environmental outcomes. To solve this problem, governments should set specific targets to reduce waste generation, provide budgets for adequate waste treatment infrastructure, and strictly monitor their implementation. Once facilities are completed, they must institute and monitor waste reduction targets and implement legislative regulations on WM.

The cluster "Low alignment among stakeholders" represents the divergence of interests related to proper WM among stakeholders, which is an additional barrier in this management. According to Soltani et al. (2015), the synergistic participation of stakeholders in the decision-making process is one of the main elements for sustainable WM. To this end, optimization tools can be used to help stakeholders make decisions by consensus based on well-defined criteria, such as multi-criteria decision analysis.

The challenge "Lack of regulation applied to waste" contemplates the lack of effective legislation that considers the several types of waste and how they should be treated in the recycling process. According to Windfeld and Brooks (2015), governments should standardize and

disseminate the definitions of the main types of waste, and define the place and process for their disposal, avoiding illegal dumping. It is also necessary to support the development of solutions to reduce the production of the main types of waste.

The challenge "Negative environmental impacts" contemplates environmental pollution from the production, collection, and destination of several types of waste. According to Miezah et al. (2015), the heterogeneity of waste hinders its use as a raw material. Therefore, there is a need for its fractionation before undergoing any treatment process. According to Sarath et al. (2015), the development of suitable options for waste treatment and recycling designed based on specific user groups, for example, the reconditioning and reuse of waste such as electronics, can lead to its decrease in landfills and reduce negative environmental impacts.

4. Results and discussions

This section presents the Framework for WM Development and Improvement built from the elaboration of the technical-scientific scenario, the identification of research opportunities and challenges, and the authors' experience (Table 4). It contains the proposals of actions for WM based on the Triple Helix.

According to Table 4, the propositions of the "Organizations" sector were structured in the domains "Technology" and "Services and Infrastructure". The actions present in "Technology" aim to automate WM and treatment and make them more efficient. In addition to the technologies identified in this study, it was possible to verify advanced experimental studies to adopt sensors with radio waves to manage truck and landfill overcrowding, providing information in real time for the reallocation of waste to other structures (Akram et al., 2021). Another action being considered is the use of bioreactor landfills, which evenly distributes leachate throughout the landfill, accelerating the biodegradation of organic waste and enabling the production of gas energy (Nanda and Berruti, 2021). In "Services and infrastructure", the actions prioritize the systematization of collection and offer better sanitary conditions to collaborators who handle the waste. One possibility that companies must contribute to waste infrastructure is the development of public-private partnerships, in which organizations invest in the facilities. However, the investing company has the right to explore the commercialization of recyclable materials and to undertake the production of energy based on waste (Batista et al., 2021).

In the "Governments" sector, the propositions are around the domains "Public policies and legislation" and "Strategies and incentives to raise awareness of correct WM practice". In the domain "Public policies and legislation", the focus is on the improvement of imprecise laws on the waste that can cause misinterpretation; on the attention directed to specific waste with high degradation potential; and on the encouragement of the participation of informal recyclers in the solid waste management process. Assuah and Sinclair (2021) identified that although there are a certain number of laws regulating WM, there is also a need for creation of enforcement tools for these laws. There are examples where people and companies are not punished for disposing of their waste in inappropriate places. If the community does not trust the enforcement of these laws and have no concerns of legal and financial consequences, a culture of disrespect to corrective instruments is created. In the second domain, the priority is the guidance and encouragement of correct waste disposal by using high-tech software and equipment. In a study conducted in Indonesia, there was a significant correlation between population involvement in household WM training with people's access to education and technology (Asteria and Haryanto, 2021). Loizia et al. (2021) emphasize that the lack of incentive from the authorities significantly decreases citizens' participation in WM strategies, and those measures such as tax reduction or even making available coupons to be used in cinema and theaters have proven positive.

In the "Academia" sector, the domains are structured into "Research and Development" and "Awareness Raising Activities and university

Table 3. Clusters of waste management challenges.

Clusters	Authors
Unreliable information	Brunner and Rechberger (2015); Butera et al. (2015); Dahlbo et al. (2015); Eriksson et al. (2015); Miezah et al. (2015); Wilson et al. (2015); Windfeld and Brooks (2015); Yay (2015); Rigamonti et al. (2016); Malinauskaite et al. (2017)
Deficient budget and urban structure	Babaei et al. (2015); Brunner and Rechberger (2015); Thi et al. (2015); Windfeld and Brooks (2015); Aghajani Mir et al. (2016); Yong et al. (2016); Czajczynska et al. (2017); Kumar et al. (2017); Nabavi-Pelesaraei et al. (2017); Rajaeifar et al. (2017); Zeng et al. (2017); Huang et al. (2018)
Low alignment among stakeholders	Soltani et al. (2015); Vucijak et al. (2016); Malinauskaite et al. (2017); Wu et al. (2017)
Lack of regulation applied to waste	Eriksson et al. (2015); Windfeld and Brooks (2015); Malinauskaite et al. (2017)
Negative environmental impacts	Gupta et al. (2015); Kanagaraj et al. (2015); Miezah et al. (2015); Sarath et al. (2015); Zaman (2015); Lee et al. (2017); Qamrani et al. (2017); Salemdieb et al. (2017); Wu et al. (2017)

Table 4. Framework for waste management development and improvement.

Sector	Domain	Action proposals	Triple-Helix Connection	Scientific and Technical References
Organizations	Technology	Create applications that facilitate the commercialization of recyclable materials	Governments and Academia	Liao (2019)
		Create a service for municipalities to track waste coming from households through trash bags with QR codes	Governments and Academia	Liao (2019)
		Develop new applications for satellite tracking systems that optimize the routes of waste collection trucks	Governments and Academia	Rodoni (2019)
		Develop technologies that slow the deterioration of food to reduce the production of organic waste	Academia	Apeel Sciences (2019)
		Invest in R&D to generate patents on new waste treatments	Academia	Neumann (2017), Zhentang and Hualong (2018), Jin et al. (2019), Tszin et al. (2019), Oberholtzer and Lesko (2019), Rodoni (2019), Envac (2020a)
		Generate and mine reliable data about waste and its indicators, generators, and management, to make more accurate diagnoses and improve decision-making by managers	Governments and Academia	Brunner and Rechberger (2015)
	Services and Infrastructure	Provide consulting services to raise awareness and train company employees about waste separation	Academia	Skrap (2018)
		Provide consulting services that teach sustainable practices and aim at zero waste in offices	Academia	Skrap (2018)
		Develop waste collection tubes and bags for body fluid waste	Governments and Academia	Jin et al. (2019); Tszin et al. (2019); Oberholtzer and Lesko (2019)
		Develop a system to send waste directly from the consumer to the recycling company	Governments	TerraCycle (2020)
		Installation in buildings and condominiums of horizontal filter presses that separate liquid waste from solid waste	Governments	Neumann (2017)
		Develop an underground waste collection system for commercial and residential buildings, hospitals, and other infrastructure	Governments	Envac (2020c)
Governments	Public policies and legislation	Create legal devices that meet the specificity of regions and municipalities to support compliance with federal legislation	Academia	Shanghai Municipal People's Government, (2019)
		Create laws that establish the gradual replacement of products with high environmental impact by biodegradable products	Organizations and Academia	Republic of India (2016)
		Create laws for managing more specific residues, such as plastics and biomedical products	Academia	Republic of India (2016)
		Centralize actions aimed at WM in a single body responsible for the implementation and inspection of its laws in each sphere of government	Academia	EPA (2020), Republic of India (2016)
		Include the informal recyclers (pickers) in the process of solid waste management and treatment, conciliating their interests with other stakeholders	Organizations	Republic of India (2016)
	Strategies and incentives to raise awareness of correct WM practice	Promote the environmental awareness of the population by clarifying the proper classification of urban solid waste for disposal. For example: advertising actions, teaching in schools, and orientation of volunteers at the waste collection points	Organizations and Academia	Zhou et al. (2019)
		Form partnerships with startups or technology companies for developing online search systems that indicate better disposal options to the population	Organizations and Academia	Liao (2019)
		Encourage the correct disposal of municipal solid waste, rewarding citizens with food vouchers and free admission to cultural events etc.	Organizations	Zhou et al. (2019)
		Make available to the population electronic waste trash cans that automatically classify waste and contribute to better disposal	Organizations and Academia	Changgang et al. (2017)
		Conduct research on technological solutions and management for solid waste in partnership with institutions and researchers from countries with high performance in WM	Governments	Ali et al. (2019)
Academia	Research and Development	Conduct research on the production of energy from landfill biomass to gradually replace non-sustainable energy sources	Organizations and Governments	Qambrani et al. (2017)
		Create WM laboratories to generate new solutions and alternatives for their treatment	Organizations and Governments	Tsinghua University (2020)
		Develop technologies aimed at the recycling of different types of waste	Organizations and Governments	Research Center of Eco-Environmental Science Chinese Academy of Sciences, (2015)

(continued on next page)

Table 4 (continued)

Sector	Domain	Action proposals	Triple-Helix Connection	Scientific and Technical References
	Awareness Raising Activities and university extension	Develop techniques to minimize the generation of plastic waste in universities and schools	Governments	UGC (2019)
		Raise the school community's awareness through actions and availability of materials about which residues are allowed in the trash cans for selective collection	Organizations and Governments	NCSU (2020a)
		Institute a cyclical period of awareness-raising in the school community about the importance of reducing waste and increasing recycling to develop habits of conscious disposal and consumption	Organizations and Governments	NCSU (2020a)
		Develop programs that encourage zero waste in events	Organizations and Governments	OSU (2020)
		Train people and/or sectors that generate hazardous waste in the educational institutions about their handling, storage, and disposal and, make people and sectors responsible for these processes	Organizations	Yale University (2020)
		Form partnership with the local community to teach about the correct disposal of waste and public cleaning	Governments	IIT (ISM) (2020)

extension". "Research and Development" emphasize the adoption of sustainable solutions and technologies for treating waste at the end of the chain, avoiding its disposal in landfills. This domain is significant to place WM in the context of the circular economy and to support international collaboration to achieve the sustainable objectives proposed by the UN (UN-SDGs). To this end, research is recommended to develop policies aimed at the decentralization of waste systems, improvement in supply chain localization, and actions that develop recycling and green recovery (Assuah and Sinclair et al., 2021). In "University awareness and extension activities" the development of sustainable practices in WM on school premises is proposed, encouraging other sectors of society to reduce waste generation. Although universities have more funds available for research activity, university extension programs (which are also known as the third academic mission) should favor actions aimed at WM. With the support of universities, it is possible to draw up plans such as the treatment and disposal of electronic waste and development of facilities that increase the efficiency of sewage networks, supporting the universal distribution of sanitation (Renault et al., 2016).

The result of the actions of these elements of the Triple Helix can be enhanced from the synergy of their work together. The "Academia" can improve waste treatment laboratories and advanced research projects through financial support from "Governments" and "Organizations". "Governments" and "Organizations" can work together with "Academia" to develop and implement technological solutions in waste collection and final disposal. "Organizations" and "Academia" can work simultaneously to gather information to support WM plans prepared by the "Governments". These and other actions could contribute to the improvement of WM. Rowan and Casey (2021) note that integrated actions by the Triple Helix are an alternative that mobilizes several important interlocutors to reduce pollution and environmental impacts. The government can financially support training and the development of green companies. This support should be provided with the support of academic institutions, which can share technological facilities and provide specialized training.

5. Conclusion

This work allowed the development of a framework with recommendations that aim at the improvement of the WM from the reduction, collection, and transport, recycling, recovery, treatment, and disposal of waste. The framework was elaborated based on the actions of the organizations, governments, and academia, on the opportunities and challenges identified in the literature and on the contribution of the authors. Thus, it was possible to answer the research question and achieve the proposed objective.

The main scientific contribution of this work was to add empirical elements from public and private institutions to the literature on WM, thus forming a new block of knowledge with characteristics like reality. The main applied contribution of this work was to provide actions to the sectors of the Triple Helix, enabling the development of solutions and technologies for improving WM, so that these sectors work separately and jointly.

The limitations of this study are related to the search criteria and database used, which if changed, could result in different countries, thus modifying the list of articles, educational institutions, organizations, and patents to be analyzed. Furthermore, the addition of new countries would allow a set of new propositions to be added to the framework proposed in this work. For future studies, it is suggested to modify these search parameters and use different databases, so that new scenarios and actions can be added to this framework. It is also suggested that the technical-scientific scenario be developed for specific segments such as municipal, food, and hospital waste; circular economy; and waste management infrastructure for rural areas since these are themes that require more in-depth study.

Declarations

Author contribution statement

Rafaela Garbelini Anuardo, Maximilian Espuny: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Ana Carolina Ferreira Costa: Performed the experiments; Wrote the paper.

Otávio José Oliveira: Conceived and designed the experiments; Analyzed and interpreted the data.

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Data availability statement

Data included in article/supplementary material/referenced in article.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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